Improving fuel efficiency for heavy-duty vehicles of 3.5–12 tonnes in India: Benefits, costs, and environmental impacts

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Table of Contents

Table of Figures

Table of Tables

Executive Summary

This report examines how deploying fuel-saving technologies for new heavy-duty vehicles (HDVs) with gross vehicle weights (GVWs) of 3.5 to 12 tonnes in India could reduce petroleum consumption and carbon dioxide (CO_2) emissions. Such HDVs play a vital role in India's economic growth, but they also consume substantial fuel and produce major environmental impacts. Analyzing the efficiency improvement potential for this category of vehicles helps clarify the potential impacts of fuel efficiency and emission standards for all HDVs in India, the home of 18 of the world's 100 worst pollution-affected cities (WHO, 2018). This report builds on a previous analysis of Indian heavy-duty vehicles over 12 tonnes.

Methods

The analytical framework previously developed to examine Indian HDVs over 12 tonnes are adapted in this study. Baseline technology profiles are created for two representative HDV types—an 11.9-tonne rigid truck and 7.5-tonne transit bus—based on top-selling vehicle models in the Indian market, using India-specific engine data and vehicle specification information from manufacturer literature and input from industry experts. For each vehicle type, seven efficiency technology packages (TPs) across five major areas, based largely on research supporting U.S. HDV fuel efficiency and associated regulations, are developed: engine, transmission and driveline, tires, aerodynamics, and weight reduction. The economic benefits and costs for each technology package and vehicle type are estimated to assist Indian stakeholders to determine feasible levels for HDV fuel efficiency standards for 3.5 to 12 tonnes category. The fuel-saving technologies for the 2025-2030 timeframe are based heavily on research done in support of the fuel efficiency and greenhouse gas regulation for HDVs in the U.S.

Another model is also developed to estimate the fleet-wide fuel demand and GHG impacts of deploying new HDVs with the TPs starting in 2020. The model is calibrated for new HDV vehicle sales, overall population, and total fuel consumption using historical statistics from the Indian government.

Results

Results show that India has substantial opportunity to improve the fuel efficiency of HDVs of 3.5 to 12 tonnes using cost-effective technologies. As shown in Table ES 1, TPs improve the fuel economy of these vehicles by 7% (TP1) to 28% (TP6) and provide a return on the initial capital investment within about one year (TP1) to three years (TP6). Since HDVs are typically driven more and have substantially higher fuel consumption compared with personally owned vehicles, fuel-saving technologies for HDVs generally have relatively short payback periods. Use of the loan shortens payback periods even more while decreasing NPV. TP7—which adds the relatively expensive hybrid-electric system—is the only exception. Its initial cost is not paid back within the lifetime of the vehicles analyzed.

Across all the technology packages and vehicle types, engine and tire technologies provide the most cost-effective efficiency improvements, primarily for two reasons: 1) under India-specific driving conditions (low average speeds and prevalent overloading), the combined energy losses due to the engine and tires represent between 75% and 85% of the total losses, and 2) engine and tire technologies are relatively inexpensive compared with advancements in other technology areas.

Most technologies in the technology packages are currently unavailable in India. However, the country's recent regulation of HDVs over 12 tonnes could spur significant deployment of such technologies, which are available in more advanced markets such as the United States and European Union.

Table ES 1. Results: Fuel consumption reduction, incremental cost, and payback time of each TP

Vehicle type	Technology packages	Fuel consumption reduction	Incremental cost, including tax and 20% markup	Payback (years)
Rigid truck	Baseline	0.0%		
	TP1. Radial tires + BS VI engine	14.0%	8.0%	1.0
	TP2. LRR tires + BS VI engine	15.4%	8.8%	1.0
	TP3. LRR tires + 'Advanced Level 1' engine + AMT	21.1%	23.4%	2.1
	TP4. LRR tires + 'Advanced Level 1' engine + Advanced AMT	22.0%	25.8%	2.3
	TP5. LRR tires + 'Advanced Level 2' engine + Advanced AMT + 1% weight reduction	24.6%	30.6%	2.4
	TP6. Advanced tires + 'Advanced Level 2' engine + Advanced AMT + Moderate truck aero + 2.5% weight reduction	27.8%	46.5%	3.5
	TP7. Advanced tires + 'Advanced Level 2' engine + hybrid + Advanced truck aero + 5% weight reduction	40.4%	257.7%	>20
Transit bus	Baseline	0.0%		
	TP1. BS VI engine	6.9%	6.8%	0.9
	TP2. LRR tires + BS VI engine	8.0%	7.8%	0.9
	TP3. LRR tires + 'Advanced Level 1 Engine' engine + AMT	14.2%	33.0%	2.6
	TP4. LRR tires + 'Advanced Level 1' engine + Advanced AMT + 1% weight reduction	15.3%	37.8%	2.8
	TP5. LRR tires + 'Advanced Level 2' engine + Advanced AMT + 2.5% weight reduction	18.2%	45.1%	2.8
	TP6. Advanced tires + 'Advanced Level 2' engine + Advanced AMT + 5% weight reduction	20.6%	56.0%	3.1
	TP7. Advanced tires + 'Advanced Level 2' engine + hybrid + 7.5% weight reduction	36.2%	410.7%	>20

AMT: automated manual transmission, BS: Bharat Stage, LRR: low rolling resistance.

Introducing fuel efficiency standards for these HDVs in India would provide significant petroleum and GHG reductions. Figure ES 1 shows diesel savings from each TP between 2020 and 2050. Compared with the baseline scenario (diesel consumption of 86 billion L and related direct CO_2 emissions of 230 million tonnes in 2050), projections show that achieving the TP scenarios would reduce annual diesel consumption and related direct CO_2 emissions by about 10% (TP1), 11% (TP2), 17% (TP3), 18% (TP4), 21% (TP5), 24% (TP6), and 38% (TP7) in 2050. Consequently, the impact of this segment of transportation on the environment would be reduced.

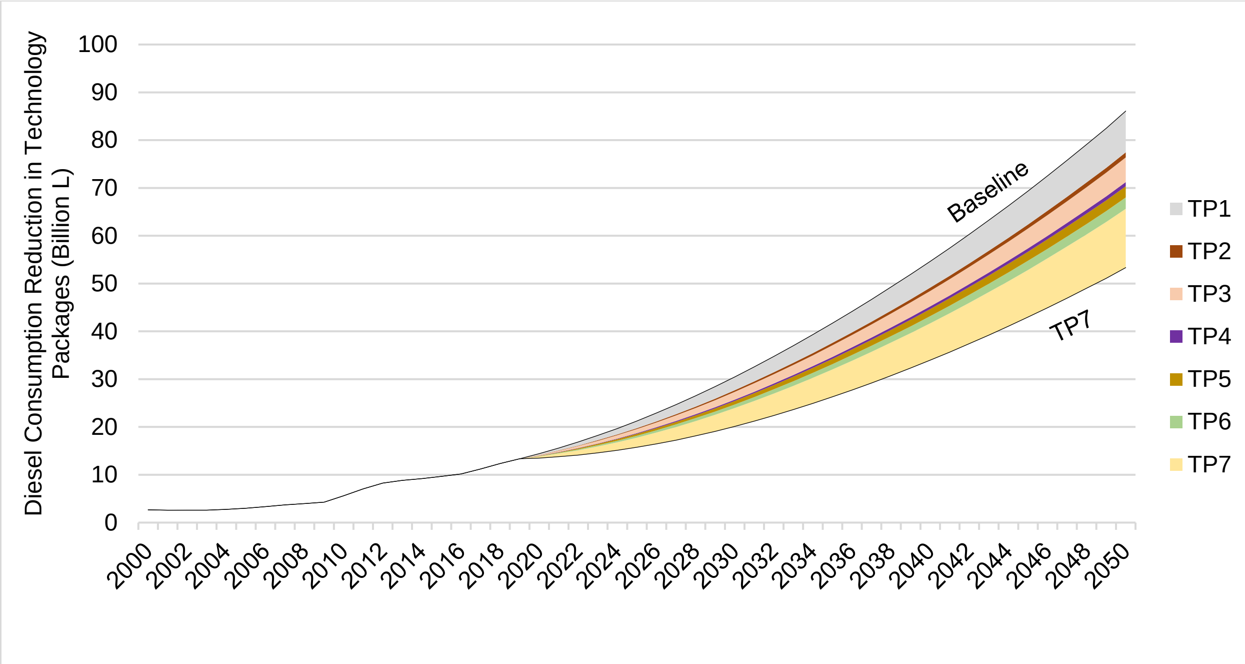

Figure ES 1. Diesel consumption reduction from each TP

Policy Recommendations

The fuel consumption and GHG reduction benefits from improving the efficiency of 3.5 to 12 tonne HDVs can best be realized via near-term implementation of fuel efficiency standards. Due to their relatively high turnover rates and extreme daily usage, freight truck and transit bus fleets in this HDV category offer great potential for rapid penetration of efficiency technologies. The following actions by policymakers and other key stakeholders in India's commercial vehicle industry can create the enabling environment and potentially pave the way for improving fuel efficiency of small and medium heavy duty vehicles:

1. **Establish fuel efficiency standards**: Since 2017, India has set up fuel efficiency standards (administered by the Bureau of Energy Efficiency) for commercial HDVs with GVW of 12 tonnes and above. These standards will be ratcheted up by 8-10%, depending on the GVW and axle configuration, in April 2021. Medium and Light HDVs with GVW between 3.5 tonnes and 12 tonnes are not governed by any fuel efficiency standards. These vehicles are responsible for roughly 40% of the total fuel consumption and thus emissions by HDVs in India (Karali et al., 2017). Given the cost-effectiveness of key efficiency technologies shown in this report, establishing fuel efficiency standards for this category of HDVs in the near future will make a large impact in the overall fuel consumption, imports, and GHG emissions. It is also important to harmonize standards for smaller and larger HDVs to avoid large differences in fuel efficiency targets at GVWs of exactly 12 tonnes.

2. **Develop fuel efficiency regulatory norms with long term targets**: Early signaling of efficiency targets gives industry sufficient time for research, development, and deployment of new and improved technologies. For example, Japan's Top Runner Program sets the fuel efficiency standard of cars as well as HDVs. The Top Runner Program determines the fuel efficiency target for a future year based on the most efficient product in that class already available in the market. Typically, this raises the efficiency target significantly, but manufacturers are given several years to comply. In the United States, the HDV fuel efficiency standards have a long-term target as well. For example, in 2011 HDV fuel efficiency and GHG emission targets were set for 2017 and targeted ~24% fuel efficiency improvement over the 2010 models. Also, 2027 fuel efficiency

norms were enforced in 2016 with a target of improving the efficiency by 30% over 2017 models. India is well positioned to leverage the lessons learned and the technical data from existing HDV fuel efficiency and GHG regulations. The Indian HDV industry needs to comply to the Bharat VI emission standards from 2020 onward.[1] Therefore, it would be advantageous to align the staging of fuel efficiency standards with the emission standards schedule. Requiring simultaneous technology upgrades for pollutant emissions and efficiency will likely ease the burden on manufacturers' design cycles, which typically occur at three to four year intervals.

3. **Cultivate testing efforts for heavy duty vehicles, engines, and component systems**. Accelerating efforts to: (a) develop and implement testing campaigns will provide the data critical for better fuel efficiency regulations and real-world benefits, (b) make the standardized test results widely accessible.[2] This will also potentially help streamline vehicle testing efforts. Moreover, streamlining testing campaigns will be immensely helpful in eventually moving towards a simulation based testing framework for more accurate representation of the vehicle efficiency in real-world driving conditions. The Government of India, industry, and research community play a part in cultivating testing regimes.

4. **Develop complementary policies for alternative fuel and electric vehicles.** Another possible pathway could be a corresponding transition to alternative powertrain technologies, such as electric buses and trucks, to reach a significant share of the on-road fleet by 2050. India has already announced an aspirational goal of electrifying all vehicles sales by 2030. Several cities have already implemented pilot programs for including electric buses in their municipal bus fleets. As a policy example at the subnational level in the U.S., California's Zero Emissions Vehicle (ZEV) mandate has been successfully used to encourage the long-term transition to cleaner mobility options.

[1] https://www.theicct.org/sites/default/files/publications/India%20BS%20VI%20Policy%20Update%20vF.pdf
[2] Test drive cycle and the real-world drive cycle of a vehicle may be significantly different from each other, which could create discrepancy between the design fuel efficiency and real-world fuel efficiency.

1 Introduction

India's transportation sector grew at an average rate of 6.8% between 2000 and 2015, and it currently accounts for 14% of the country's final energy consumption (IEA, 2015). The sector's energy consumption is dominated by diesel fueled heavy-duty vehicles (HDVs). About 70% of the country's diesel is consumed by the transportation sector (PPAC, 2013). Trucks and buses together account for 54% of the total diesel consumed by road transport (PPAC, 2013). India's diesel consumption has doubled in the past decade, increasing from 36.6 million metric tonnes (MMT) in 2002 to 79.3 MMT in 2017. (MoPNG, 2018). Overall the import dependence of India's petroleum product consumption is very high. For example, nearly 87% of total crude oil consumption (220.4 MMT) in 2017-18 was imported.

Between the 1950s and 2011, road transportation's share of passenger travel in India increased from 15% to 86%, and its share of freight movement increased from 14% to roughly 70%, while total road network length increased from 0.4 million km to 4.7 million km (Malik and Tiwari, 2017). Most of the growth has been realized in the last two decades. For example, road freight movement (in tonne-kilometers) and road passenger movement (in passenger-kilometers) increased at an average annual growth rate of 8.9% and 10.2% between 2002 and 2012, respectively (MoRTH, 2015). The HDV population, including all bus and truck categories, increased from about 1.7 million in 2000 to about 4.7 million in 2016 (International Council on Clean Transportation, 2018). This growth in HDVs is expected to continue and increase India's petroleum import dependency from 76% to 90% by 2030 (Sharma et al., 2014).

In addition to consuming substantial petroleum, HDVs in India release large amounts of toxic air pollutants and greenhouse gases (GHGs). Emission analyses for different cities in India suggest that diesel operated commercial vehicles are the largest contributors to overall emissions (Clean Air Asia, 2012; Goel and Guttikunda, 2015; Guttikunda and Kopakka, 2014; Guttikunda and Mohan, 2014; Ravinder et al., 2014; Sharma et al., 2014).

In Karali et al. (2017), it was estimated that HDVs with a gross vehicle weight (GVW) above 12 tonnes represent 60% of total fuel use and GHG emissions from the entire Indian HDV fleet. In the same study, the costs and benefits of fuel-saving technologies for new HDVs above 12 tonnes over the next 10 years was analyzed. The study also explored how various scenarios for the deployment of vehicles with these technologies would impact oil consumption and carbon dioxide (CO_2) emissions over the next three decades. On August 16, 2017, India regulated HDVs with a GVW of 12 tonnes or greater. Phase 1 went into effect on April 1, 2018, while Phase 2 is effective beginning April 1, 2021 (Garg and Sharpe, 2017).

This study complements Karali et al. (2017) by focusing on heavy-duty trucks and buses with GVW between 3.5 and 12 tonnes. As seen in Figure 1, HDVs within this category represented about 34% of India's total HDV fleet in 2016. These vehicles are responsible for roughly 40% of India's total HDV fuel consumption and emissions (Karali et al., 2017), which corresponds to about 15% of total diesel consumption of India. Currently, India has no fuel efficiency standards for this category of vehicles.

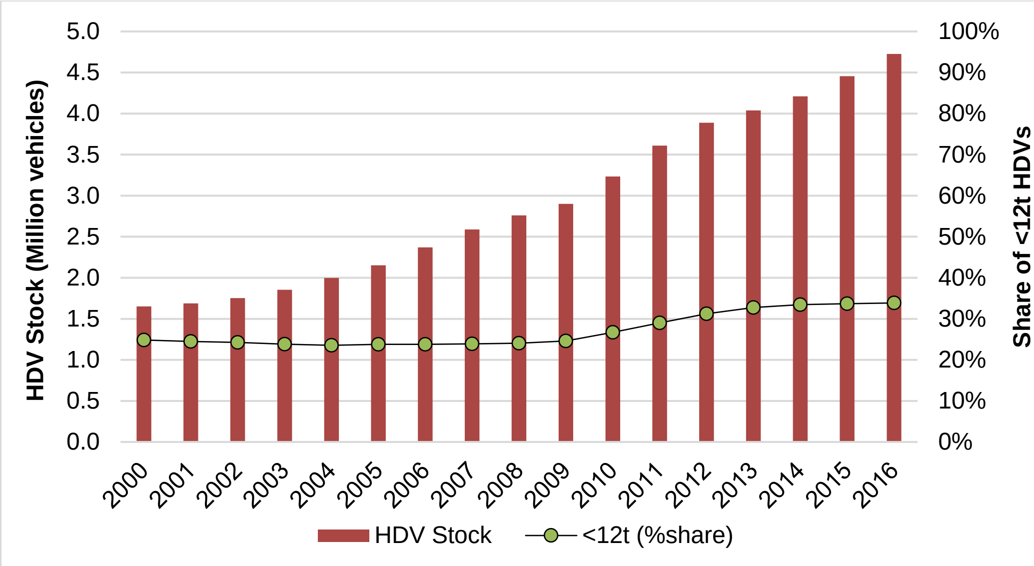

Figure 1. HDV stock and share of HDVs with GVW between 3.5 and 12 tonnes in India, 2000–2016

This category of HDVs are divided into four subcategories based on chassis type and vehicle weight (Table 1). Trucks with GVW under 7.5 tonnes are light-heavy-duty trucks (LDTs), and those with GVW between 7.5 and 12 tonnes are medium-heavy-duty trucks (MDTs). Similarly, buses with GVW under 7.5 tonnes are light-heavy-duty buses (LDBs), and those with GVW between 7.5 and 12 tonnes are medium-heavy-duty buses (MDBs).

Table 1. Classification of HDVs between 3.5 and 12 tonnes

Vehicle type	Class	Weight
Rigid truck	LDT	3.5 tonnes < GVW < 7.5 tonnes
	MDT	7.5 tonnes < GVW < 12 tonnes
Transit bus	LDB	3.5 tonnes < GVW < 7.5 tonnes
	MDB	7.5 tonnes < GVW < 12 tonnes

In Section 2, seven different HDV technology packages that combine advanced technologies to improve fuel efficiency for these classes of HDVs are analyzed. The benefit-cost analysis (BCA) method from Karali et al. (2017) are used to understand when the technology packages are economically beneficial for fleet operators (Section 3). Then, the HDV fleet energy model from Karali et al. (2017) are applied to estimate petroleum savings and CO_2 emissions reductions due to the technology packages (Section 4). Figure 2 summarizes the methods used in this study. Finally, Section 5 presents conclusions, recommendations, and areas for future research.

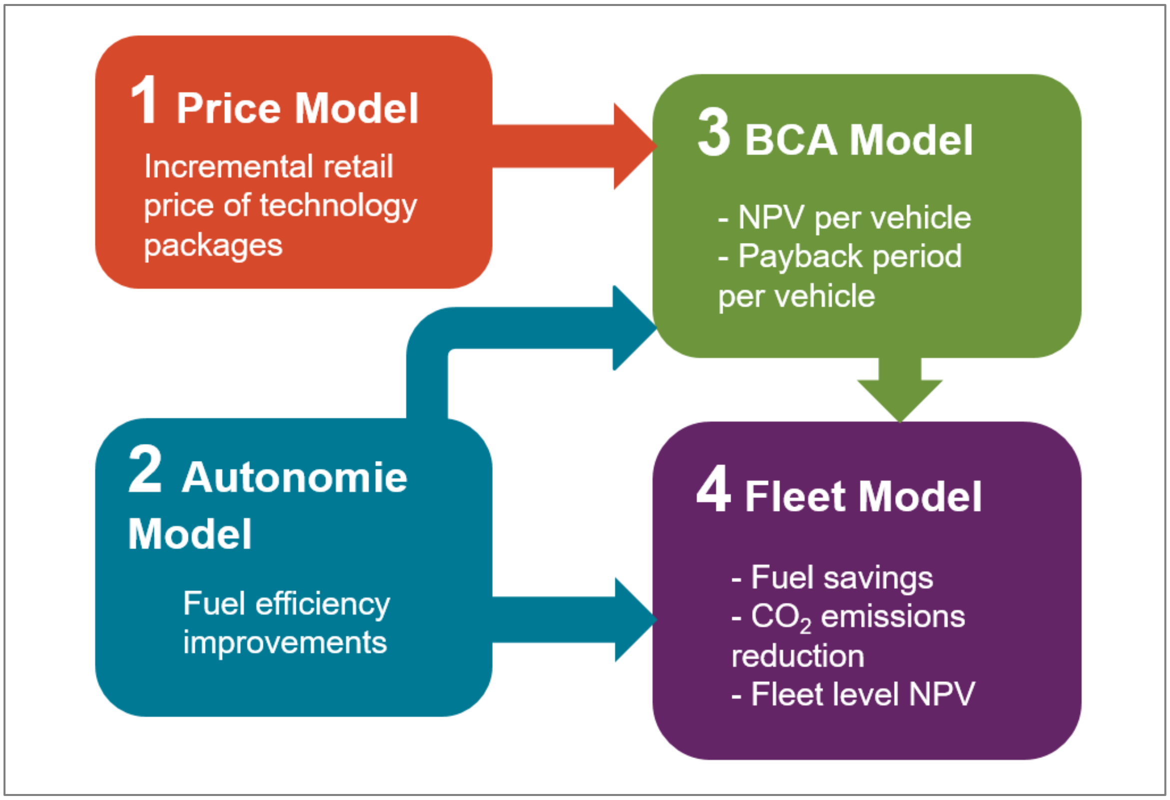

Figure 2. Summary of methods

2 Baseline and Efficient Vehicle Technologies

This section describes the representative vehicle models and technology areas explored in this analysis. After discussing the baseline vehicle technology levels and the methods used to project opportunities for efficiency technologies, the vehicle-level fuel consumption reduction potential for seven technology packages are estimated.

2.1 Baseline Vehicle Characteristics

The baseline vehicle technology levels are derived from manufacturer specification sheets and insights provided by industry experts for the India's best-selling new, less than 12 tonne vehicles in fiscal year 2013–2014 (Table 2).[3] Both vehicles have the same 3.8-L diesel engine with a peak rated power of 92 kW, which simulated using brake-specific fuel consumption data developed from engine dynamometer testing performed by an automotive research facility in India. The engine is certified at the Bharat Stage IV (BS IV) emission level.

Table 2. Baseline vehicle parameters

Parameter	Rigid truck	Transit bus
Model year	2017	
Engine	Bharat Stage IV with exhaust gas recirculation, 3.8 liter, 92.1 kW	
Transmission	6-speed manual	
(gear ratios: 1st, 2nd, 3rd, …, 6th)	(7.9 (reverse), 9.2, 5.3, 3.2, 2.1, 1.4, 1)	

[3] Total sales for each model include all currently available models sold in India.

Maximum payload (kg)	8,405	4,698 (roughly 80 passengers if 60 kg per person is assumed)[4]
Gross vehicle weight (kg)	11,990	7,490
Coefficient of aerodynamic drag (C_D)	0.7	
Frontal area (m^2)	5.5	6.2
Coefficient of rolling resistance (C_{RR})	0.0088	0.0072
Final drive ratio	5	5

There is no available data on typical loading factors for trucks or buses in India, so these vehicles are modeled assuming maximum GVW and thus maximum payload. Discussions with fleets and experts from the trucking industry indicate that very heavy loading is common for the HDV sector in India. For the technology packages in which it is assumed that weight-reduction technologies such as material substitution reduce the curb (or empty) weight of the vehicle, the payload is increased such that the GVW remains constant. For example, if the curb weight of the vehicle is decreased by 200 kg, the payload value is increased by 200 kg. The simulations are performed using Autonomie, a modeling tool developed in the United States (UChicago Argonne LLC, 2016), to evaluate the reduced fuel consumption due to individual technologies and technology packages. The packages are detailed in Sections 2.2. through 2.6, and the simulation results are discussed in Section 2.7.

2.2 Engine Technologies

Beginning on April 1, 2017, all HDVs in India were required to achieve the BS IV emission standard. BS IV is the Indian version of the Euro IV emission-control regulation that was introduced in the European Union in January 2005 (Central Pollution Control Board, 2017). In early 2016, India's Ministry of Road Transport and Highways issued a draft notification for leapfrogging BS V to go directly to the BS VI emission standard starting April 1, 2020.

The shift from BS IV to BS VI requires manufacturers to make substantial investments in technology, primarily diesel particulate filters (DPFs). DPFs are highly effective in reducing particulate matter emissions. However, as a result of increased backpressure and elevated fuel use that is often required during periodic regeneration, DPFs tend to increase fuel consumption by around 2%–3%. Manufacturers in other markets such as Europe, North America, and Japan have introduced fuel efficiency technologies to mitigate this increased fuel consumption.

Table 3 shows the three additional steps in engine technology advancement beyond BS VI assumed in this analysis. On the basis of interview responses from industry experts in India, it is assumed that roughly comparable engine technologies can be used in the Indian HDV market. These engine technology areas include:

- Friction reduction
- On-demand accessories
- Combustion system optimization
- Advanced engine controls
- Turbocharger improvements
- After treatment improvements
- Waste heat recovery systems, including turbo compounding and Rankine bottoming cycles

In Table 3, the fuel consumption reduction percentages for each of the four engine levels beyond the baseline (BS IV engine) are approximations based on Delgado and Lutsey (2015) and on the required engine efficiency improvements for tractor-trailers and vocational vehicles in the U.S. Phase 1 and 2

[4] While the manufacturer product specification sheet lists this bus as having a 32-person capacity, anecdotal evidence suggests that passenger over-loading is fairly commonplace in India, this is why this study evaluates the bus at maximum allowable weight.

regulations. Delgado and Lutsey assume a U.S. model year 2010 baseline, which is roughly equivalent to a BS VI (or Euro VI) engine, because both emission levels require roughly the same emission control technologies to achieve about the same emission benefits (Sharpe and Delgado, 2016). The U.S. fuel efficiency and GHG regulations for commercial vehicles have separate requirements for engines in tractor-trailers and vocational vehicles. In both phases of the U.S. regulations, the stringency targets for the engines of tractor-trailers and vocational vehicles are similar in magnitude.[5] However, it is assumed that similar levels of engine improvements are applicable for rigid trucks and transit buses, although the specific technology pathways vary according to differences in load and duty cycle. Nearly equivalent levels of fuel efficiency technology potential have been evidenced in engines across the various HDV classes and engine sizes in the U.S. regulatory program (US Environmental Protection Agency and Department of Transportation, 2016).

In addition, it is assumed the transit buses in this analysis are not loaded with air conditioning, since this is more representative of the current baseline in India. However, if the buses with air conditioning become the preferred choice for transit agencies, it would be prudent to include air conditioning in the analysis due to the additional associated auxiliary loads on the engine.

Table 3. Engine technology progression

Engine technology level	Approximate U.S. model year, based on improvements required by U.S. Phase 1 and 2 fuel efficiency regulations	Reduction in engine fuel consumption versus baseline
Baseline: BS IV engine	2004	—
BS VI engine	2010	5%
Advanced Level 1 engine	2014	10%
Advanced Level 2 engine	2017	12.5%
Advanced Level 3 engine	2021	15%

2.3 Transmission Technologies

Advanced transmission technologies include various friction-reduction measures and more highly integrated engine/transmission strategies, which allow increased engine operation near the highest-efficiency speed/torque points. Automated manual transmissions (AMTs) are standard manual transmissions with additional sensors and actuators that allow the transmission control module to shift gears automatically and without intervention from the driver. Fuel savings are realized because the engine operates for a larger percentage of time in higher-efficiency regimes. Although the fuel savings benefits of AMTs are different for the rigid truck and transit bus, data from U.S. regulatory agencies suggest that these differences are likely one to two percentage points or less ((U.S. Environmental Protection Agency and Department of Transportation, 2016). Therefore, as a simplification in this study, it is assumed that the AMT efficiency benefits are the same for both vehicle types. This study assumes two levels of AMT in operation for India: 1) equivalent to the commercial AMTs currently available in more advanced markets such as North America and Europe, and 2) accounting for the improvements in AMT operational efficiency expected to occur in the post-2020 timeframe.

Beyond AMTs, the transmission technology is assumed to have the greatest impact and can be commercialized between 2020 and 2030 in India is the hybrid-electric drivetrain. A hybrid-electric drivetrain derives power from two energy sources: the internal combustion engine and the onboard battery pack. The fuel consumption benefits of a hybrid-electric drivetrain primarily stem from enabling the engine to operate in higher-efficiency regimes for a larger percentage of the time and from recovering a portion of the energy otherwise lost as heat during the braking process. Hybrid-electric powertrains are generally most beneficial in highly transient driving situations. Many HDVs in India, especially the ones under 12-tonne category, operate in stop-and-go urban driving conditions, so hybrid-electric trucks and

[5] Tractor-trailer engines are evaluated over a steady-state cycle, which is meant to represent highway driving. In contrast, vocational vehicles, which are assumed to operate much more frequently in urban conditions, have their engines evaluated with a transient cycle.

buses would likely be highly effective in the Indian context. However, as is the case in other major markets, hybrid HDVs have seen very limited adoption in India, largely because of prohibitively high vehicle costs and advances in other fuel-saving technologies areas that are more cost-effective.

Simulating benefits is more difficult for transmission technologies such as AMTs and hybrid-electric drivetrains than for other technology areas, because much of the fuel-savings potential of these systems is based on proprietary manufacturer control systems and sophisticated integration of the engine and transmission. Therefore, the fuel consumption benefits of AMTs and hybrid drivetrains are estimated during post-processing. For the conventional and advanced AMTs, overall vehicle fuel consumption reductions of 2.5% and 3.5% are assumed, respectively, based on values in Delgado and Lutsey (2015) and U.S. HDV GHG regulations. Although the fuel-savings benefits of AMTs are different for the rigid truck and transit bus, data from the U.S. regulatory supporting materials suggest that these differences are likely one to two percentage points or less. Therefore, as a simplification in this study, it is assumed that the AMT efficiency benefits are the same for both vehicle types. For hybrid-electric drivetrains, a 15% overall fuel efficiency benefit for both the rigid truck and transit bus are assumed, based on values for light heavy-duty urban vehicles in the U.S. Phase 2 rule (U.S. Environmental Protection Agency and Department of Transportation, 2016).

Beyond the adoption of advanced transmission technologies such as AMTs and hybridization, it is also assumed that improvements in axles and lubrication will provide benefits for trucks and buses in India. As discussed in the Regulatory Impact Analysis for the U.S. Phase 2 regulation, low friction axle lubricants and other friction-reduction approaches across the driveline can reduce overall fuel consumption by up to 2% (U.S. Environmental Protection Agency and Department of Transportation 2016). As shown in Table 4, axle efficiency and lubrication improvements are assumed to provide between 0.8% (TP1) and 1.5% (TP7) fuel savings and that these percentages are the same across the two vehicle types.

Table 4. Percentage reduction in fuel consumption due to axle and lubrication improvements

Technology package	Fuel savings due to low friction axle lubricants and other driveline friction-reduction inventions
1	0.8%
2	0.9%
3	1.0%
4	1.1%
5	1.3%
6	1.4%
7	1.5%

2.4 Tire Technologies

Rolling resistance, or rolling friction, is the force resisting the motion of the tires on a surface. As the vehicle moves, the tire undergoes repeated cycles of deformation to adopt a moving contact patch with the surface. The energy difference between deformation and recovery results in hysteresis losses in the form of heat energy. The force can be calculated as a function of vertical load, the wheel radius, and the tow force applied on the vehicle. The constant of proportionality is termed the coefficient of rolling resistance (CRR) and is defined as follows:

$$C_{RR} = resistive\ axial\ force\ /\ normal\ force \qquad \text{(Eq.1)}$$

Values for C_{RR} are dimensionless and are typically less than 0.01 (Committee to Assess Fuel Economy Technologies for Medium- and Heavy-Duty Vehicles, 2010). The two different types of tire construction are bias-ply (“bias”) and radial. Bias tires consist of layering, where rubber plies overlap one another and run across the tires in alternating layers. In radial tires, the casing ply runs perpendicular to the circumference of the tire, thereby increasing the tire flexibility, because the sidewalls of a radial tire are not as thick as those of a bias tire. Increased tire flexibility results in lower hysteresis losses as well as a larger contact patch with the road surface. The biggest advantage of bias tires is their lower cost, whereas radial tires yield better fuel efficiency, longer useful life, and better performance. Interviews in 2016 with tire manufacturers in India indicate that roughly 80% of the HDV market in India uses bias tires. According to industry experts, the continued prevalence of bias tires is driven primarily by upfront cost sensitivity of the Indian market. In contrast, the transition to radial tires for HDVs is virtually complete in regions such as North America, Europe, and Japan (Malik et al., 2016).

Beyond the transition from bias to radial tires, two additional levels of radial tire technology improvements are used, based on advances that have happened, or are anticipated, in more technologically advanced regions. These two levels of low-rolling-resistance (LRR) tires represent improvements in the choice of elastomers, arrangement of belts and reinforcement, and tread design. Adjustments in each of these factors work together to reduce CRR values, but reduced rolling resistance must be balanced with sufficient traction and braking performance. The three tire technology levels beyond the baseline and their respective reduction in CRR values are shown in Table 5. The CRR values for each technology level are based on input from industry experts and data from both phases of the U.S. HDV fuel efficiency and GHG regulation. While simulation modeling results indicate that as vehicle weight increases, the tire rolling resistance contribution to overall losses increases, this study does not try to take into account the potential impacts of vehicle overloading beyond the maximum GVW.

Table 5. Tire technology progression

Tire technology level	Reduction in C_{RR} versus the baseline
Baseline: Bias tires*	—
Radial tires	15%–30%
LRR radial tires	30%–40%
Advanced LRR radial tires	40%–50%

* Bias tires are the baseline technology for the rigid truck; radial tires are the assumed baseline for the transit bus.

On the basis of information from tire industry experts in India, it is assumed that bias tires are the baseline for rigid trucks. However, radial tires are already used with transit buses on a large scale, so radial tires are applied as the baseline technology level for the bus.

In addition to improved tire designs, systems such as automatic tire inflation and air pressure monitoring can help reduce rolling resistance by maintaining optimum air pressure. As the amount of air in the tire decreases, the area of the tire in contact with the surface increases, resulting in higher frictional losses. According to Goodyear, the approximate relationship is that every 10 psi (69 kPa) of under inflation results in 1.5% lower fuel economy (Goodyear Tire and Rubber Company, 2015). On the basis of conversations with tire manufacturers and other industry experts, it is assumed that tire pressure management systems can play an important role in improving the fuel efficiency of commercial vehicles in India.

2.5 Aerodynamic Technologies

As a vehicle moves down the road, a pressure distribution acts on the vehicle's surface and exerts a normal pressure on the body. The summation of these normal forces that act downstream to the direction of motion represents the drag force acting on the vehicle. The aerodynamic drag force, F, is defined as:

$$F = 0.5\, C_{\mathrm{D}} A\, V^2 \qquad \text{(Eq.2)}$$

where A is the frontal area of the vehicle around which the air must flow, V is the velocity of the vehicle, and C_D is the coefficient of drag. Aerodynamic improvements allow the air around the vehicle to move more smoothly, thereby decreasing the drag force exerted on the vehicle. Because aerodynamic force is directly proportional to the square of the velocity of the vehicle, aerodynamic improvements have a greater effect at highway speeds than in urban settings, which typically have lower speeds and include stop-and-go conditions. It is assumed that there are limited opportunities for aerodynamic improvements on transit buses in India because of their low average speeds and frequent stops. Therefore, this study does not include aerodynamic technologies in any of the transit bus technology packages. For rigid trucks, a larger percentage of operations at higher speeds and apply aerodynamic interventions in the more advanced technology packages are assumed.

2.6 Weight-Reduction Technologies

Reducing vehicle weight results in lower power requirements, thereby making the vehicle more fuel-efficient. Across all types of HDVs, manufacturers have commercialized and continue to develop products using alternative materials such as aluminum and composites that lower vehicle curb (empty) weight.

In addition to reducing inertial and rolling resistance forces, the efficiency benefits of weight reduction are compounded if the operator can increase the payload as a direct result of reducing the vehicle curb weight. The potential benefit of increasing payload as a result of vehicle weight reduction is substantial in India, where freight vehicles often exceed maximum allowable GVW limits. This study represent reduced vehicle weight as a lower curb weight; the payload value is kept constant, and thus the total weight (i.e., vehicle curb weight + payload) decreases in the simulations. However, it is likely that if lightweighting presented opportunities for additional payload, trucking fleets in India would take advantage and increase the payload accordingly. For the sake of showing the fuel efficiency benefits of lightweighting, payload is held constant in the simulations.

In the technology packages described below, the first four levels for rigid trucks and the first three levels for transit buses have no weight reduction beyond baseline values; the more advanced levels incorporate weight reductions incrementally, reaching 5% for trucks and 7.5% for transit buses. The more aggressive approach to weight reduction for transit buses is evidenced in the literature (Committee to Assess Fuel Economy Technologies for Medium- and Heavy-Duty Vehicles, 2010), and it addresses the lack of aerodynamic improvement for the transit bus in this study.

2.7 Technology Packages

Fuel efficiency technology packages are developed by incrementally adding increasingly efficient technologies in the following areas:

- Engine
- Transmission and driveline
- Tires
- Aerodynamics (trucks only)
- Weight reduction

Table 6 summarizes the technology packages for the rigid truck and transit bus. Figures 3 summarizes the per-vehicle fuel consumption results for each technology package, and Figure 4 shows the incremental cost breakdown for each package by major technology area (i.e., showing the differences between costs for the baseline vehicles versus the vehicles with specified technology packages).

Table 6. Efficient technology packages

Vehicle	Technology Packages
Rigid truck	Baseline
	TP1. Radial tires + BS VI engine
	TP2. LRR tires + BS VI engine
	TP3. LRR tires + 'Advanced Level 1' engine + AMT
	TP4. LRR tires + 'Advanced Level 1' engine + Advanced AMT
	TP5. LRR tires + 'Advanced Level 2' engine + Advanced AMT + 1% weight reduction
	TP6. Advanced tires + 'Advanced Level 2' engine + Advanced AMT + Moderate truck aero + 2.5% weight reduction

	TP7. Advanced tires + 'Advanced Level 2' engine + hybrid + Advanced truck aero + 5% weight reduction
Transit bus	Baseline
	TP1. BS VI engine
	TP2. LRR tires + BS VI engine
	TP3. LRR tires + 'Advanced Level 1 Engine' engine + AMT
	TP4. LRR tires + 'Advanced Level 1' engine + Advanced AMT + 1% weight reduction
	TP5. LRR tires + 'Advanced Level 2' engine + Advanced AMT + 2.5% weight reduction
	TP6. Advanced tires + 'Advanced Level 2' engine + Advanced AMT + 5% weight reduction
	TP7. Advanced tires + 'Advanced Level 2' engine + hybrid + 7.5% weight reduction

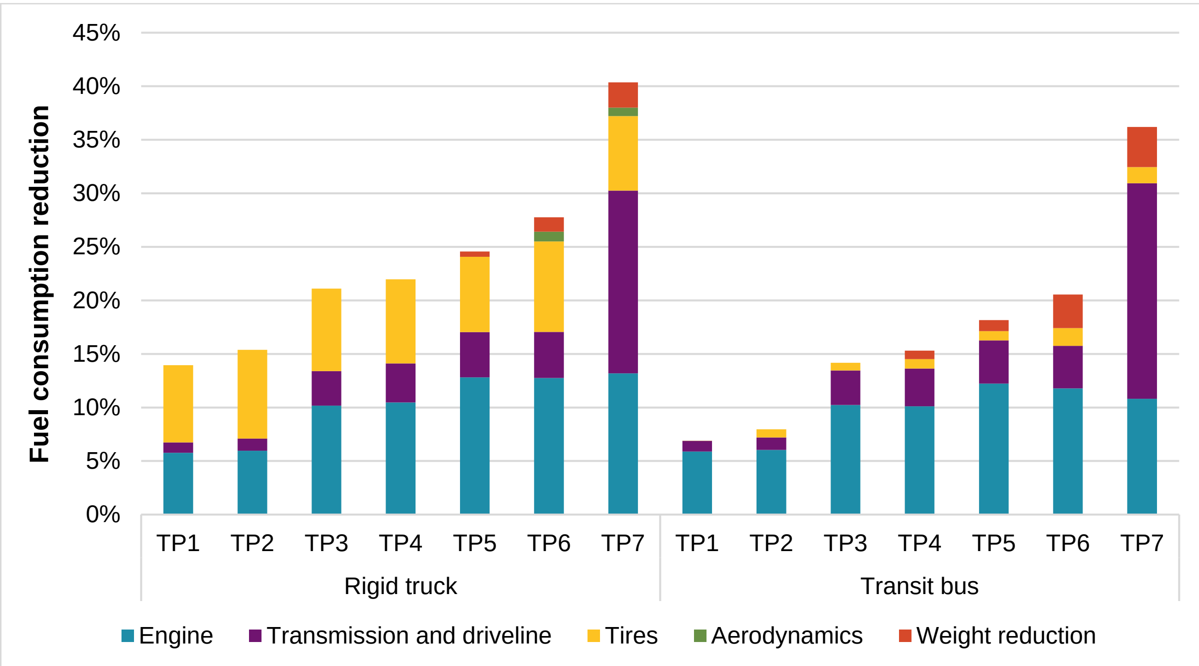

Figure 3. Fuel consumption reduction for each technology package

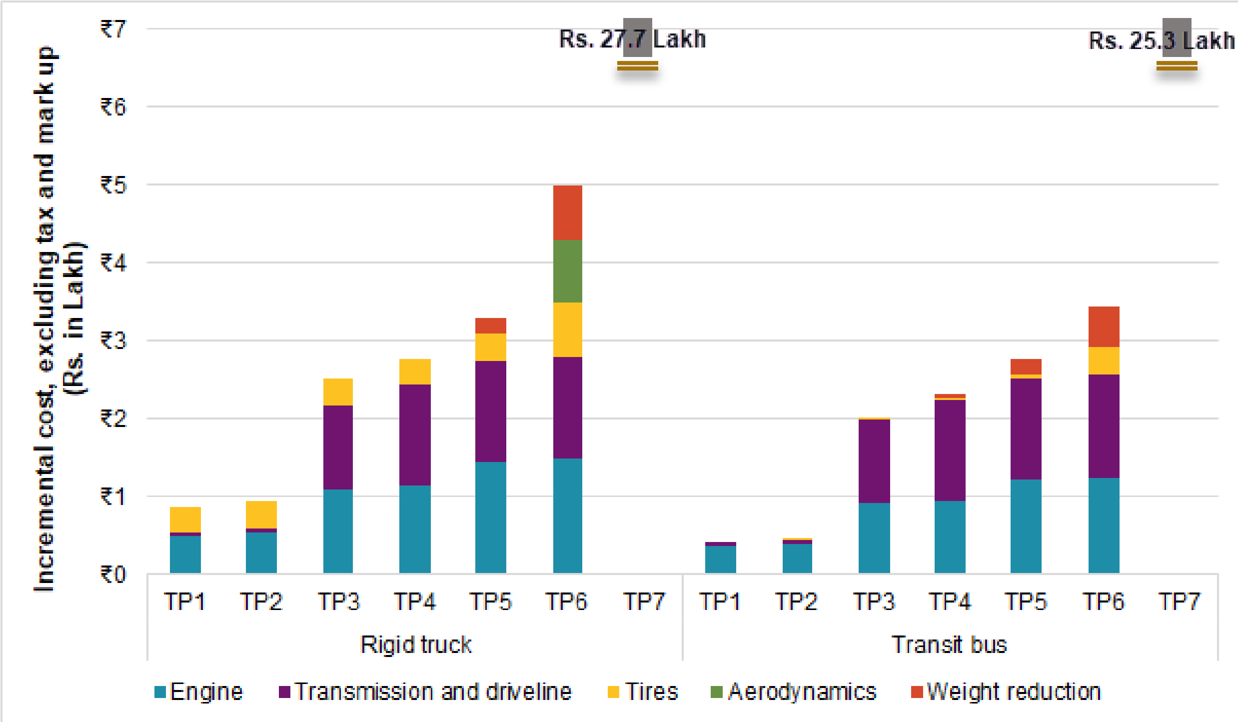

Figure 4. Incremental cost breakdown for each technology package

Note: Cost breakdown for a TP7 truck: 11% engine, 77% transmission and driveline, 2 % tires, 4% aerodynamics, and 6% weight reduction. Cost breakdown for a TP7 bus: 11% engine, 84% transmission and driveline, 1.5 % tires, and 3.5% weight reduction.

3 Benefit-Cost Analysis

In this section, a comprehensive assessment of the costs and benefits associated with each of the technology packages defined in Section 2 are performed.

3.1 Methods and Key Assumptions

The HDV BCA follows a standard BCA approach to estimating common socioeconomic indicators, such as net present value (NPV) and payback period (Figure 5). See Karali et al. (2017) for a detailed description of the model and equations. The inputs include annual vehicle kilometers traveled (VKT), vehicle fuel efficiency, fuel prices, driver labor rates, vehicle inflation rate, discount and interest rates, and incremental technology costs. This study only considers costs and benefits directly experienced by truck and bus owners and operators in India, including the benefits of fuel cost savings and reduced refueling time. Please note that this study does not include the economic value of reduced GHG emissions and air pollution as well as improvements in energy security due to oil import reductions (grayed-out benefits in Figure 5) in the current analysis. A separate analysis would be required to determine such benefits in India. For context, India imported 2.25 Billion bbl of oil/refined products in 2017.

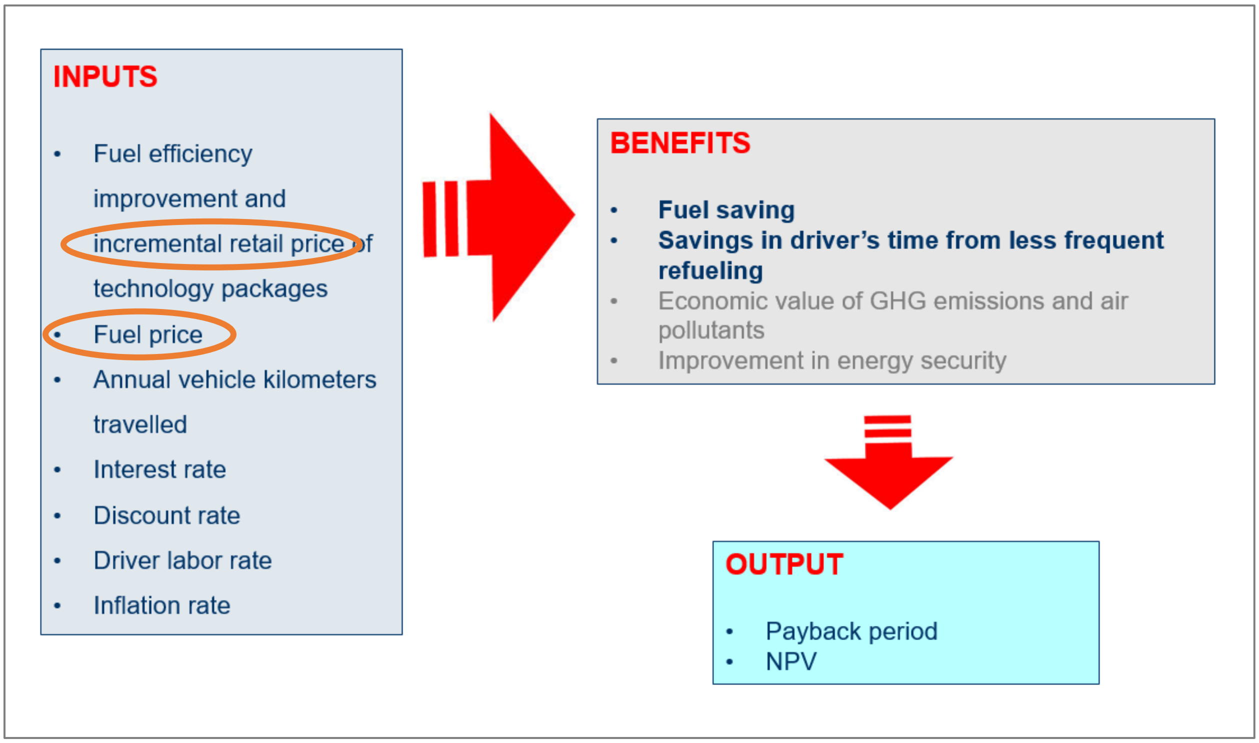

Figure 5. General structure of the HDV BCA model

Note: See Karali et al. (2017) for the details of the model and equations. Sensitivity analysis is performed for the input parameters circled in orange.

3.1.1 Baseline Fuel efficiency Values

Baseline fuel efficiency levels for the representative vehicles in each category are summarized in Table 7.

Table 7. Baseline HDV fuel efficiencies used in BCA calculations

	Weight (tonnes GVW)	Fuel Efficiency (km/L)
LDT	7.5	4.91
MDT	11.9	4.44
LDB	7.5	4.94
MDB	10.0	4.55

3.1.2 Annual Vehicle Kilometers Traveled

First-year VKTs for new trucks of 35,000 km for LDTs and 65,000 km for MDTs are assumed. The first-year VKT for all transit buses is 114,425 km (Association of State Road Transport Undertakings, 2012). It is also assumed that VKT per vehicle decreases exponentially with vehicle age, as is generally the case in other vehicle activity, fuel, and emissions models (US Environmental Protection Agency, 2011; California Air Resources Board, 2015). The equation to calculate VKT over time is as follows:

$$vkt_{age} = vkt_{1styear} * e^{-\alpha * age} \qquad \text{(Eq.3)}$$

where vkt_{age} represents the annual VKT of the vehicle at a certain age,

$vkt_{1styear}$ is the first-year VKT of the vehicle,

age is the age of the vehicle,

α is a decline parameter that controls how fast VKT declines over time.

α is set at 0.07 for trucks and buses, based on Karali et al. (2017).

3.1.3 Diesel Prices

The average price of transportation diesel fuel in India was about 65 Rs/L in 2018 (PPAC, 2018). Because the phase-in of diesel price deregulation was completed in 2014, there is no longer diesel price certainty in India (Editorial Board of the Times of India, 2014). To account for this, the diesel price is kept constant at 65 Rs/L and varied by ± 25% in a sensitivity analysis, and there is also another sensitivity analysis based on the U.S. Energy Information Administration's (EIA) diesel price growth forecasts in the United States (US Energy Information Administration, 2018).

3.1.4 Other Parameters

Other parameters relating to the operational characteristics of HDVs in India are summarized in Table 8. In addition, the assumed discount rate is 6.25% (U.S. Central Intelligence Agency, 2018). The annual depreciation and interest charges are applied as 16% and 12%, respectively, of the purchase price (Axis Bank India, 2018). The total markup is subject to large variation, and there is no evidence to back up any markup rate in India. The markup rate on manufacturing cost in this study is assumed to be 20% based on the markup value used in the U.S. HDV GHG regulation (U.S. Environmental Protection Agency and Department of Transportation, 2016).

In 2015, the Federation of Indian Chambers of Commerce and Industry (FICCI, 2015) assumed that average life for diesel trucks was 13–16 years. The average life of buses in India is 10–12 years according to the Association of State Road Transport Undertakings (2012). It is assumed that average lifetimes of trucks and buses are 14 and 12 years, respectively.

Table 8. Operational characteristics of HDVs in India

	Average lifetime (years)	Driver labor rate* Rs/hour)	Tank volume** (L)	Fuel dispensing rate*** (L/min)	Refueling fixed time*** (min/refill)
LDT and MDT	14	63	160	76	3.5
LDB and MDB	12	63	160	38	3.5

Note: The average age is assumed to be 5 years for both rigid trucks and transit buses in 2000, based on the CSIR-CRRI report (Ravinder et al., 2014).
* Source: TCI (2016). The driver labor rate was increased by the inflation rate of 4.36% (Ministry of Statistics and Programme Implementation, 2018).
** Source: Assumption based on vehicle specification sheets (Tata Motors 2018a, Tata Motors 2018b).
*** Source: Assumption based on refueling rates presented in US Environmental Protection Agency and Department of Transportation (2016).

3.2 Benefit-Cost Analysis Results

3.2.1 BCA Fuel efficiency Scenario Results

Figure 6 shows payback periods of the technology packages versus the baseline scenario for 11.9-tonne rigid trucks, and Figure 7 shows the results for 7.5-tonne transit buses, which are the two primary weight categories analyzed in this project. For the trucks, the payback period is about 1 year with TP1 and TP2, less than 2.5 years with TP3, TP4, and TP5, and about 3.5 years with TP6. For the buses, the payback period is less than 1 year with TP1 and TP2, less than 2 years with TP3, TP4, and TP5, and 2.2 years with TP6. For both vehicle types, the payback time with TP7—which adds the relatively expensive hybrid-electric system—is over 20 years and thus longer than the vehicle lifetimes.

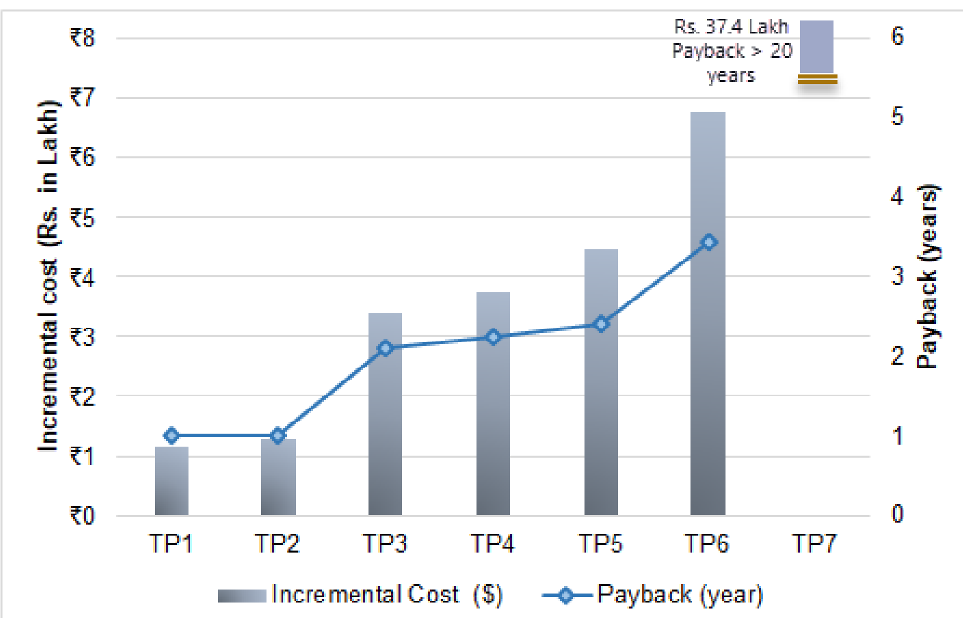

Figure 6. Payback periods for the 11.9-tonne rigid truck with each technology package, assuming one-time upfront payment
Note: Bars represent incremental cost, and markers represent payback.

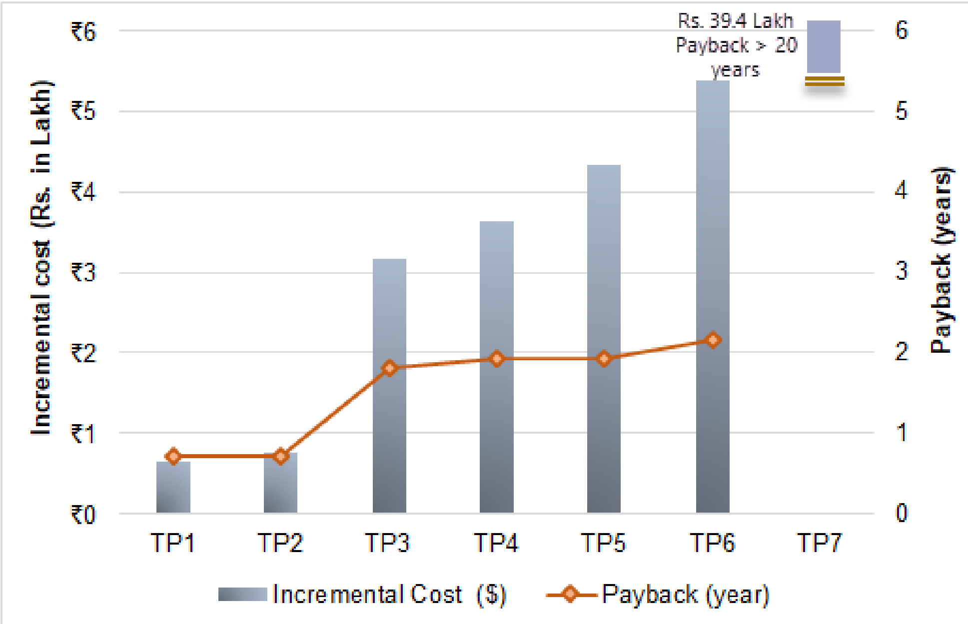

Figure 7. Payback periods for the 7.5-tonne transit bus with each technology package, assuming one-time upfront payment
Note: Bars represent incremental cost, and markers represent payback.

Figure 8 shows the NPV of the two vehicle types. Investing in an efficient technology package would save between $11,573 (TP1) and $16,254 (TP5) per rigid truck, and between $8,895 (TP1) and $20,644 (TP6) per transit bus over the lifetime of each vehicle. From the customer point of view, the most attractive technology packages are TP5 for the rigid truck and TP6 for the transit bus, because they provide the highest NPV over the vehicle lifetime. The truck's NPV with TP6 is slightly lower than with TP5, because the net-present cost increase more than offsets the net-present benefit increase when moving from TP5 to TP6 (Figure 9). The NPV is higher for the truck than for the bus when both vehicle types have TP1 or TP2, but the bus has a higher NPV under all the other TP scenarios owing to more favorable combinations of cost and benefit (Figure 9, Figure 10). For both vehicle types, NPV with TP7 is negative (Figure 8).

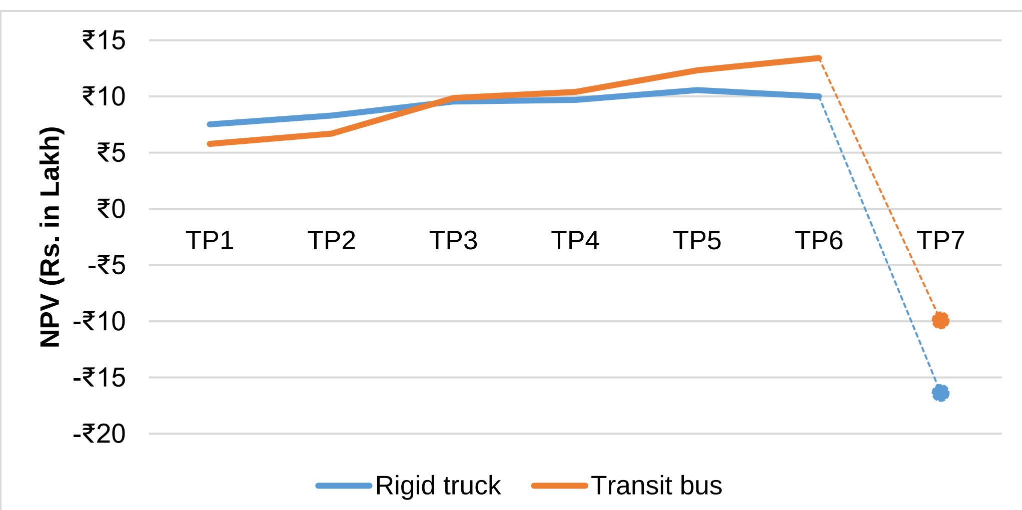

Figure 8. NPV results for each technology package and HDV category, assuming one-time upfront payment

Note: HDV categories illustrated here represents a 11.9-tonne rigid truck and 7.5-tonne transit bus.

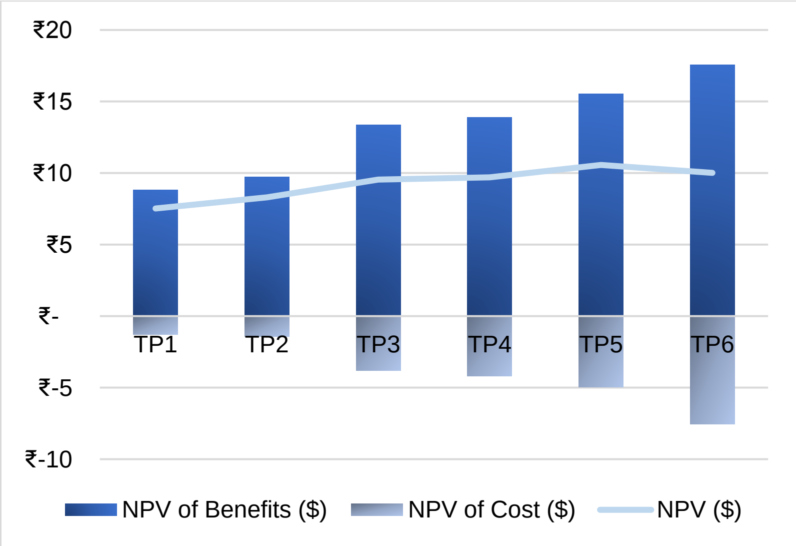

Figure 9. Benefits, costs, and NPV of rigid truck for TP1–TP6
Note: HDV categories illustrated here represents a 11.9-tonne rigid truck and 7.5-tonne transit bus.

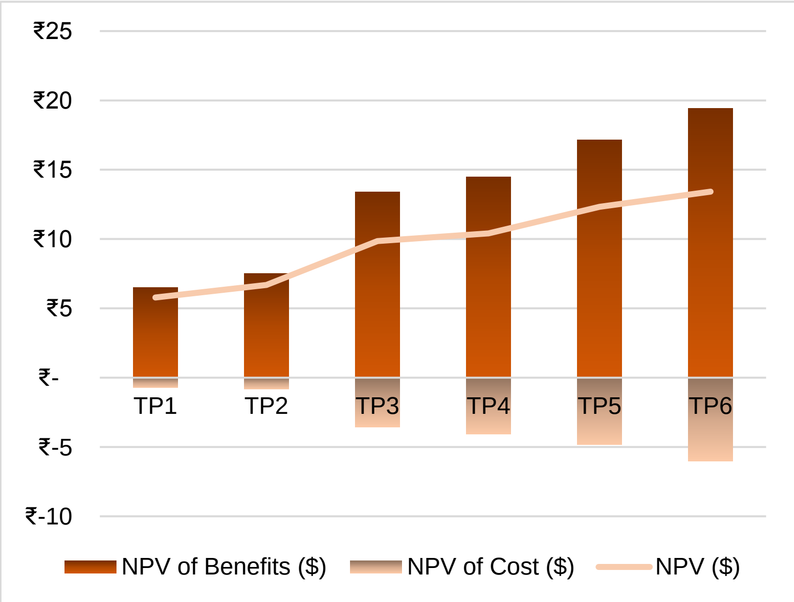

Figure 10. Benefits, costs, and NPV of transit bus for TP1–TP6
Note: HDV categories illustrated here represents a 11.9-tonne rigid truck and 7.5-tonne transit bus.

3.2.2 BCA Sensitivity Analysis Results

The incremental costs of future technologies and long-term diesel prices likely represent the largest uncertainties in this analysis. Figures 11 and 12 shows the sensitivity of the payback period and NPV to a ± 25% change in incremental cost for TP1–TP6. The payback variations are less than 1 year under most scenarios, except for the 1.2 years for trucks with TP6 (Figure 11). NPV shows an opposite trend as expected. NPV goes down as incremental cost goes up (Figure 12). For trucks, changes in NPV range from about ± $500 with TP1 to about ± $3,000 with TP6. For buses, the range is about ± $280 with TP1 to about ± $2,300 with TP6. With TP7 (not shown), a 25% reduction in incremental cost results in payback periods of above 20 years for trucks and 11.1 years for buses (just below the bus lifetime).

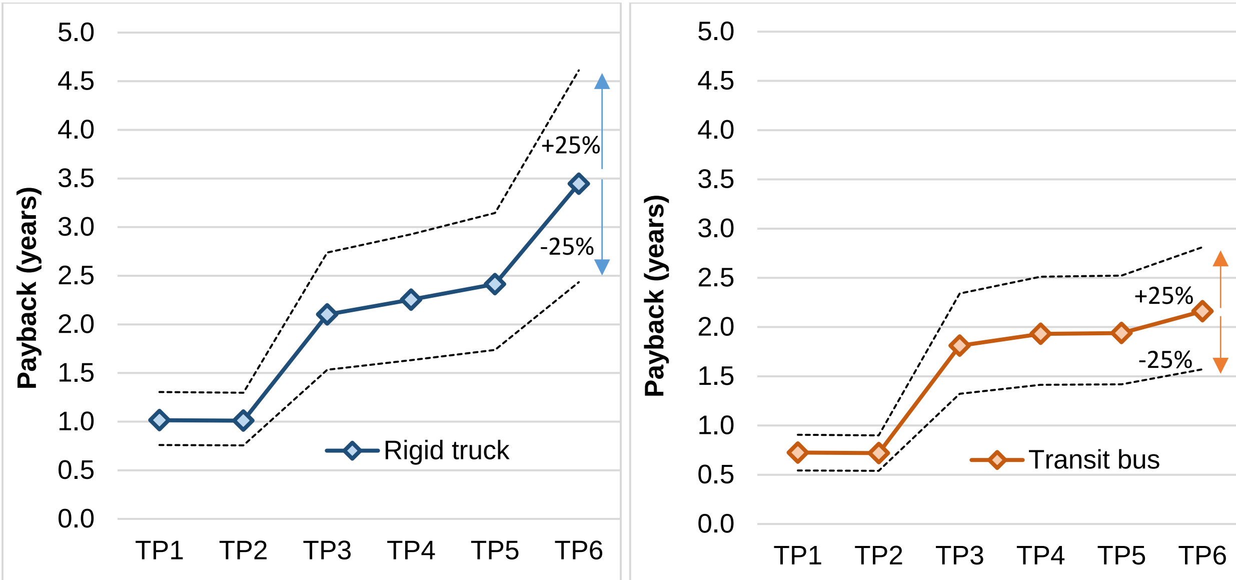

Figure 11. Sensitivity of the payback period to ± 25% change in incremental cost

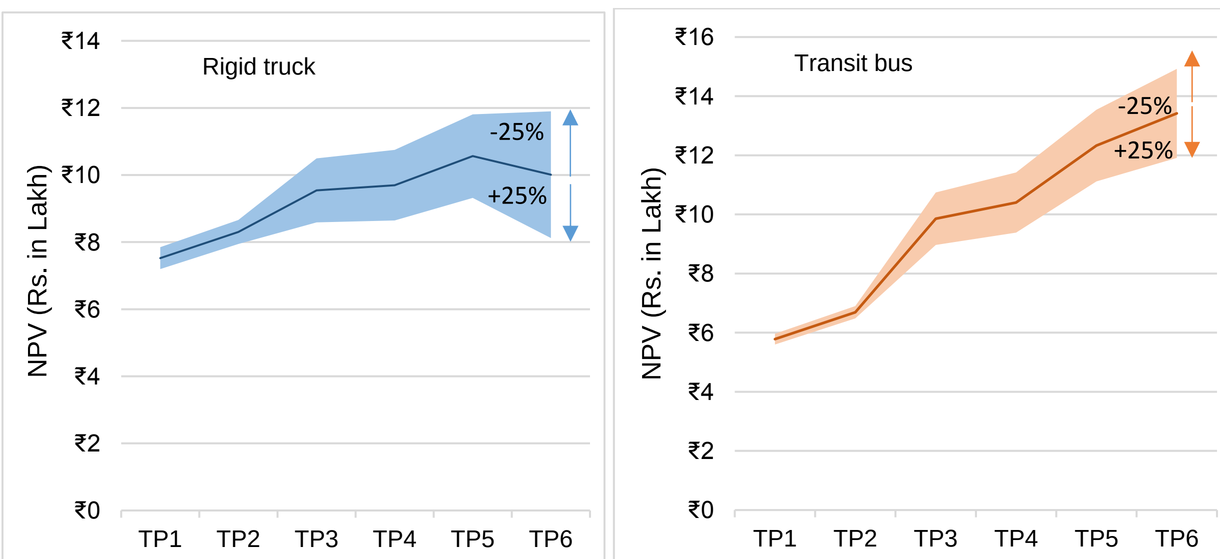

Figure 12. Sensitivity of the NPV to ± 25% change in incremental cost

Diesel prices in India fluctuates in a range of 25% since the price deregulation at October 2014, i.e., 25% difference between minimum and maximum price. In the base case, it was assumed that cost of diesel stay constant at current levels through the lifetime of the vehicle. Considering the fluctuation of the fuel prices, it is valuable to capture the changes in the results due to 25% change of the diesel price that are used. Figures 13 and 14 show the sensitivity of payback period and NPV to a ± 25% change in diesel price, for TP1–TP6. Decreasing the diesel price by 25% results in longer payback periods: with TP1, the payback period increases from 1 to 1.4 years for trucks and 0.7 to 1 years for buses; with TP6, it increases from 3.4 years to 5 years for trucks and 2.2 to 3 years for buses. Decreasing diesel prices has a larger impact on payback period than increasing prices does for both vehicle types. With TP7 (not shown), a 25% reduction in diesel price results in payback periods of above 20 years for trucks and 8.8

years for buses—the high VKTs of transit buses result in shorter bus payback periods. As Figure 14 shows, NPV increases as diesel price increases, with the effect generally greater for the more advanced technology packages: for a ± 25% diesel price, the change in NPV is about ± 30% with TP1 and about ± 40% with TP6 across both vehicle types.

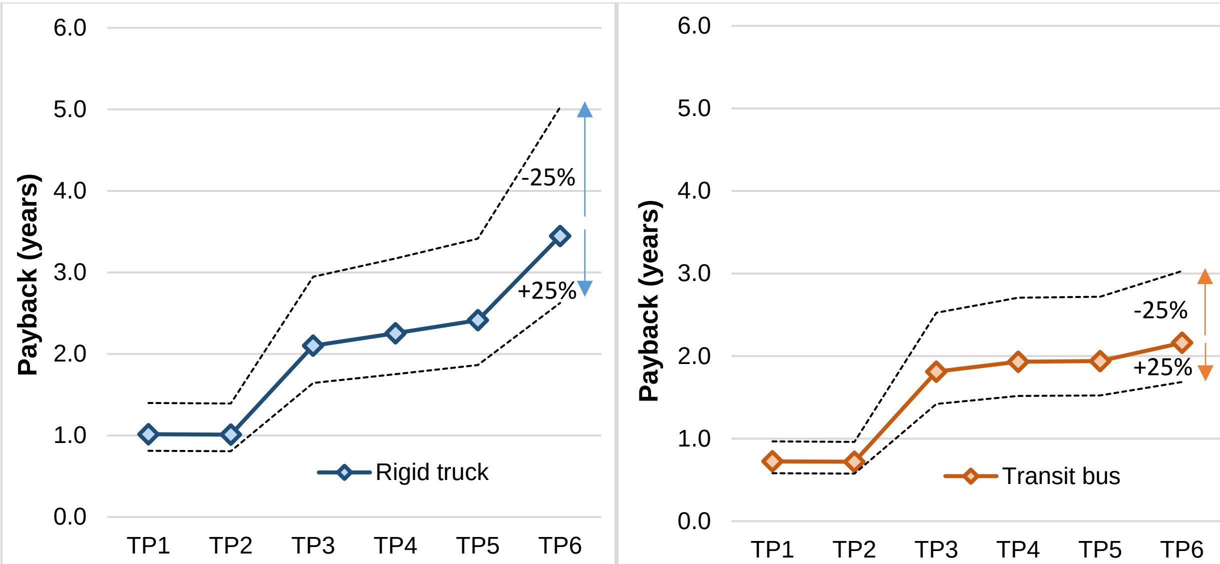

Figure 13. Sensitivity of the payback period to ± 25% change in diesel price

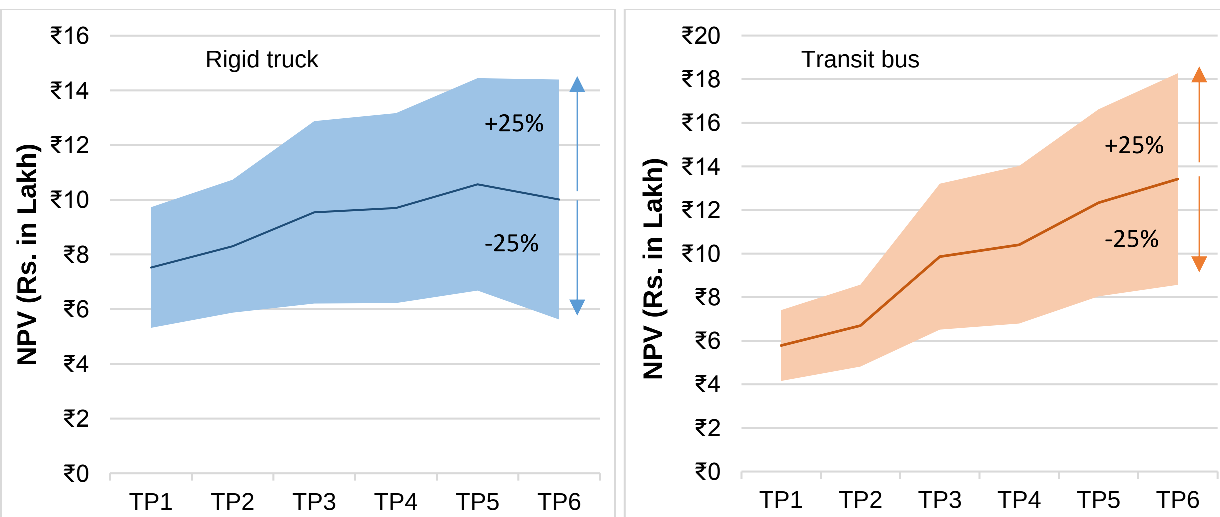

Figure 14. Sensitivity of NPV to ± 25% change in diesel price

This study also analyzes a case with increasing diesel prices in the future. To that end, an average diesel price in India in 2018 is used and increased per EIA's forecast of future diesel price growth in the U.S. (U.S. Energy Information Administration, 2018). Results show a minimal payback period change for trucks and buses, while NPV increases 10%–15% depending on the package (Figure 15).

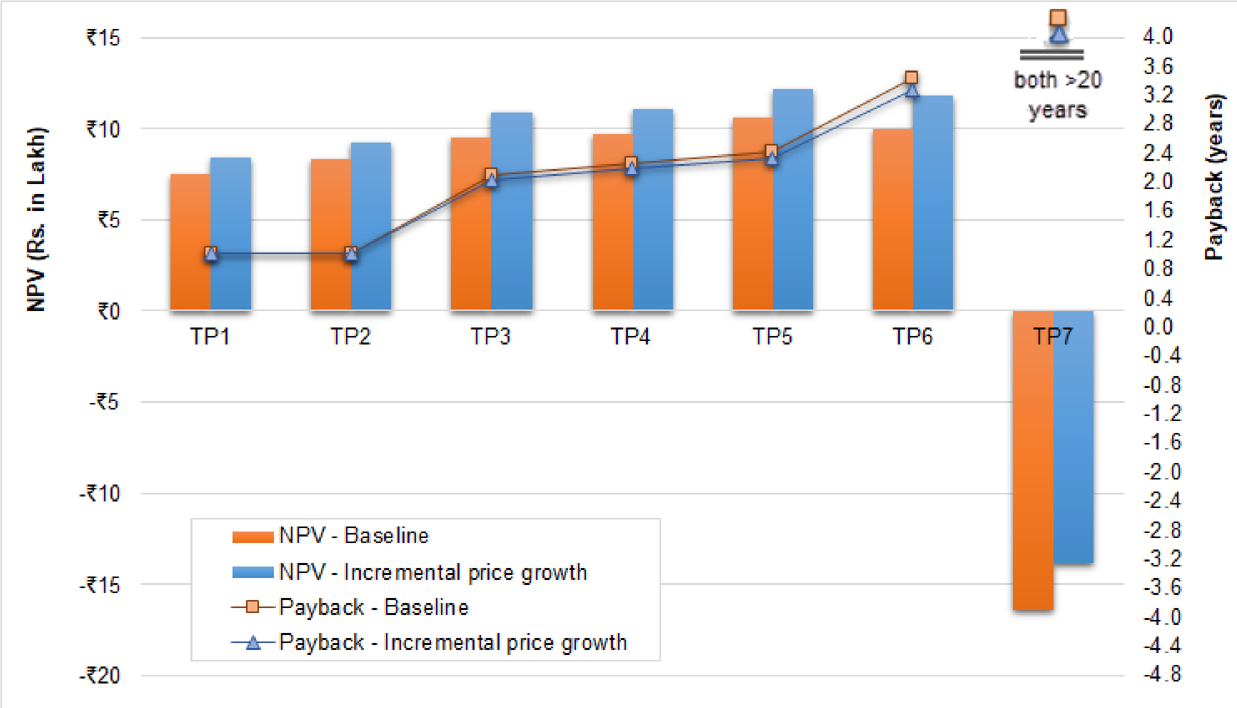

Figure 15. Sensitivity of the payback period and NPV of rigid trucks to diesel price growth

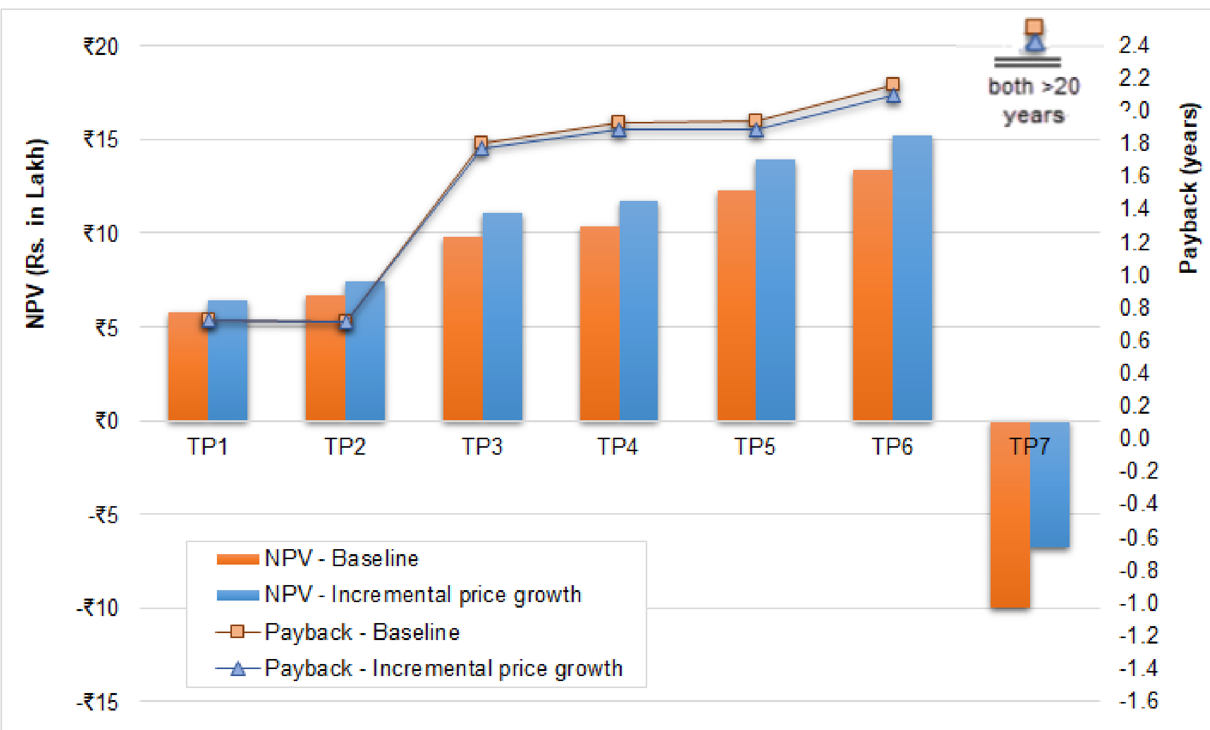

Figure 16. Sensitivity of the payback and NPV of transit buses to incremental growth of diesel price

To finance vehicle acquisition, truck operators in India typically take a loan for 2–5 years. Based on this information, a sensitivity analysis assuming a 3-year loan are performed. Use of the loan shortens payback periods while decreasing NPV. As an example, Figures 17 (trucks) and 18 (buses) show the change in payback period and cumulative benefits for TP6 with and without the loan.

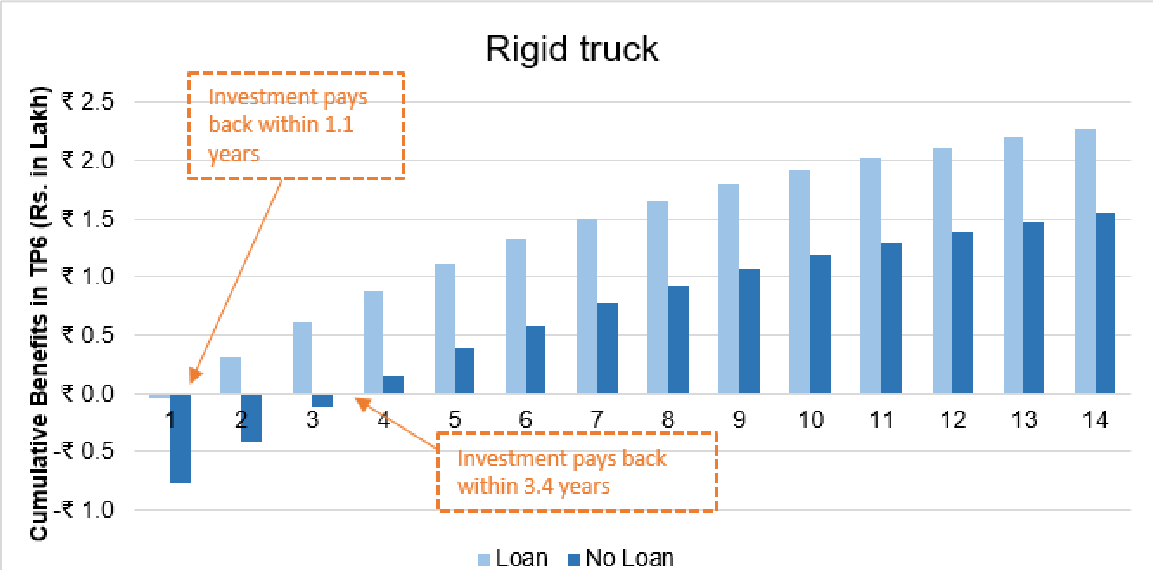

Figure 17. Cumulative benefits for rigid truck with TP6, with and without 3-year loan

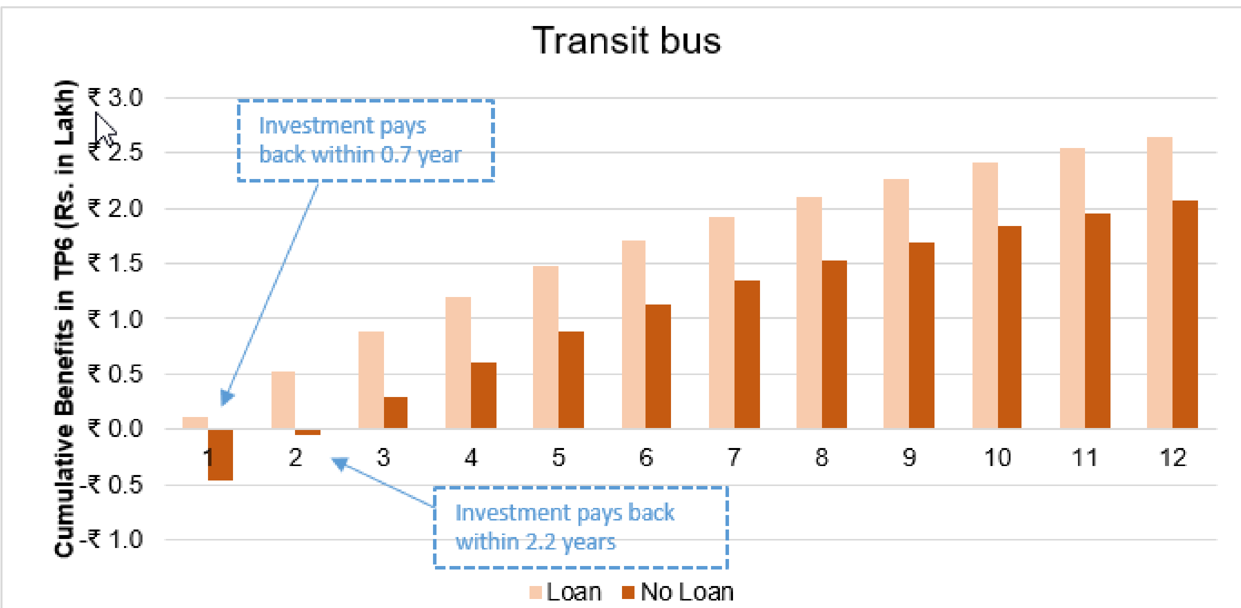

Figure 18. Cumulative benefits for transit bus with TP6, with and without 3-year loan

4 Oil and CO_2 Emissions Projections

This section investigates the fuel savings and CO_2 emissions reduction potential of the seven HDV technology packages.

4.1 HDV Fleet Energy Model and Key Assumptions

The HDV fleet energy model estimates and projects annual vehicle sales and stock, annual total VKT, annual fuel consumption, average fleet efficiency, and GHG and air pollutant emissions of HDVs (Figure 19). The model spans the years 2000 to 2050 and has annual time-steps. The initial year of the fleet analysis is 2017, and the model is calibrated against the historical data between 2000 and 2016. See Karali et al. (2017) for a more detailed description of the model and equations.

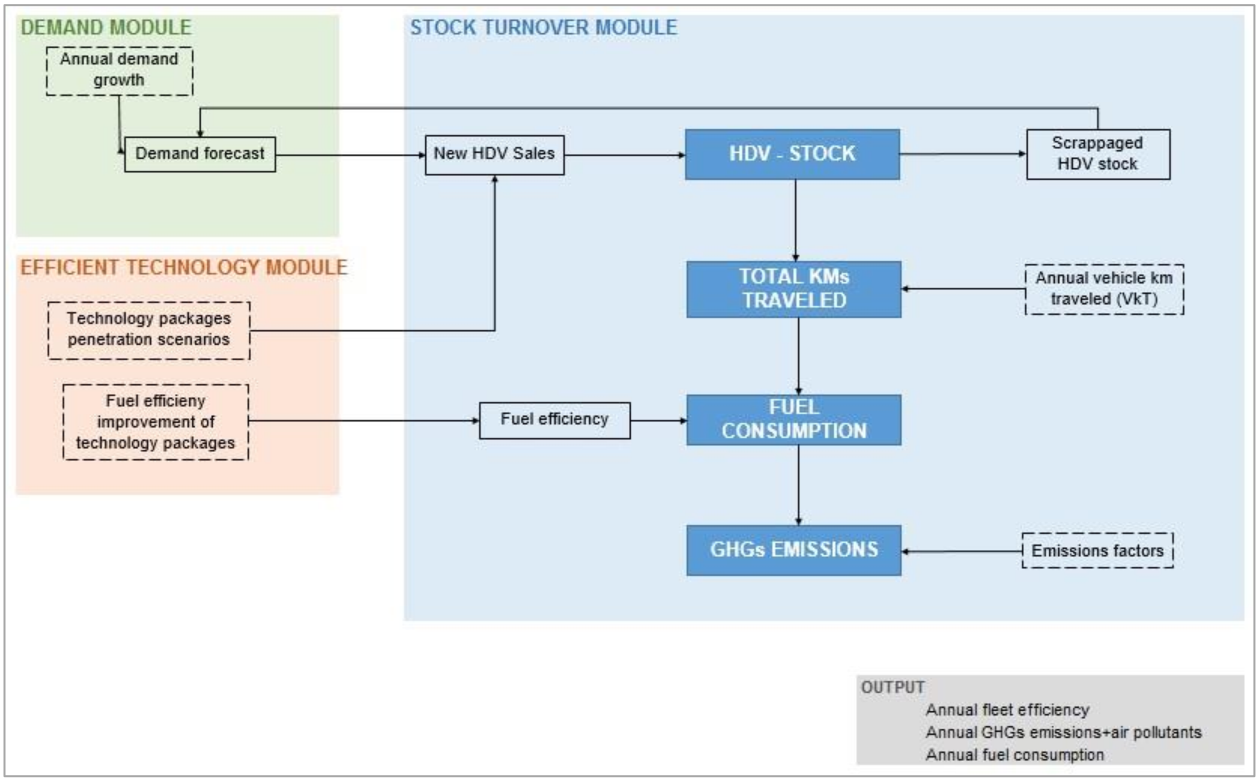

Figure 19. HDV fleet energy model
Note: See Karali et al. (2017) for details of the model and equations.

The model can also capture any change due to a rebound effect. Improving vehicle efficiencies may reduce fuel costs for trucking firms or bus companies, which may induce increased activity or demand for the HDV services that essentially ‘‘give back’’ some of the intended energy savings. For a variety of reasons discussed in Winebrake et al. (2012), there is no widely accepted estimate of the rebound effect from HDV efficiency improvements. Some studies examine elasticities—such as fuel price elasticities—as proxies for the rebound effect under certain assumptions (Winebrake et al., 2015). However, some evidence in the literature suggests that these assumptions may not hold (e.g., Dargay and Gately, 1997; Gately, 1993; Greene, 2012; Hymel and Small, 2015; Sentenac-Chemin, 2012; Winebrake et al., 2012). This analysis assumes no rebound effect in India’s HDV sector due to improved efficiency, an assumption supported by discussions with government officials, manufacturers, and other industry experts in the Indian HDV sector. However, impact of the rebound on the results are evaluated with a sensitivity analysis. The following sections detail the parameters used in the analysis.

4.1.1 Scrappage Function

The literature around scrappage rates for motor vehicles, particularly HDVs, is very limited. For this study, India-specific scrappage rates are calculated through a logistic curve. The logistic curve used in this analysis is shown as:

$$survival(t) = 1 - 1/(1 + e^{-\beta(t-t_0)}) \qquad \text{(Eq.4)}$$

where t_0 is the median lifetime of the vehicle[6],
t is the age in a given year,

[6] Median lifetime represents "middle" value not the average.

β is a growth parameter that determines how fast vehicles are retired around t_0.

Median lifetimes and the value for parameter β for Indian HDVs are determined by comparing survival rates from MOVES2010a (US Environmental Protection Agency, 2011). The assumed median lifetime is 15 years for new rigid trucks and transit buses under 12 tonnes. The parameter β is applied as 0.20 for new rigid trucks (including both LDTs and MDTs), 0.20 for new LDBs, and 0.25 for new MDBs.

Vehicle stock of the base year (2000) is analyzed using the same logistic curve. The average age of the stock in 2000 is a user-defined input into the model, because no data are available about the average age of HDVs under 12 tonnes in that year. The average age is assumed to be 5 years for both rigid trucks and transit buses in 2000, based on the CSIR-CRRI report (Ravinder et al., 2014).

4.1.2 Vehicle Fuel Consumption

In this analysis, baseline fuel efficiency levels of HDVs (summarized in Section 3.1.1) are assumed to be constant at 2017 levels. Fuel efficiency values tend to improve gradually over time owing to technological advances. However, to compare the benefits of various levels of fuel-saving technology deployment, holding baseline fuel efficiency levels constant is most illustrative.

4.1.3 Others Parameters

The average fleet utilization—the ratio of vehicles in active operation to the total number of vehicles in the fleet—for buses has remained nearly constant at approximately 90% for the last decade (MoRTH, 2018). Trucks, on the other hand, held much lower utilization rates of 55%–70% in the same period (Gibbs, 2015). Historical data is used when possible for 2000–2014 and assume that bus and truck utilizations are 90% and 70%, respectively, over the study period, 2017–2050.

4.1.4 Demand Projection

Annual demand for HDVs under 12 tonnes (in number of vehicles in stock) in India from the 2017 baseline to 2050 are projected using regression analysis. The number of HDVs under 12 tonnes increased at an average annual growth rate of 9% between 2000 and 2016, while gross domestic product (GDP) grew at an average rate of 6.8%. Figure 20 shows the relationship between annual HDV stock and GDP in India between 2000 and 2014. The growth trends are very similar, which makes sense given that HDV activity—particularly that of freight trucks—is directly tied to economic productivity. In addition, Table 9 indicates that growth in HDV stock is significantly correlated with growth in GDP. Based on these findings, it is assumed that GDP is the key driver of annual HDV demand.

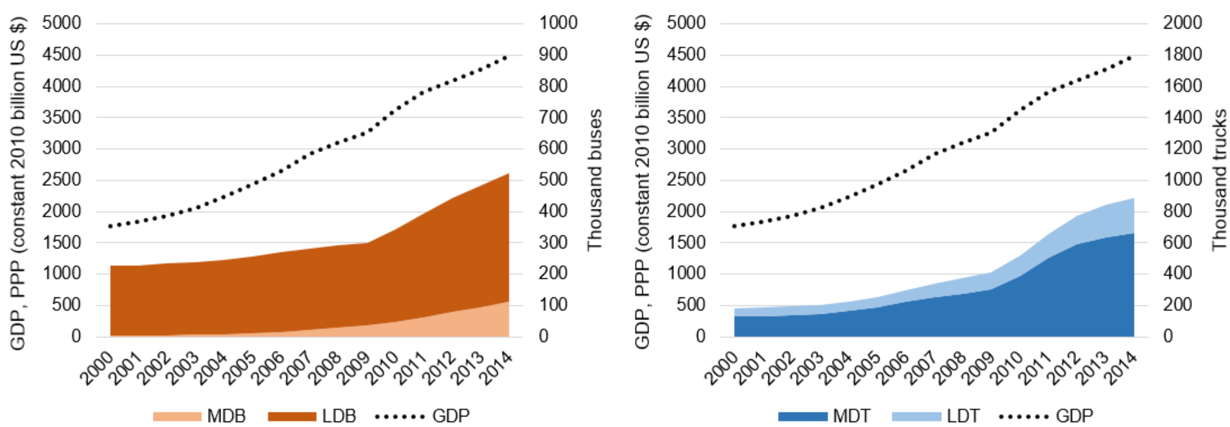

Figure 20. Correlation of HDV stock between 3.5 and 12 tonnes with per-capita GDP using data from 2000 to 2014

Sources: GDP from the World Bank (World Bank, 2016) and HDV stock estimates from ICCT (International Council on Clean Transportation, 2018)

Table 9. Correlation of GDP with vehicle stock, 2000–2014

	LDB Demand	LDT Demand	MDB Demand	MDT Demand
GDP	0.95	0.97	0.96	0.97

The projections are disaggregated at the level of HDV type—i.e., LDT and MDT, and LDB and MDB—and use the types as inputs for the HDV stock turnover module. The regression equations are as follows:

$$LDT\ Stock = -87{,}423.1 + 0.066 * GDP \quad \text{(Eq.5)}$$

$$MDT\ Stock = -277{,}427.8 + 0.199 * GDP \quad \text{(Eq.6)}$$

$$LDB\ Stock = 1{,}466{,}596.3 + 0.189 * GDP \quad \text{(Eq.7)}$$

$$MDB\ Stock = 768{,}905.2 + 0.113 * GDP \quad \text{(Eq.8)}$$

Baseline GDP growth forecasts are used for 2017–2050 from OECD (2018). Two additional growth-rate scenarios for sensitivity analysis are also ran, because PricewaterhouseCoopers (PWC)'s projections differ from OECD's: 1) PWC India growth forecast (PWC, 2017), 2) higher growth forecast, which is 10% higher than OECD growth projections (Figure 21).

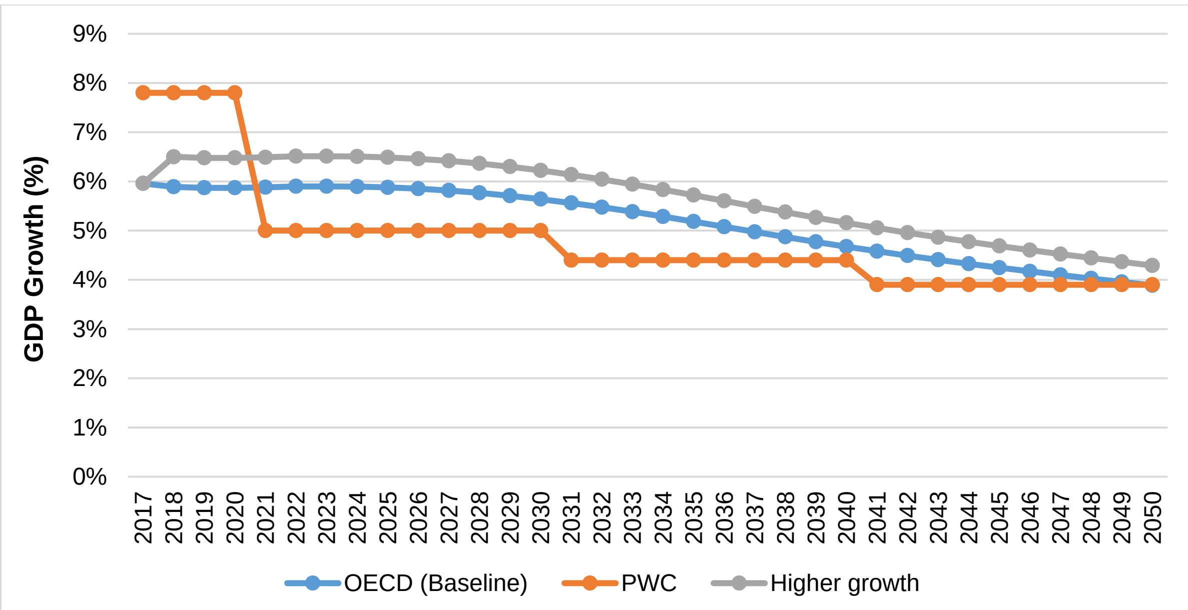

Figure 21. GDP growth forecasts for India between 2017 and 2050

Figure 22 shows the projection of HDV demand derived from the regression analysis using the baseline GDP projections from OECD. These results are not intended to be an accurate forecast of the future, but rather to explore a potential future scenario. In 2050 the number of HDVs under 12 tonnes will be 13.8 million, an increase of 8.7 times from 2016 as follows: 7.1 million rigid trucks (total of LDTs and MDTs) and 6.7 million transit buses (total of LDBs and MDBs). The total number of registered trucks in this category in the U.S. was approximately 13 million in 2014, which is almost twice as much as our India heavy-duty truck projection in 2050.

Because it is assumed that demand for HDVs is based primarily on GDP, growth of HDV stock follows GDP growth closely. Stock values over time for each HDV category are shown in Figure 22.

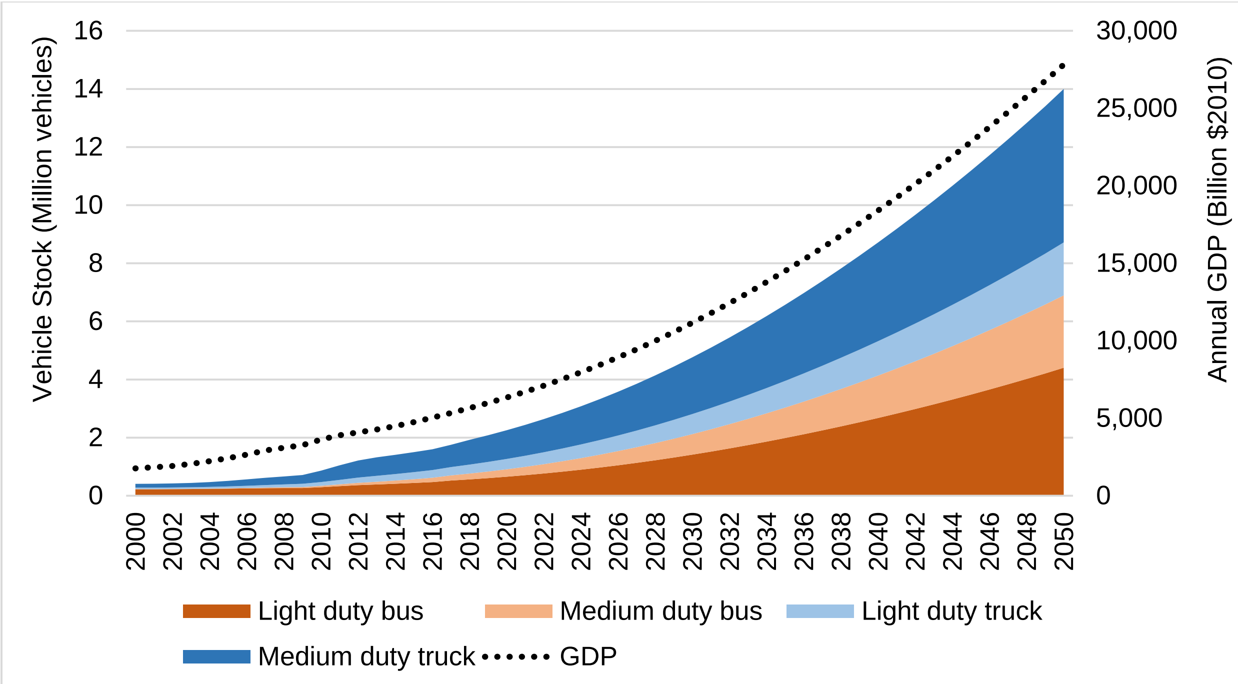

Figure 22. Demand projection for HDVs between 3.5 to 12 tonnes (using the baseline GDP projections from OECD)

Note: Points between 2000 and 2014 represent actual data.

4.1.5 Model Calibration and Validation

Before evaluating future projections of sales and stock for HDVs under 12 tonnes, here the model results against historical trends by sales and diesel consumption are evaluated.

Sales

The number of HDVs under 12 tonnes from 2000 to 2016 are acquired from the ICCT database (International Council on Clean Transportation, 2018). Figure 23 compares the modeled new HDV sales with actual statistics, showing that the model results match real data reasonably well.

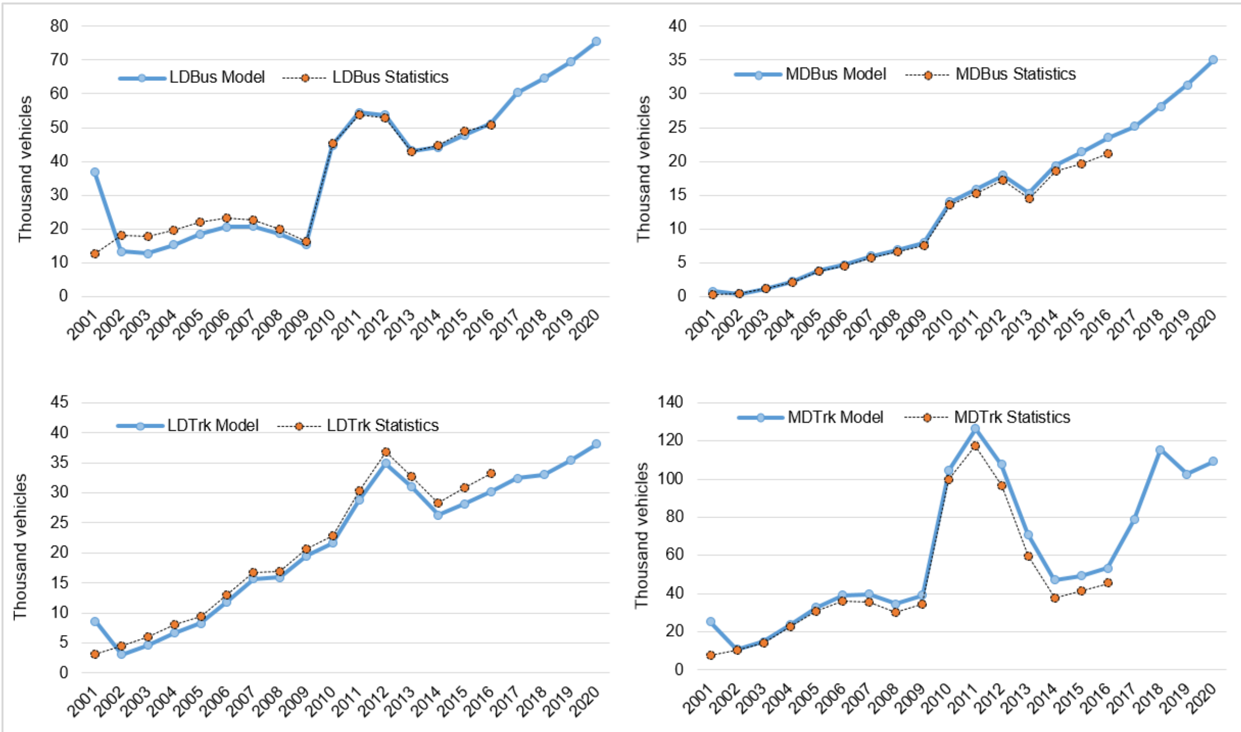

Figure 23. New HDV sales of 3.5 to 12 tonnes, 2001–2016: model results versus historical data

Fuel Consumption

Figure 24 shows an example of the model's ability to nearly replicate historical diesel consumption of all Indian HDVs between 2010 and 2016. Because historical diesel consumption based on tonnage levels are not publicly available, the results are checked against diesel consumption of total truck and bus categories, which represents all HDVs. The model results for HDVs over 12 tonnes are from our earlier work on this category (Karali et al., 2017) and summed with diesel consumption of HDVs less than 12 tonnes modeled in this study. The error margin is within the range of -6% to 3.5%. However, while the disagreement between modeled and actual consumption is relatively small, we caution against interpreting this agreement as an indication of very high precision owing to the uncertainty around the model input parameters.

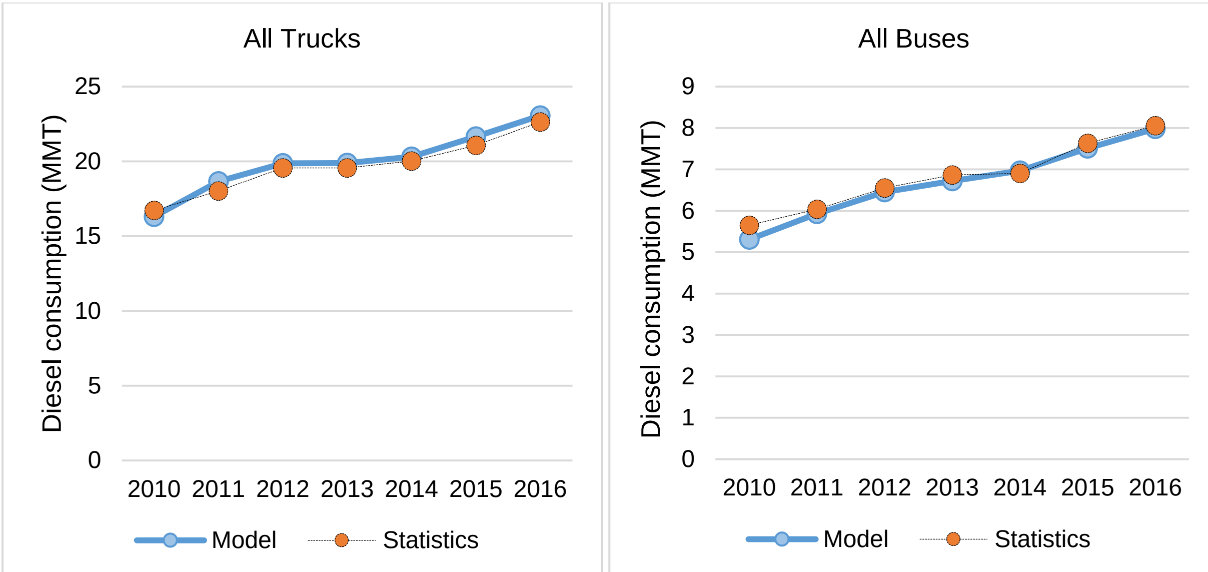

Figure 24. Total diesel consumption of HDVs in Million Metric tonne (MMT), 2010–2016: model results versus historical data
Sources: MoPNG (2018), PPAC (2013).

4.2 Oil and CO_2 Emissions Results

This section discusses the fuel savings and CO_2 emissions reduction results for the fuel efficiency technology packages. Figure 25 shows VKT calculated by the HDV fleet model. Even though VKT per vehicle declines with age, as described in Section 2, the total VKT in each HDV category increases with growing new sales and stock. The rate of stock growth outpaces the age-related decline in VKT. The projections show an annual increase in rigid trucks' VKTs of 5.7% (for LDT) - 6.1% (for MDT) between 2016 and 2050, while transit buses' VKT increase annually by 6.7% (for LDB) - 8.1% (for MDB).

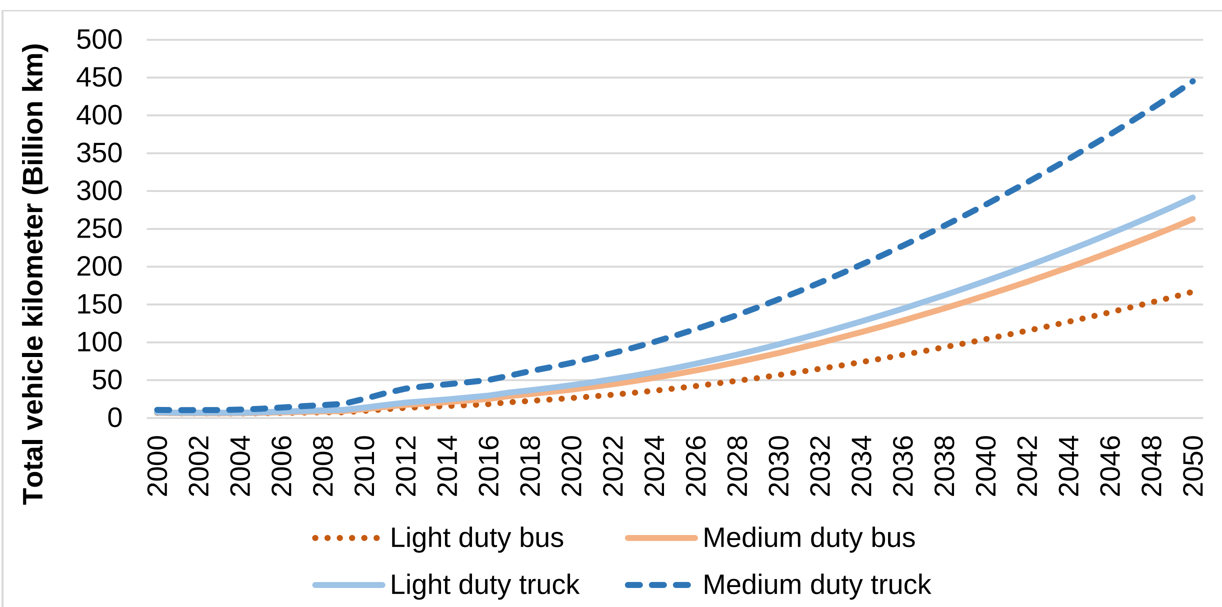

Figure 25. Annual VKT by HDV type

Figure 26 shows the total diesel consumption and CO_2 emissions projections for HDVs under 12 tonnes between 2020 and 2050 in the baseline scenario, compared to the 2016 level. Baseline scenario results indicate that Indian HDVs under 12 tonnes would require 30.5 billion liters of diesel to meet demand in 2030, increasing to around 86 billion liters in 2050. Correspondingly, CO_2 emissions from these HDVs increase by a factor of 3 in 2030 and a factor of 8.5 in 2050, compared to the 2016 level.

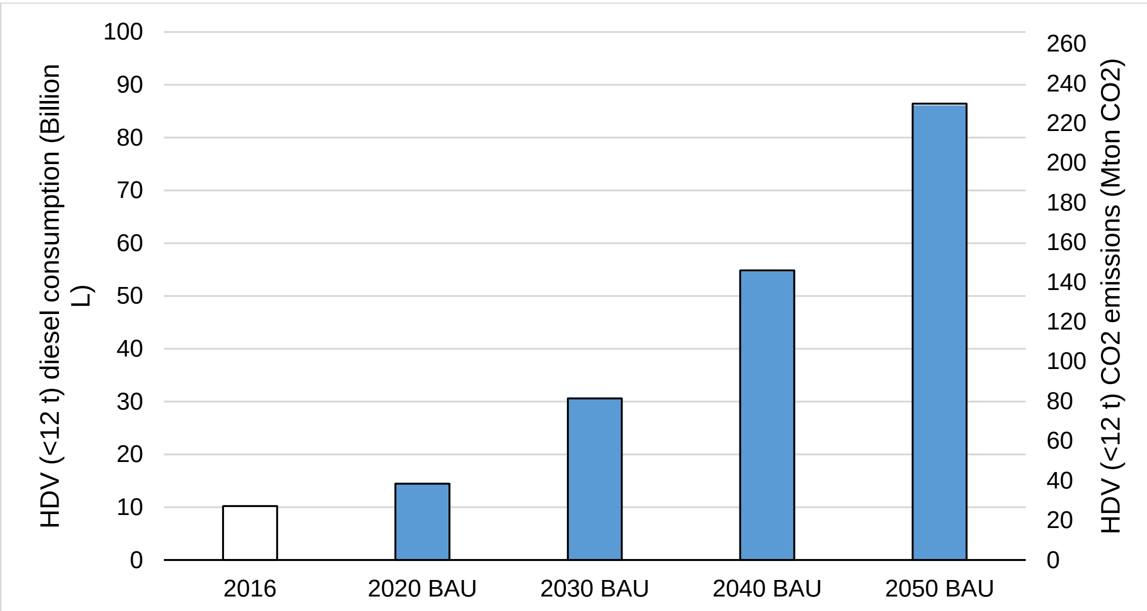

Figure 26. Baseline HDV diesel consumption and CO_2 emissions

4.2.1 Fuel efficiency Scenario Results

This section illustrates the impact on the Indian HDV sector of deploying the technology packages in terms of diesel demand and CO_2 emission reductions. Because all new HDV sales are deployed with technology packages in all of the fuel efficiency scenarios starting in 2020, the share of vehicles with technology packages in the total HDV stock does not differ among the scenarios. However, diesel demand and emissions vary among scenarios owing to the different levels of fuel efficiency improvement in each technology package. As shown in Figure 27, the total share of vehicles with technology packages covers 11.4% of the HDV stock as soon as deployment starts in 2020, and it increases rapidly to about 50% in 2025. About 92% of the total HDV stock has technology packages in 2035, and all HDVs in the fleet have technology packages in 2050. Correspondingly, HDVs with technology packages rapidly dominate the total VKT from HDVs.

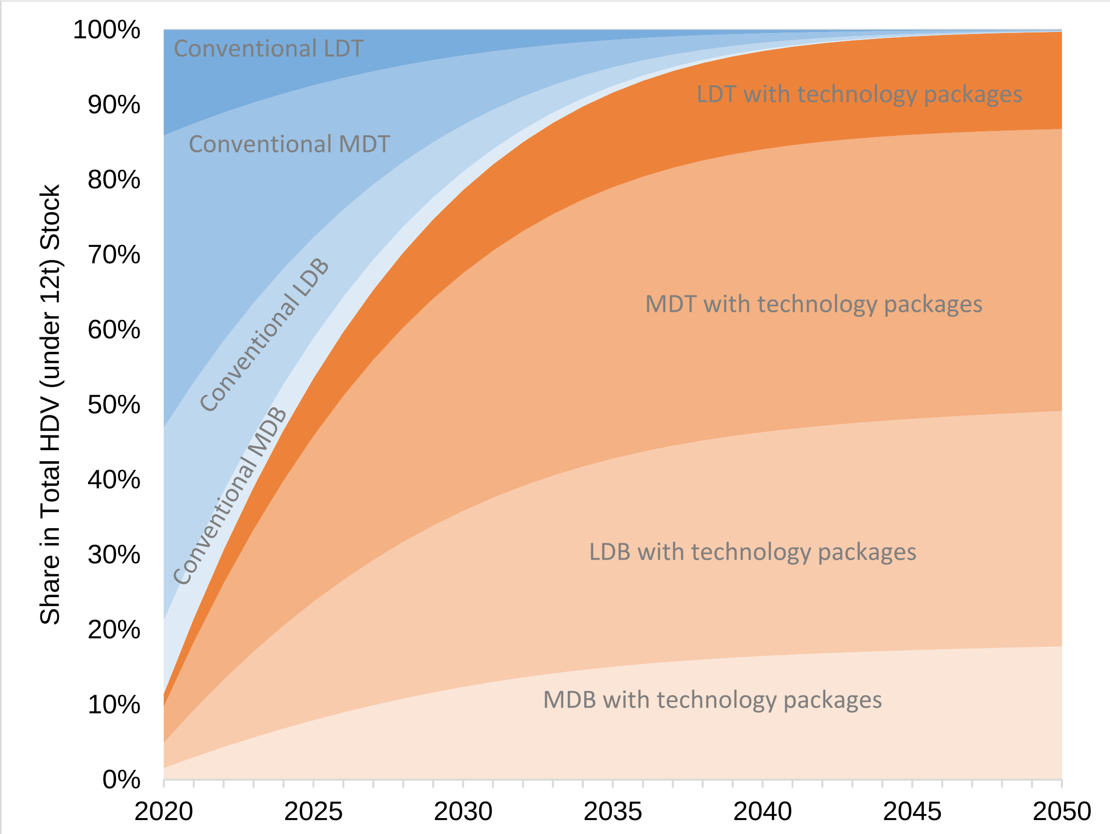

Figure 27. Populations of HDVs under 12 tonnes with and without efficiency technology packages over the study period

Deploying HDV technology packages reduces diesel consumption and CO_2 emissions compared to the baseline scenario, in which about 86 billion liters of diesel are consumed and 230 million tonnes of CO_2 are directly emitted in 2050 (Figure 28, Figure 29). Specifically, the reductions compared with the baseline are about 10% (TP1), 11% (TP 2), 17% (TP3), 18% (TP4), 21% (TP5), 24% (TP6), and 38% (TP7) in 2050.

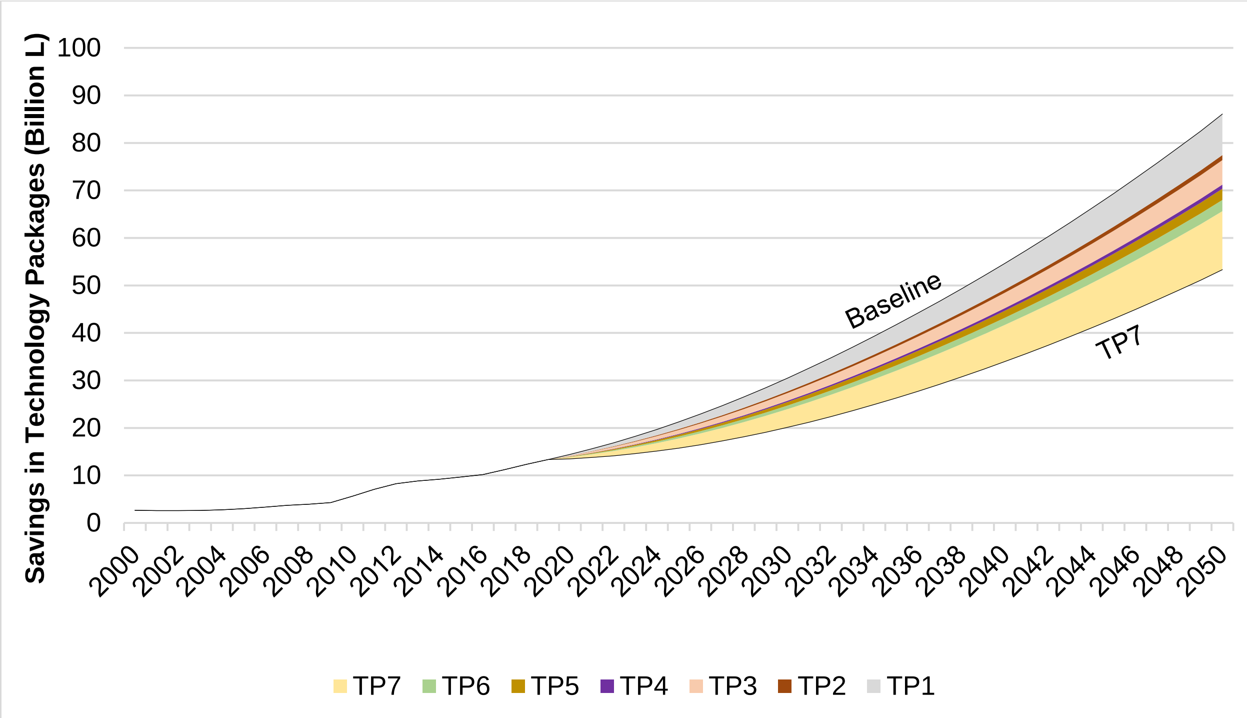

Figure 28. HDV diesel consumption reduction from each technology package

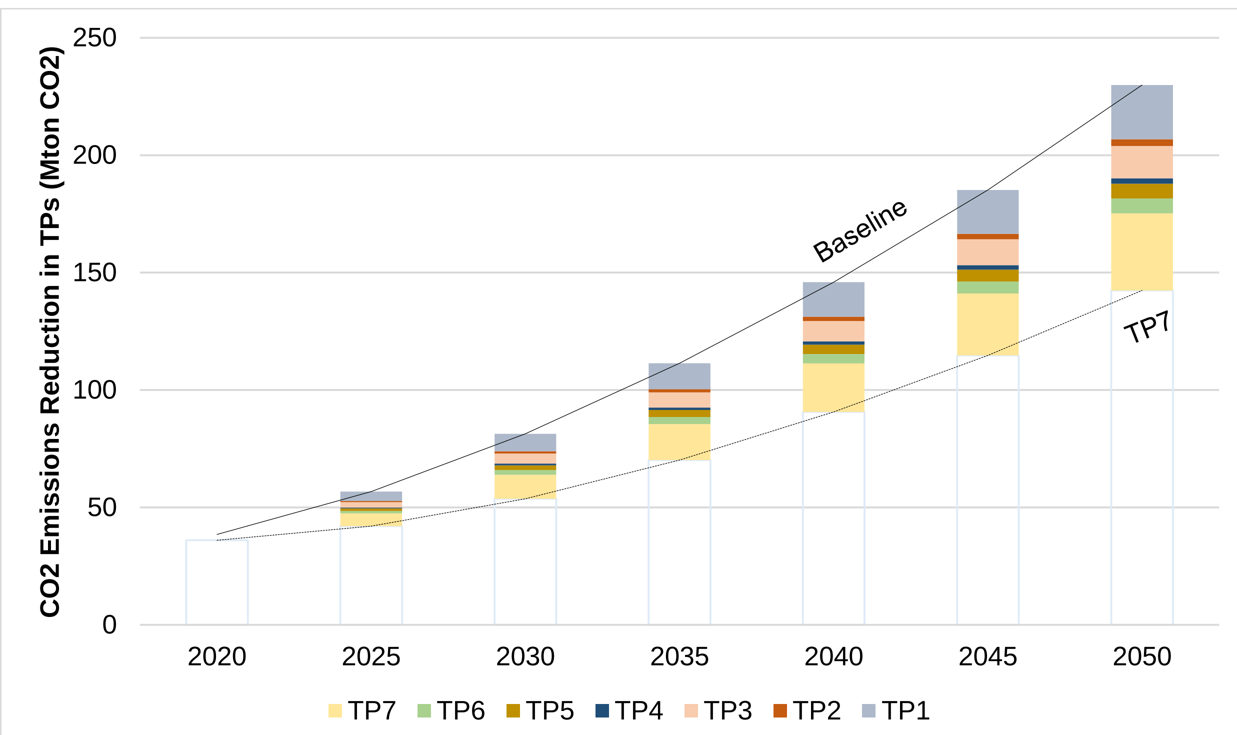

Figure 29. HDV CO_2 emissions reduction from each technology package

4.2.2 Sensitivity Analysis Results

There is uncertainty surrounding many of the variables relevant to the fuel use and CO_2 reduction analysis. Sensitivity analyses with different GDP growth rates are performed to capture uncertainties in the evolution of HDV demand between 2015 and 2050 (see Section 4.1). Uncertainties in HDV activity are also assessed through ± 25% variations of the parameter α (VKT decline rate by age), utilization rate,[7] and vehicle lifetime. Finally, two rebound sensitivity analyses are ran, with 5% and 10% rebound impacts.

Figure 30 shows the sensitivity of diesel consumption to GDP growth rates in the Baseline (no technology packages) scenario. The PWC scenario has lower GDP growth rates compared with the other two scenarios after 2020. Consequently, this scenario generates lower HDV demand and diesel consumption than the baseline OECD scenario. The higher GDP growth scenario produces higher HDV demand and annual diesel consumption. In 2050, the total diesel consumption of HDVs under 12 tonnes increases from 86.1 billion liters in the OECD scenario to 104.7 billion liters with higher GDP growth rates, and it decreases to 73.7 billion liters in the PWC scenario.

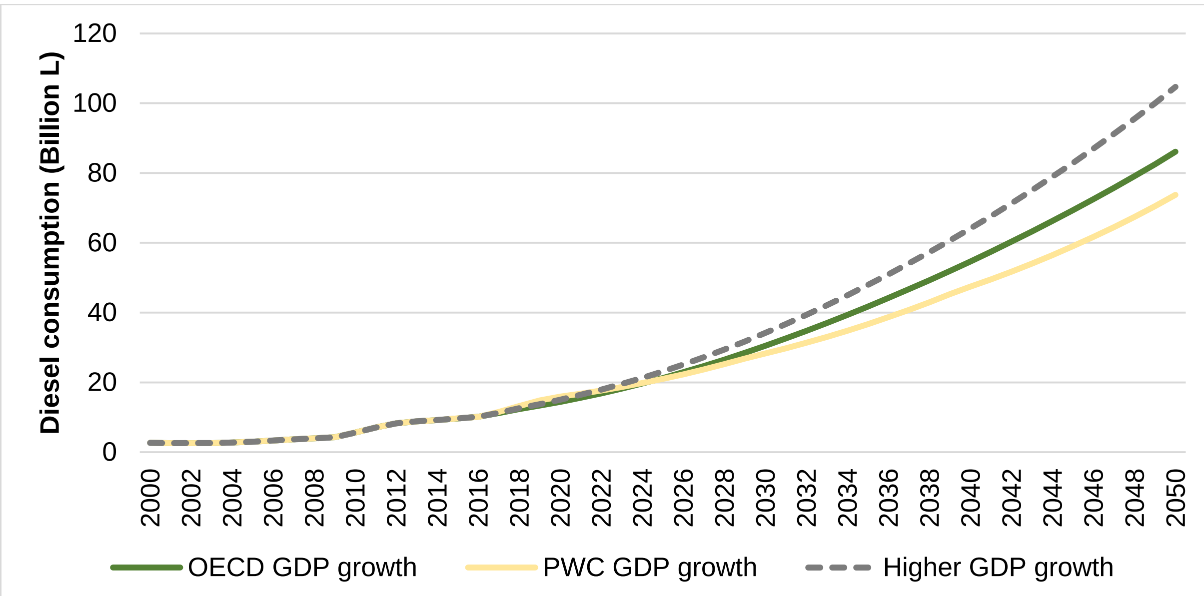

Figure 30. Baseline diesel consumption sensitivity to different GDP growth rates

Figure 31 shows the sensitivity of total fuel savings in the TP1 scenario (compared with the baseline scenario) to changes in demand growth, VKT decline by age (α), utilization rate, and vehicle lifetime. Utilization rate has the largest impact on fuel savings, followed by α and vehicle lifetime. This order is the same across all the TP scenarios. Figure 31 also shows the changes in savings with the lower and higher demand projections presented in Figure 30.

[7] Since bus utilization is already around 90% in India, it is only increased to a maximum of 100%.

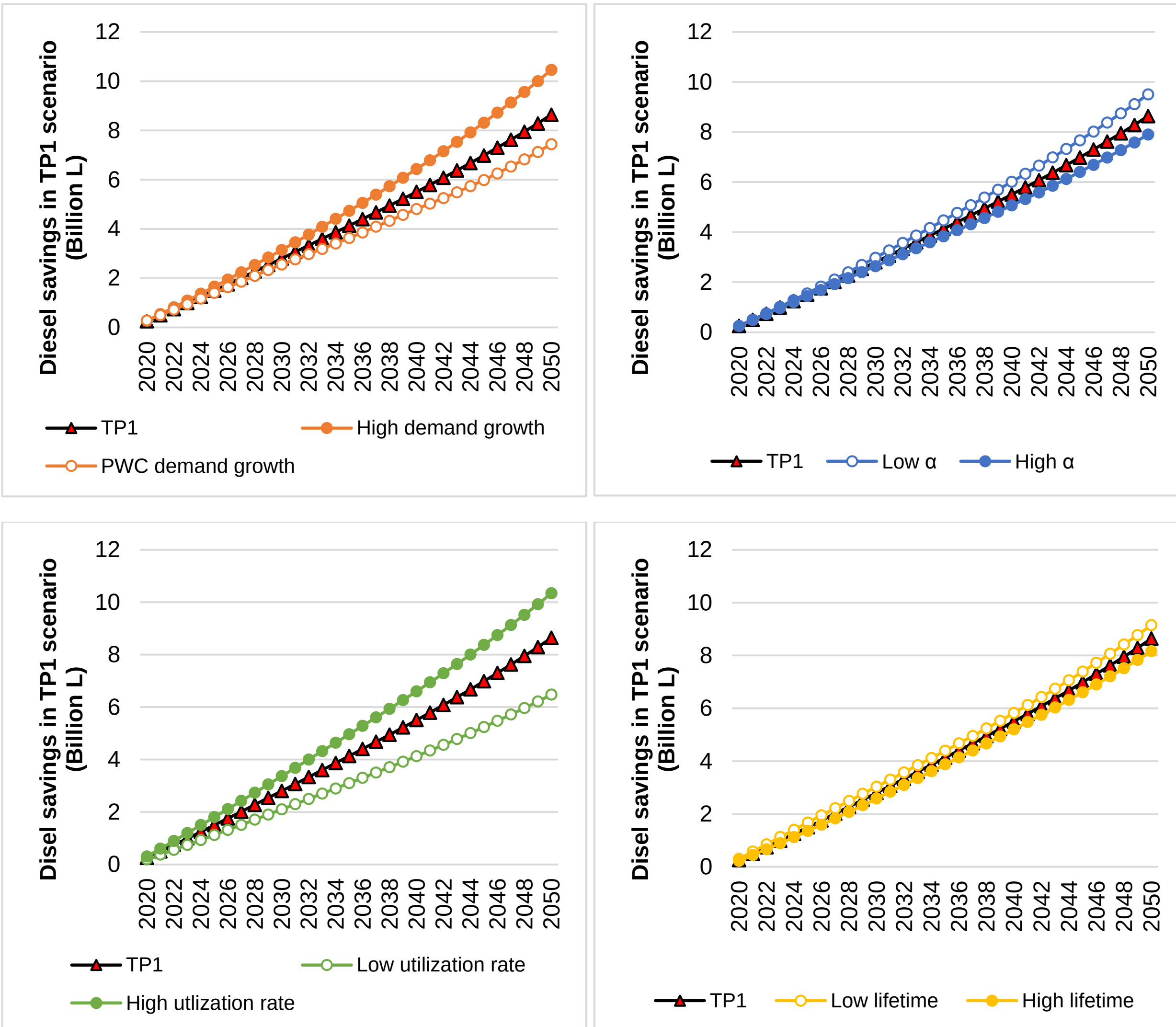

Figure 31. Sensitivity of fuel savings in the TP1 scenario (compared with the baseline scenario) to variations in demand growth, VKT decline by age (α), utilization rate, and vehicle lifetime

Figure 32 shows the sensitivity of total fuel savings in the TP1 scenario (compared with the baseline scenario) to two different levels of rebound impact. In 2050, diesel savings in the TP1 scenario drop 45% and 90% with 5% and 10% rebound, respectively. This result is the same across all the TP scenarios, suggesting that the savings gained from technology packages are lost if there is a 10% rebound impact.

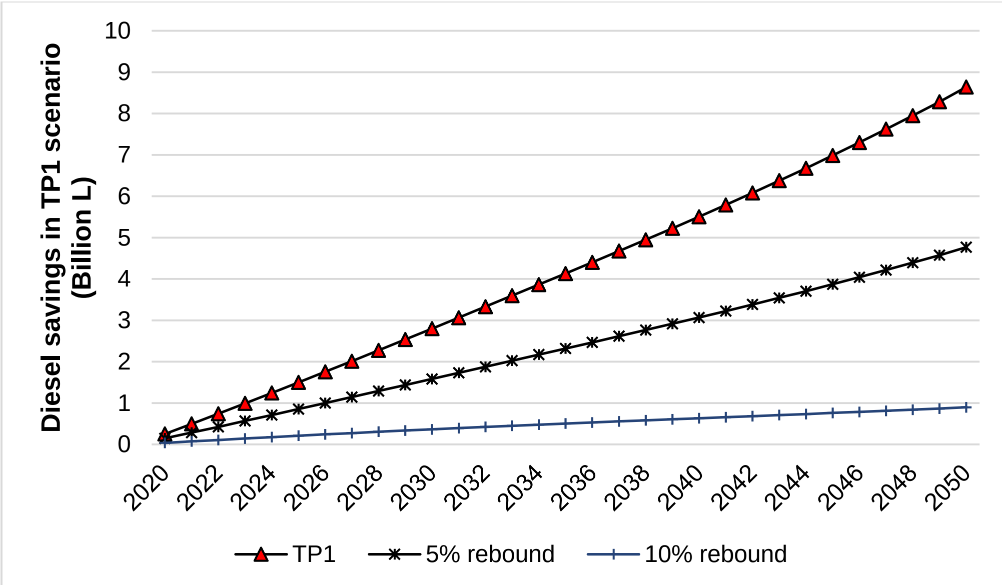

Figure 32. Sensitivity of fuel savings in the TP1 scenario (compared with the baseline scenario) to 5% and 10% rebound impacts

5 Conclusions and Recommendations

The research presented in this paper extends our previous analysis on fuel efficiency technologies for Indian HDVs over 12 tonnes, to include heavy-duty trucks and buses of 3.5 to 12 tonnes. Adding these smaller HDVs to our analysis improves our understanding of the potential impacts of HDV fuel efficiency and emission standards in India, the home of 33 of the world's 100 worst pollution-affected cities (WHO, 2016).

The results show that India has substantial opportunity to improve the fuel efficiency of HDVs of 3.5 to 12 tonnes using cost-effective technologies. The modeled technology packages improve the fuel economy of these vehicles by 7% (TP1) to 28% (TP6) and provide a return on the initial capital investment within about one year (TP1) to three years (TP6). TP7, which adds the relatively expensive hybrid-electric system, is the only exception—its initial cost is not paid back within the lifetime of the vehicles analyzed.

Across all the technology packages and vehicle types, engine and tire technologies provide the most cost-effective efficiency improvements, primarily for two reasons: 1) under India-specific driving conditions (low average speeds and prevalent overloading), the combined energy losses due to the engine and tires represent between 75% and 85% of the total losses, and 2) engine and tire technologies are relatively inexpensive compared with advancements in other technology areas.

Although most technologies in the technology packages are currently unavailable in India, the country's recent regulation of HDVs over 12 tonnes could spur significant deployment of such technologies, which are available in the United States. In addition, India's recent regulation of HDVs over 12 tonnes could spur significant deployment of such technologies.

If widely deployed, the modeled technology packages could have a significant impact on India's petroleum consumption and GHG emissions in the 2030–2050 timeframe. The fleet model is calibrated for all categories of HDVs in India to capture sales, stock, and diesel consumption within each category with an error range of ± 6%. For HDVs under 12 tonnes, projected diesel savings range from 9.2% under the least-aggressive package (TP1) to 34% under the most-aggressive package (TP7) in 2030—with corresponding CO_2 emissions reductions. In 2050, the range of savings is 10% (TP1) to 38% (TP7).

Heavy duty vehicles between 3.5-12 tonnes have a greater diversity of use cases, which will require significantly more data and nuanced technical analysis. This is a major area of future work and needs to be explored further.

Policy Recommendations

The fuel consumption and GHG reduction benefits from improving the efficiency of 3.5 to 12 tonne HDVs can best be realized via near-term implementation of fuel efficiency standards. Due to their relatively high turnover rates and extreme daily usage, freight truck and transit bus fleets in this HDV category offer great potential for rapid penetration of efficiency technologies. The following actions by policymakers and other key stakeholders in India's commercial vehicle industry can create the enabling environment and potentially pave the way for improving fuel efficiency of small and medium heavy duty vehicles:

1. **Establish fuel efficiency standards**: Since 2017, India has set up fuel efficiency standards (administered by the Bureau of Energy Efficiency) for commercial HDVs with GVW of 12 tonnes and above. These standards will be ratcheted up by 8-10%, depending on the GVW and axle configuration, in April 2021. Medium and Light HDVs with GVW between 3.5 tonnes and 12 tonnes are not governed by any fuel efficiency standards. These vehicles are responsible for roughly 40% of the total fuel consumption and thus emissions by HDVs in India (Karali et al., 2017). Given the cost-effectiveness of key efficiency technologies shown in this report, establishing fuel efficiency standards for this category of HDVs in the near future will make a large impact in the overall fuel consumption, imports, and GHG emissions. It is also important to harmonize standards for smaller and larger HDVs to avoid large differences in fuel efficiency targets at GVWs of exactly 12 tonnes.

2. **Develop fuel efficiency regulatory norms with long term targets**: Early signaling of efficiency targets gives industry sufficient time for research, development, and deployment of new and improved technologies. For example, Japan's Top Runner Program sets the fuel efficiency standard of cars as well as HDVs. The Top Runner Program determines the fuel efficiency target for a future year based on the most efficient product in that class already available in the market. Typically, this raises the efficiency target significantly, but manufacturers are given several years to comply. In the United States, the HDV fuel efficiency standards have a long-term target as well. For example, in 2011 HDV fuel efficiency and GHG emission targets were set for 2017 and targeted ~24% fuel efficiency improvement over the 2010 models. Also, 2027 fuel efficiency norms were enforced in 2016 with a target of improving the efficiency by 30% over 2017 models. India is well positioned to leverage the lessons learned and the technical data from existing HDV fuel efficiency and GHG regulations. The Indian HDV industry needs to comply to the Bharat VI emission standards in 2020.[8] Therefore, it would be advantageous to align the staging of fuel efficiency standards with the emission standards schedule. Requiring simultaneous technology upgrades for pollutant emissions and efficiency will likely ease the burden on manufacturers' design cycles, which typically occur at three to four year intervals.

3. **Cultivate testing efforts for heavy duty vehicles, engines, and component systems**. Accelerating efforts to develop and implement testing campaigns will provide the data critical for better fuel efficiency regulations and real-world benefits.[9] This will also potentially help streamline vehicle testing efforts. Moreover, streamlining testing campaigns will be immensely helpful in eventually moving towards a simulation based testing framework for more accurate representation of the vehicle efficiency in real-world driving conditions. The Government of India, industry, and research community play a part in cultivating testing regimes.

4. **Develop complementary policies for alternative fuel and electric vehicles.** Another possible pathway could be a corresponding transition to alternative powertrain technologies, such as electric buses and trucks, to reach a significant share of the on-road fleet by 2050. India has already announced an aspirational goal of electrifying all vehicles sales by 2030. Several cities have already implemented pilot programs for including electric buses in their municipal bus fleets. As a policy example at the subnational level in the U.S., California's Zero Emissions Vehicle (ZEV) mandate has been successfully used to encourage the long-term transition to cleaner mobility options.

[8] https://www.theicct.org/sites/default/files/publications/India%20BS%20VI%20Policy%20Update%20vF.pdf

[9] Test drive cycle and the real-world drive cycle of a vehicle may be significantly different from each other, which could create discrepancy between the design fuel efficiency and real-world fuel efficiency.

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