

Fuel efficiency technology potential of heavy-duty vehicles between 3.5 and 12 tonnes in India

Authors: Ben Sharpe, Mehul Garg, and Oscar Delgado

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1. Introduction

India remains one of the fastest-growing economies of the world, with a gross domestic product annual growth rate of 7.1%. In accordance with that growth, India's annual transportation energy consumption has grown at a rate of 6.8% every year since 2000 (IEA, 2015). The use of oil for road transportation accounts for 90% of the increase measured. Consumption of diesel fuel, the primary fuel for heavy-duty vehicles (HDVs) in India, has more than doubled since 2000¹ (Ministry of Petroleum and Natural Gas, 2017).

On August 16, 2017, the Bureau of Energy Efficiency published final fuel consumption standards for HDVs (Garg & Sharpe, 2017). This move puts India alongside four other countries—the United States, Japan, China, and Canada—that have standards for HDVs. These standards require fuel efficiency improvements for HDVs with a gross vehicle weight (GVW) of 12 tonnes or greater. This paper focuses on diesel HDVs between 3.5 and 12 tonnes, which are currently not covered by the fuel

consumption standards but represent roughly 34% of sales and 40% of fuel consumption from the overall HDV sector in India. This paper builds upon the analysis from our previous study that examined the fuel efficiency technology potential of diesel HDVs greater than 12 tonnes in India, along with the associated costs (Karali et al., 2017). The primary objective of this paper is to identify both the existing and future technologies and technology packages for trucks and buses between 3.5 and 12 tonnes, in order to estimate the fuel savings potential for these vehicles in the 2025 to 2030 time frame.

The remainder of the paper is organized as follows.

- Section 2 provides data and analysis concerning the market for sales of new trucks and buses between 3.5 and 12 tonnes.
- Section 3 describes the development of representative vehicle models and the drive cycle used in this analysis.
- Section 4 details the powertrain and road-load technologies included in this fuel consumption reduction assessment.

- Section 5 describes technology packages developed for this analysis and presents their fuel consumption results.
- Section 6 presents conclusions and provides policy recommendations.

2. Market analysis

The sales data referenced in this paper were acquired from Segment Y Automotive Intelligence. The data represent commercial vehicles sold during fiscal year (FY) 2013–2014 (April 1, 2013 to March 31, 2014) and include sales figures for passenger buses, vans, and trucks weighing more than 3.5 tonnes. The second data source for this study is the Society of Indian Automobile Manufacturers (SIAM), which provided sales figures for FY 2016–2017. The SIAM data are in a similar format but do not distinguish sales numbers for different models. Instead, the data are presented as overall sales for a particular manufacturer in each vehicle segment.

The market for HDVs lighter than 12 tonnes in India can be broken down according to the following categories:

- Category M2 and M3: HDVs used for carriage of passengers having

¹ 36.6 million metric tonnes in 2000 versus 76.0 million metric tonnes in 2017.

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a GVW less than or exceeding 5 tonnes, respectively (i.e., buses)

- Category N2 and N3: HDVs used for carriage of goods and having a GVW less than or exceeding 12 tonnes, respectively

These categories are defined by the Central Motor Vehicles Rules of 1989 and mandated by the government (Ministry of Road Transport and Highways, 1989). Total sales of these four subcategories approached 390,000 vehicles in FY 2016–2017, according to data obtained from SIAM.

As shown in Figure 1, vehicles less than 12 tonnes represent 34% of all HDVs sold during FY 2016–2017; of this percentage, trucks account for 54% and buses account for the remaining 46% of total HDV sales. The remaining 66% of HDVs sold were 12 tonnes or more.

Figure 2 shows the distribution of the two vehicle types by GVW. The overall percentage of vehicles sold in 2016–2017 with GVW less than 12 tonnes was much higher for buses than for trucks. However, in terms of absolute numbers, sales of buses and trucks less than 12 tonnes were 70,983 and 80,574, respectively.

Figure 3 shows cumulative sales of trucks and buses in FY 2013–2014 according to GVW (Sharpe, 2015). A sizable proportion of trucks (more than 10% of total sales of trucks greater than 3.5 tonnes) is concentrated just below 12 tonnes GVW, as represented by the blue vertical line segment that overlies the dashed line. At present, these vehicles are not covered by India's fuel consumption standards for on-road commercial vehicles, which only regulate trucks and buses with a GVW of 12 tonnes or more.

The largest manufacturer of HDVs less than 12 tonnes in India—both trucks and buses—is Tata Motors, which is responsible for more than half of all

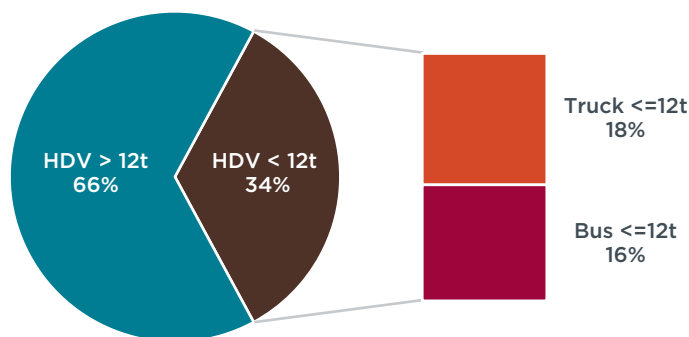


Figure 1. Breakdown of HDV sales in India by GVW and type. Total sales in FY 2016–2017 were roughly 390,000 units.

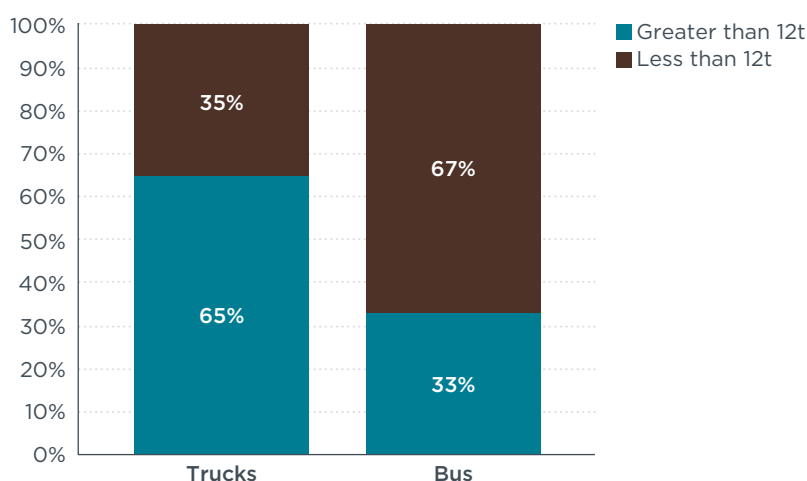


Figure 2. Percentage of truck and bus sales less than and greater than 12 tonnes in fiscal year 2016–2017.

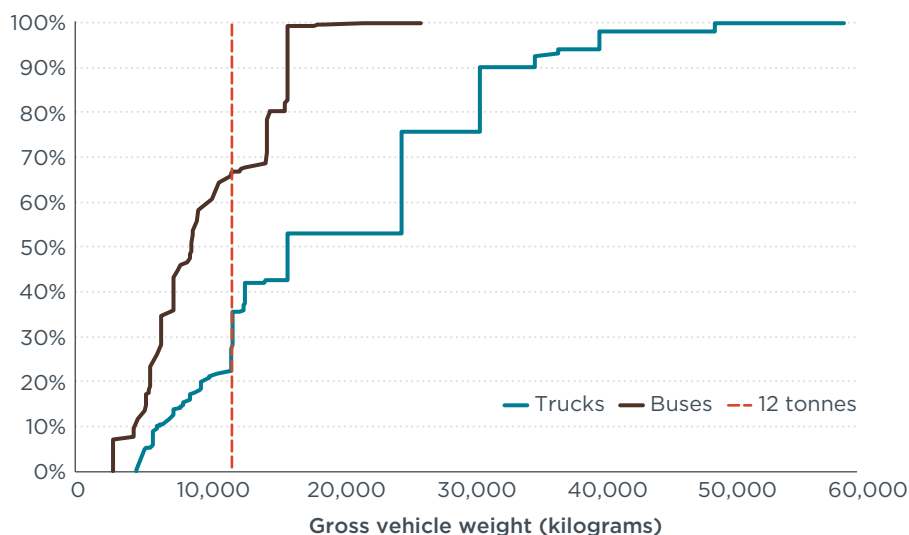


Figure 3. Cumulative sales of trucks and buses by gross vehicle weight in fiscal year 2013–2014.

sales. Since 2013–2014, Tata’s market share for HDVs less than 12 tonnes has decreased from nearly 70% to 54%. Most of this market share was captured by VECV Ltd. (VE Commercial Vehicles, a joint venture between Volvo and Eicher Motors Ltd.), which accounted for 24% of sales in 2016–2017.

The ICCT’s previous study of the Indian HDV market (Sharpe, 2015) shows that a large percentage of engines installed in trucks and buses are manufactured by Cummins. However, Cummins’ substantial presence in the HDV market only applies to vehicles weighing more than 16 tonnes. In contrast, all of the manufacturers selling vehicles less than 12 tonnes install their own engines.

To better understand the market characteristics for trucks and buses, we further break down sales for these GVW ranges: (a) between 3.5 and 7.5 tonnes, and (b) between 7.5 and 12 tonnes. Figure 4 shows the manufacturer market shares for each of these two weight classes for trucks and buses.

For the lightest heavy-duty rigid trucks (i.e., trucks that have the cargo-carrying body permanently attached to the truck chassis) between 3.5 and 7.5 tonnes, Tata was the dominant manufacturer in FY 2016–2017, accounting for 54% of sales. The next largest producer in the segment was VECV with 23% of the market. SML Isuzu, Mahindra, and Force Motors made up 9%, 8%, and 5% of sales, respectively.

For rigid trucks between 7.5 and 12 tonnes, VECV is the leading manufacturer. This has changed from 2013–2014, when Tata held 42% of the market while VECV had 36%. In 2016–2017, VECV and Tata remained the dominant companies in this segment, with 39% and 33% of the market, respectively; SML

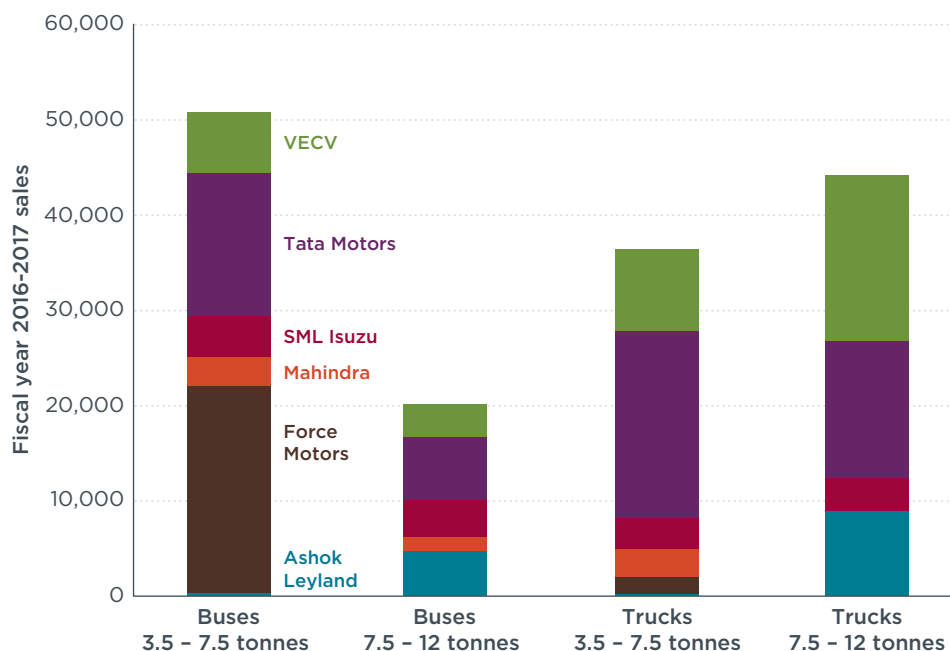


Figure 4. Manufacturer market shares for buses and trucks in FY 2016–2017.

Isuzu and Ashok Leyland accounted for the remaining 28%.

For transit buses between 3.5 and 7.5 tonnes, overall sales have gone up more than 50% since FY 2013–2014. The highest-selling manufacturer now is Force Motors Ltd., which has emerged as a popular brand for small transit buses. This shift in the market has happened relatively quickly, as Tata was the dominant manufacturer in FY 2013–2014, with 79% of sales. The increase in overall sales in the segment represents gains for Force Motors and lost market share for other manufacturers. In absolute terms, Tata has maintained roughly the same sales as in previous years, at almost 16,000 units. Force Motors sold more than 21,000 vehicles during FY 2016–2017 in this segment.

For transit buses between 7.5 and 12 tonnes, Tata has a sizable share at 37%. However, its share of that market is not as large as in the other segments included in this study. Ashok Leyland,

SML Isuzu, and VECV have market shares ranging from 17% to 23%.

3. Baseline vehicle performance

This section describes the process used to create the representative vehicle models and the drive cycle used in this analysis.

3.1 BASELINE VEHICLE CHARACTERISTICS

To select representative vehicle models for this analysis, we used both publicly available information and data acquired from an automotive market consultancy. Baseline vehicle technology levels were gleaned from manufacturer specification sheets as well as insights provided by industry experts.

In this analysis, one representative truck and bus each were chosen from the less than 12-tonne segment. The following models were chosen based

on new vehicle sales data from FY 2013–2014. The Tata LPT 1109 and Tata LP 712 are the highest-selling rigid truck and bus, respectively, in the less than 12-tonne category (total sales for each model includes all currently available variants). The characteristics of each of these vehicles are summarized in Table 1.

These values represent most closely the actual parameters of the Tata LPT 1109 rigid truck and the Tata LP 712 transit bus. The engine used in both vehicles is the same. A 3.8-liter diesel engine with a peak rated power of 92 kW is modeled 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.

For both the rigid truck and transit bus, all of the simulation runs in this analysis were performed at maximum GVW and thus maximum payload. Interviews with fleets and experts from the trucking industry have provided ample anecdotal evidence that very heavy loading is a common feature of the HDV sector in India. We did not have access to data that provided any quantitative estimates for typical loading factors for trucks or buses in India. As such, we made the simplifying assumption that the two representative vehicles in this study would be modeled at maximum GVW. For the technology packages in which we assume that weight reduction technologies such as material substitution can be used to reduce the curb (or empty) weight of the vehicle, the payload is increased by an amount 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.

Table 1. 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 (gear ratios: 1st, 2nd, 3rd, ..., 6th)	6-speed manual (7.9 (reverse), 9.2, 5.3, 3.2, 2.1, 1.4, 1)	
Maximum payload (kg)	8,405	4,698 (roughly 80 passengers if we assume 60 kg per person)
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

We created vehicle simulation models using the data in Table 1 in a computer simulation tool called Autonomie, which was developed in the United States (Argonne National Laboratory, 2016). Autonomie is the analytical tool that we used to evaluate the fuel consumption reduction efficacy of individual technologies and combinations of technologies (i.e., technology packages). The fuel efficiency technology packages are described in detail in Section 4, and the simulation results are discussed in Section 5.

3.2 DRIVE CYCLE

In this analysis, each of the two vehicle types was evaluated over the WHVC-India drive cycle. The World Harmonized Vehicle Cycle (WHVC) was the basis for the development of the World Harmonized Transient Cycle (WHTC), an engine dynamometer cycle that is used as a certification test for regulated pollutants (Steven, 2001). The main purpose of the WHVC is to cover a wide range of driving situations for commercial vehicles. As such, the cycle contains distinct urban, rural, and motorway sections,

as shown in Figure 5. The WHVC-India cycle was derived for this analysis to account for the fact that HDV speeds in India are typically much slower than in other major markets such as the United States and the European Union (Transport Corporation of India Limited and Indian Institute of Management Calcutta, 2016). The WHVC-India cycle is identical to the WHVC for roughly the first 20 min, after which the speeds of the WHVC are multiplied by 0.7 to produce the speeds for the WHVC-India. As shown in Figure 5, during the highway portion at the end of the cycle, the maximum speed of the WHVC-India is approximately 60 km/hour, as compared to roughly 87 km/h in the WHVC. This maximum speed of 60 km/hour is reasonably representative of commercial vehicle cruising speeds in India. However, the acceleration and deceleration rates in the WHVC-India are roughly identical to those in the WHVC.

To more closely account for the different in-use driving behaviors of the two representative vehicle types, we used weighting factors for the urban, rural, and motorway portions

in the cycle. These weighting factors, shown in Table 2, are based on cycle breakdowns in the regulatory programs of the United States and China, as well as the authors' best judgment (Delgado, 2016; U.S. EPA and NHTSA, 2016).

Table 2. Drive cycle weightings for the segments of the World Harmonized Vehicle Cycle-India.

	Urban	Rural	Motorway
Rigid truck	40%	30%	30%
Transit bus	85%	15%	0%

4. Fuel efficiency technologies

The following section discusses five fuel-saving technology areas that were included in this analysis. The assessment includes technologies that are currently available on the market as well as technologies that we project will be commercially available in India over the next 10 years. As with our companion study of the greater than 12-tonne HDV segment, input from manufacturers, suppliers, and industry experts in India informed our assumptions about technologies that are likely to be commercialized in the 2025 to 2030 time frame.

4.1 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, the 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.

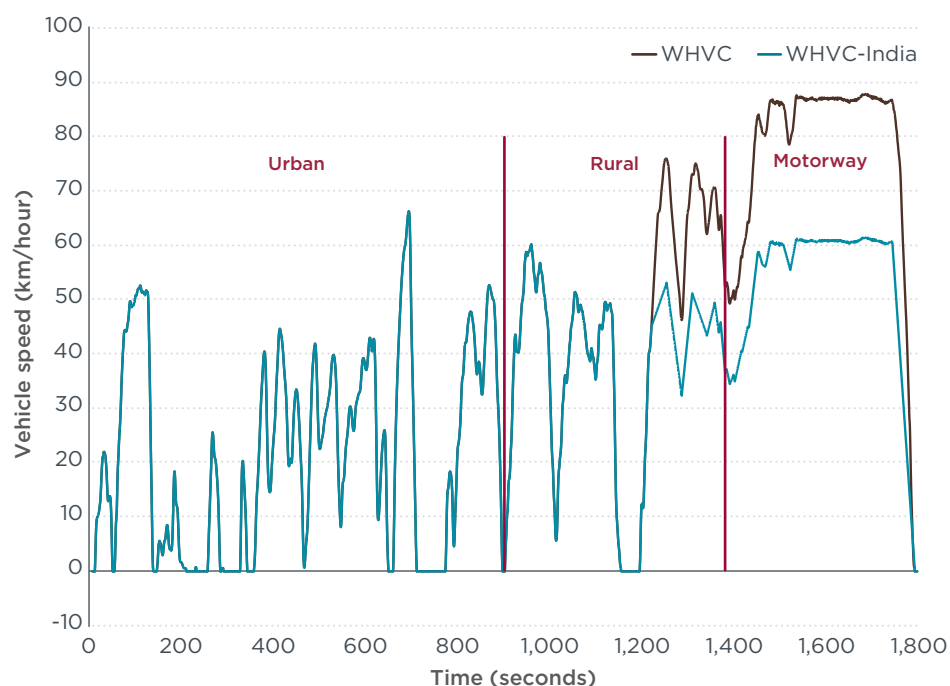


Figure 5. Vehicle speed/time trace for the World Harmonized Vehicle Cycle (WHVC) and the WHVC-India cycle.

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%

The shift from BS IV to BS VI requires manufacturers to make substantial investments in technology to meet the proposed emission standards. The primary technology in the shift from BS IV to BS VI is the introduction of 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 levels—typically on the order of 2 to

3%. Manufacturers in other markets such as Europe, North America, and Japan have introduced several fuel efficiency technologies to mitigate this increase in fuel consumption.

Table 3 shows the three additional steps in engine technology advancement beyond BS VI assumed in this analysis. These levels of engine efficiency improvements use the same methodology as in Delgado and Lutsey (2015). On the basis of interview responses from industry experts

in India, we assume that roughly comparable engine technologies can be used in the India HDV market. These engine technology areas include:

- Friction reduction
- On-demand accessories
- Combustion system optimization
- Advanced engine controls
- Turbocharger improvements
- Aftertreatment improvements
- Waste heat recovery systems, including turbocompounding 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 regulations. Delgado and Lutsey assumed a U.S. model year 2010 baseline, which is roughly equivalent to a BS VI (or Euro VI) engine, as both emission levels require roughly the same emissions control technologies that achieve about the same emission benefits (Sharpe & Delgado, 2016). In the fuel efficiency and greenhouse gas (GHG) regulations for commercial vehicles in the United States, there are separate requirements for engines in tractor-trailers and vocational vehicles. In both phases of the U.S. regulation, the stringency targets for the engines of tractor-trailers and vocational vehicles are similar in magnitude.²

² 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.

However, we assume 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 (U.S. EPA and NHTSA, 2016).

4.2 TRANSMISSION TECHNOLOGIES

In addition to engine efficiency improvements, transmission technology is another important fuel savings area for HDVs. Advanced 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. The fuel savings are realized as the engine operates for a larger percentage of time in higher-efficiency regimes. This study assumes two levels of AMT in operation for India: (a) equivalent to the commercial AMTs that are available in more advanced markets such as North America and Europe, and (b) taking into account the improvements in operational efficiency that are expected to occur in the 2020 time frame.

Beyond AMTs, the transmission technology that we assume would 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 are primarily due to two phenomena. First, the hybrid system allows the engine to operate in higher-efficiency regimes for a larger percentage of the time. Second, the system recovers a portion of the energy that is lost during the braking process. By recovering energy that would otherwise be lost as heat, a hybrid powertrain is generally most beneficial in highly transient driving situations. Many HDVs in India operate in stop-and-go urban driving conditions, so hybrid-electric trucks and 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 costs of the vehicles and advances in other fuel-saving technology areas that are more cost-effective.

Assessing the benefits of transmission technologies such as AMTs and hybrid-electric drivetrains in simulation is more difficult than for the 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. To overcome this barrier, the study team opted to estimate the fuel consumption reduction benefits of AMTs and hybrid drivetrains during post-processing, as was done with engine accessories. For the conventional and advanced AMTs, we assumed overall vehicle fuel consumption reductions of 2.5% and 3.5%, respectively,

based on values in Delgado and Lutsey (2015), the U.S. HDV GHG regulations, and the authors' best judgment. 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 1 to 2 percentage points or less. Therefore, as a simplification in this study, we assume that the AMT efficiency benefits are the same for both vehicle types. For hybrid-electric drivetrains, we assume a 15% overall fuel efficiency benefit for both the rigid truck and transit bus, based on values for light heavy-duty urban vehicles in the U.S. Phase 2 rule and the authors' best judgment (U.S. EPA and NHTSA, 2016).

4.3 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 (C_{RR}) and is defined as follows:

$$C_{RR} = \text{resistive axial force} / \text{normal force}$$

Values for C_{RR} are dimensionless and are typically less than 0.01 (National Research Council, 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 flexibility of tires. Thus, the sidewalls of a radial tire are not as thick as those of a bias tire. This results in the radial tire being more flexible. Increased flexibility of the tire 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 the 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, we selected two additional levels of radial tire technology improvements for this analysis 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 C_{RR} 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 C_{RR} values are shown in Table 4. The C_{RR} 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.

Table 4. Tire technology progression.

Tire technology level	Reduction in C_{RR} versus the baseline
Baseline: Bias tires*	—
Radial tires	15 - 30%
Low-rolling-resistance (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, we assume that bias tires are the baseline for rigid trucks. However, in the case of transit buses, radial tires are already used on a large-scale basis, so we have set radial tires 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 also help to reduce rolling resistance by maintaining optimum air pressure in the tires. 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 underinflation results in 1.5% lower fuel economy (Goodyear Tire and Rubber Company, 2008). On the basis of conversations with tire manufacturers and other industry experts, we assume that tire pressure management systems can play an important role in improving the fuel efficiency of commercial vehicles in India.

4.4 AERODYNAMIC TECHNOLOGIES

As a vehicle moves down the road, there is a pressure distribution acting on the vehicle's surface that 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

$$F = 0.5 C_D A V^2$$

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.

In this analysis, we assume that there are limited opportunities for aerodynamic improvements on transit buses in India because of their low average speeds and frequent stops. Therefore, we do not include aerodynamic technologies in any of the transit bus technology packages. For rigid trucks, we assume a larger percentage of operations at higher speeds (see Table 2) and apply aerodynamic interventions in the more advanced technology packages (see Section 5).

4.5 WEIGHT REDUCTION TECHNOLOGIES

Reducing the weight of the vehicle results in lower power requirements,

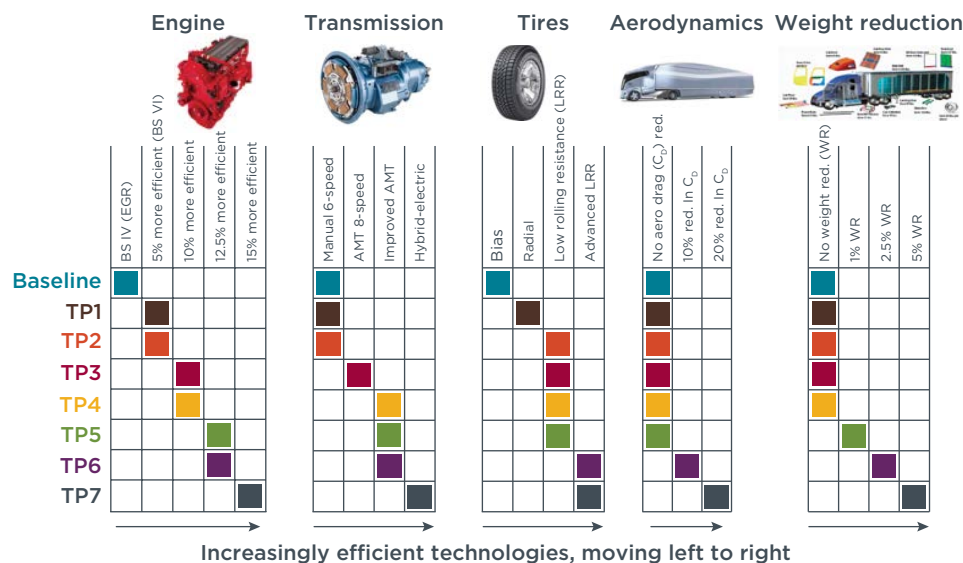


Figure 6. Individual fuel-saving technologies included in each technology package for the rigid truck.

thereby making the vehicle more fuel-efficient. Across all types of HDVs, manufacturers have commercialized and continue to develop products that make use of alternative materials such as aluminum and composites that lower the curb weight of the vehicle.

In addition to reducing inertial and rolling resistance forces, the efficiency benefits of weight reduction are compounded if the operator is able to increase the payload as a direct result of reducing the curb (or empty) weight of the vehicle. 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.

The reduction in vehicle weight is represented as a decrease in the curb weight of the vehicle. In other words, the payload value is kept constant, and thus the total weight (i.e., vehicle curb weight + payload) decreases in the simulation modeling.

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 (National Research Council, 2010) and also addresses the lack of aerodynamic improvement devices that have not been incorporated for the transit bus in this study.

5. Technology package descriptions and results

The fuel efficiency technology packages—that is, groups of individual technologies—were developed by incrementally adding increasingly efficient technologies in the following areas:

- Engine
- Transmission and driveline

- Tires
- Aerodynamics (trucks only)
- Weight reduction

Figures 6 and 7 summarize the technology levels and/or fuel-saving technologies used for each of the technology areas above for the rigid truck and transit bus, respectively. Figures 8 and 9 summarize the fuel consumption results for each technology package for the rigid truck and bus, respectively.³

TP1, in which the vehicles move to BS VI engines and have radial tires,⁴ provides fuel savings ranging from 7% (transit bus) to 14% (rigid truck). As described above, the BS VI engine is assumed to consume 5% less fuel than the BS IV, and this 5% decrease in engine fuel burn translates to roughly 5% fuel consumption reduction for the full vehicle. Therefore, the marginal benefit of adopting radial tires is approximately 9 percentage points for the rigid truck. Figure 10 shows the approximate breakdown of fuel savings by major technology area (i.e., engine, transmission and axles, tires, aerodynamics, and weight reduction) for the rigid truck and bus.

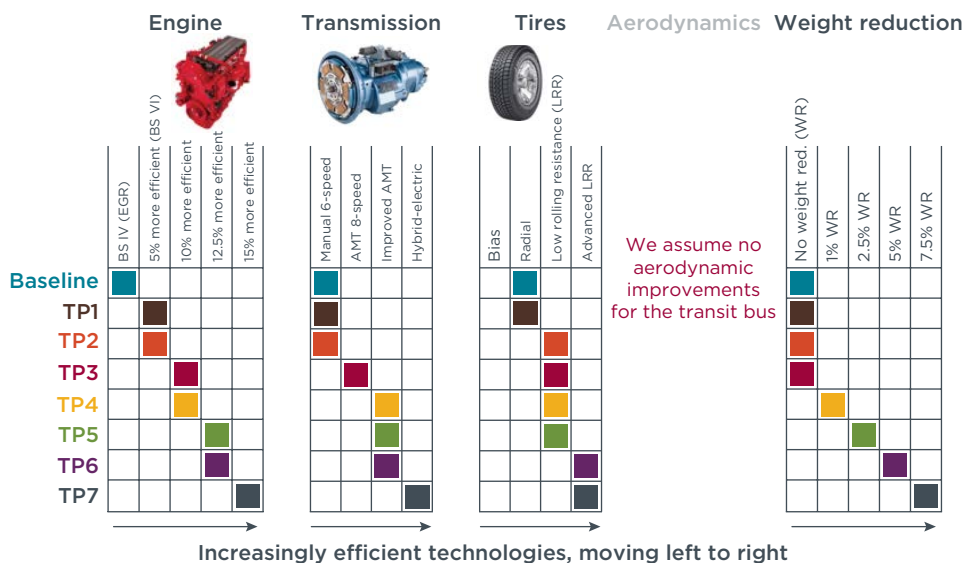


Figure 7. Individual fuel-saving technologies included in each technology package for the transit bus.

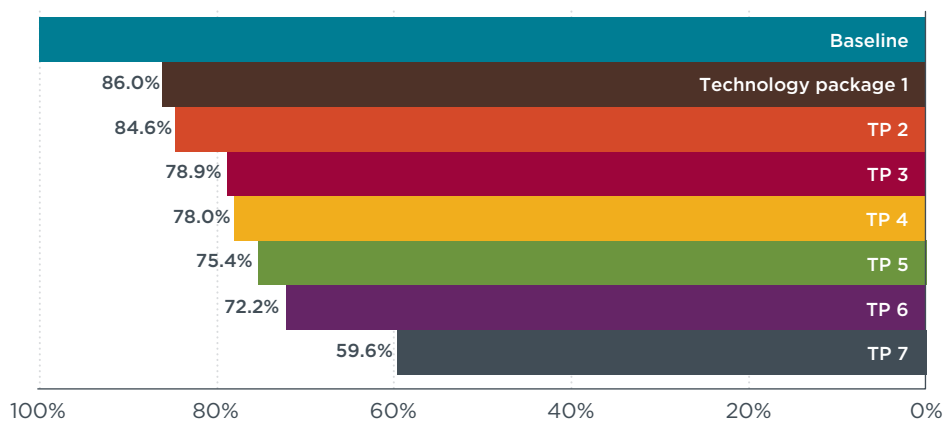


Figure 8. Fuel consumption versus the baseline for the rigid truck.³

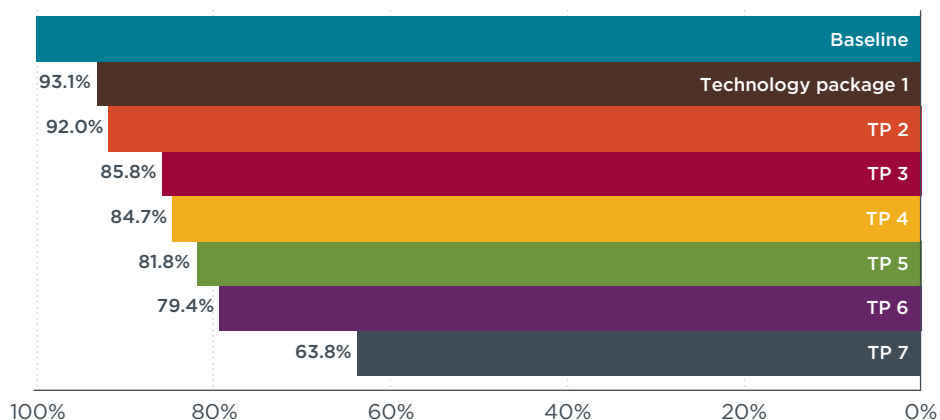


Figure 9. Fuel consumption versus the baseline for the transit bus.

³ We used the formula below to estimate the combined fuel reduction of the technologies modeled in Autonomie (i.e., tires, aerodynamics, weight reduction, and engines) and the technologies that were added into the analysis in post-processing:

$$FC_{\text{total}} = 1 - (1 - FC_{\text{Autonomie}}) \times (1 - FC_{\text{AMT or hybrid}}) \times (1 - FC_{\text{axles}}) \times (1 - FC_{\text{accessories}}) \times (1 - FC_{\text{ATIS}})$$

where FC_{total} denotes the combined fuel savings, and each separate FC value corresponds to the percent reduction in fuel consumption due to technology improvements in the following areas:

- $FC_{\text{Autonomie}}$ = tires, aerodynamics, weight reduction, and engines
- $FC_{\text{AMT or hybrid}}$ = automated manual or hybrid drivetrain
- FC_{axles} = axles and lubrication
- $FC_{\text{accessories}}$ = accessory loads
- FC_{ATIS} = automatic tire inflation systems

⁴ For the transit bus, radial tires are assumed to be the baseline technology level; both the baseline and TP1 have radial tires.

TP2 integrates LRR tires into the technology mix, and for both vehicle types this improvement provides roughly 1 percentage point of additional fuel savings beyond TP1. TP3 introduces the “Advanced Level 1” engine (10% less fuel burn than the baseline BS IV engine) and the AMT in lieu of the manual transmission. Together, these powertrain improvements deliver roughly 6 percentage points of fuel savings beyond TP2. The transition to the AMT accounts for about 1.5 percentage points of these savings.

For the rigid truck and transit bus, TP4 introduces an advanced AMT, which yields another percentage point of fuel savings. In addition, TP4 also has a 1% reduction in curb weight for the bus, which results in about 1 percentage point of benefits. TP5 includes a transition to the “Advanced Level 2” engine for both vehicle types, which gives 2.5 percentage points of fuel savings beyond the Level 1 engine. In addition, TP5 has a 1% and 2.5% curb weight reduction for the truck and bus, respectively. These weight reductions lead to about 0.5 percentage point in fuel savings for the truck and 1 percentage point for the bus.

TP6 brings an additional improvement in tire technology, the addition of tire pressure management systems, and additional weight reduction (2.5% versus the baseline for the rigid truck and 5% for the transit bus). This package delivers roughly 2 to 3 percentage points of additional fuel consumption reductions versus TP5.

Finally, TP7 includes the most efficient engine level in this analysis by adding waste heat recovery (WHR) technology to the Level 2 engine. The WHR recovery system yields another 2 percentage points in savings beyond the Level 2 engine. In addition to the

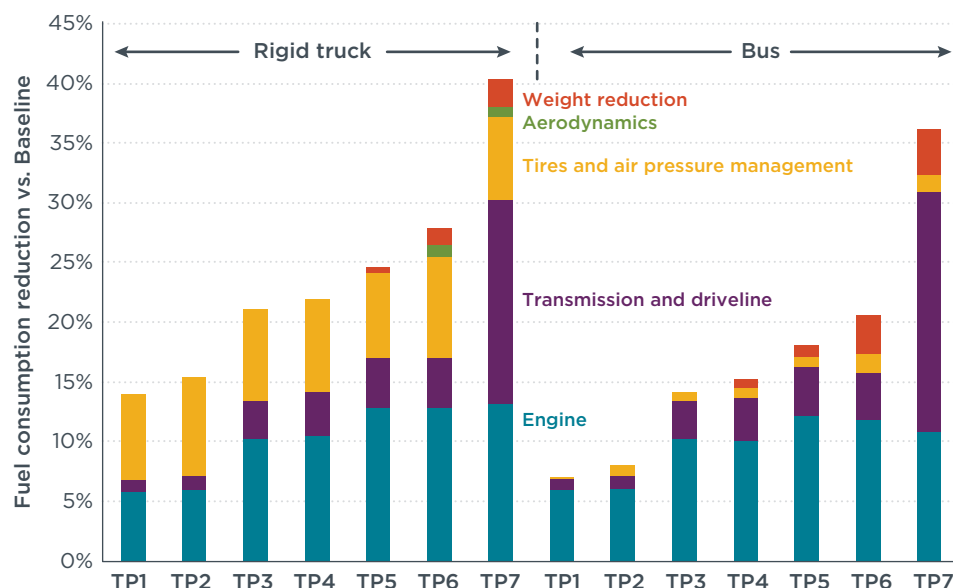


Figure 10. Fuel consumption reduction by technology area for each technology package.

improved engine, the powertrain of TP7 is enhanced by the introduction of a hybrid-electric system, which takes the place of the advanced AMT. By capturing a portion of braking energy and allowing the engine to run more frequently in high-efficiency operating regimes, the hybrid system results in 15 percentage points of fuel consumption reduction for the truck and 18 percentage points for the bus. This final package also boosts the curb weight reduction to 5% and 7.5% for the truck and bus, respectively, which results in 0.7 to 1 percentage point of fuel savings beyond TP6. Together, adoption of TP7 for the rigid truck and transit bus will yield fuel consumption reduction potentials of 40% and 36%, respectively.

6. Conclusions

This study examines the technology potential for trucks and buses less than 12 tonnes in India over the next 10 years. It builds on a previous technical analysis carried out by the ICCT and Lawrence Berkeley National Laboratory focused on commercial vehicles greater than 12 tonnes. Trucks

and buses less than 12 tonnes represent approximately one-third of total sales of the overall HDV market (i.e., on-road vehicles greater than 3.5 tonnes).

Results from our simulation modeling of two representative HDV types—a 12-tonne rigid truck and a 7.5-tonne transit bus—reveal that per-vehicle fuel consumption reductions between roughly 35% and 40% are possible versus the current baseline. Although most of these technologies are currently unavailable in India, experiences in other more advanced markets such as the United States and Europe suggest that with sufficient incentives and robust regulatory design, substantial progress can be made in developing and deploying efficiency technologies that can provide real-world fuel savings for new commercial vehicles in India over the next 10 years.

In future work, the study team will again collaborate with Lawrence Berkeley National Laboratory to estimate the costs and benefits of various deployment scenarios for each of the technology packages at the fleetwide level.

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