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Engines and tires as technology areas for efficiency improvements for trucks and buses in India

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India is in the process of developing fuel efficiency standards for new heavy-duty vehicles (HDVs), and one of the most critical inputs to regulatory development is a technology potential analysis to determine the efficiency levels that the fleet can reasonably achieve over the duration of the regulation. Typically, one of the first steps in any comprehensive technology potential analysis is determining what technology areas can make the most significant contributions to overall vehicle efficiency improvements. For reasons we have discussed in an earlier working paper[1] and elsewhere,[2] an engine standard, coupled with a regulation promoting more fuel-efficient tires, will maximize fuel and emissions benefits as soon as possible and put India on the best path forward. The objective of this paper is to present a primary analysis to estimate how improvements in engine and tire technology will translate to fuel consumption reductions for a select number of representative HDV types in India.

This paper is narrowly focused around two research questions:

1. How do engine efficiency improvements—as measured over an engine dynamometer—translate to fuel consumption reductions in full vehicles over a range of different drive cycles?
2. How do reductions in aerodynamic drag compare to reductions in rolling resistance drag in terms of overall fuel consumption impacts over a range of different vehicle types and drive cycles?

1 Sharpe (2015) Testing methods for heavy-duty vehicle fuel efficiency: trends from regulatory programs around the world and implications for India. http://www.theicct.org/hdv-efficiency-test-procedures-trends-implications-india

2 Sharpe (2015) Why heavy-duty engine standards put India on the best path forward. http://www.theicct.org/blogs/staff/why-heavy-duty-engine-standards-put-india-best-path-forward

For this analysis, we developed vehicle simulation models for three representative HDV types based on popular models in the Indian market: a tractor truck, rigid truck, and transit bus. Each of these three representative vehicles is modeled using data on vehicle characteristics from sales database that we acquired for fiscal year 2013-2014. Based on that sales market database, the HDV models that we chose to analyze were designed in simulation to resemble the top-selling models in their respective vehicle segments. The key modeling parameters of the three vehicle types are summarized in Table 1. The engines, transmissions, and gross vehicle weight characteristics are based on the specifications of particular vehicle models, and the remaining parameters are based on data from comparable vehicles in other markets and the authors' best judgment.

As shown in Table 1, all three of the vehicles have the same engine model. This particular 5.9-liter engine with a power rating of 134 kW is the best-selling engine in the Indian commercial vehicle market and is found in 14% of the HDVs sold in fiscal year 2013-14. In terms of emission standards, this engine is at a Bharat Stage III (i.e., Euro III) level.

With the objective of answering the first research question, two engine models were created: 1) a baseline engine and 2) an enhanced efficiency engine. The first step in the modeling process was to create a model of the baseline engine to be used in Autonomie[3], our vehicle simulation software platform. Detailed fueling maps that give an engine's fueling rate across its entire operating range are proprietary, so we created an approximate fueling map for this engine based on a torque curve found in the literature for this engine model along with a generic Euro III fueling map calibration.

3 For more information on Autonomie, please see www.autonomie.net

Table 1: Baseline vehicle characteristics

Parameter	Tractor truck	Rigid truck	Transit bus
Engine	Bharat Stage III, 5.9 liter, 134 kW		
Transmission (gear ratios: 1st, 2nd,…, 6th)	6 speed manual (9.2, 5, 3, 1.9, 1.4, 1)	6 speed manual (9.2, 5, 3, 1.9, 1.4, 1)	6 speed manual (6.6, 3.8, 2.3, 1.5, 1, 0.8)
Payload	13,615 kg	9,245 kg	1,837 kg
Gross vehicle weight	40,200 kg	25,000 kg	16,200 kg
Aerodynamic drag coefficient	0.7		
Frontal area	7.2 m2	6.8 m2	7.5 m2
Coefficient of rolling resistance	0.008		
Final drive ratio	6.8	6.1	6.1

With the baseline engine model completed, the next step in the analysis was to develop a more efficient version of this engine. The enhanced efficiency engine was created by scaling the fuel consumption of the baseline engine based on improvements in combustion, air-handling, and engine friction.[4]

With fueling maps for both the baseline and enhanced efficiency engines, the next step was to estimate the difference in fuel efficiency between the two engines. In order to estimate fuel consumption reduction over engine test cycles, a Matlab lookup function was created to act as a *virtual* engine dynamometer. The engine torque and speed points of different engine test cycles were used along with the aforementioned engine fueling maps to estimate fuel consumption over these engine cycles. Since a steady-state fueling map (a two-dimensional lookup table) is used for this analysis, the engine's transient behavior cannot be captured as in an engine dynamometer test bench. Consequently, fuel consumption values are underestimated when using this method. However, the relative differences are expected to be consistent, assuming that transient behavior is similar on a test bench for both engines. To estimate the bias introduced by the absence of transient behavior in the virtual engine dynamometer, we used a different engine model for which we have access to a very accurate fueling map as well as actual test results from an engine dynamometer evaluation. Over the heavy-duty Federal Test Procedure (FTP) cycle, the simulated fuel consumption using the virtual engine dynamometer was 2.8% lower than the measured fuel consumption in the real-world test. This bias is expected to be very similar for both the baseline and enhanced efficiency engines, so the actual relative changes in efficiency between the two engines reasonably approximated by use of the virtual engine dynamometer.

4 At each torque-speed data point, the percentage change from a US model year (MY) 2017 engine (i.e., an engine compliant with the US Phase 1 regulation) to a MY 2027 engine (i.e., Phase 2 compliant) was applied to the baseline fueling map to obtain an enhanced fueling map that represents improvements in combustion, air-handling, and engine friction.

We evaluated the baseline and enhanced efficiency engines on three engine torque-speed cycles: the FTP, World Harmonized Transient Cycle (WHTC), and the World Harmonized Stationary Cycle (WHSC). For the full vehicle analysis, we simulated each of the three vehicle types with the baseline and enhanced efficiency engine over four different cycles: the World Harmonized Vehicle Cycle (WHVC), the 'WHVC-India' cycle, the ARB Transient cycle, and the ACEA Regional Delivery cycle. These cycles represent a range of different driving conditions. The speed-time traces for the first three cycles are shown in Figure 1.

The WHVC was the basis for the development of the engine test cycle WHTC. Since the WHTC is used as a certification test for regulated pollutants, where it is important to have low emissions in all relevant driving conditions, the main purpose of the WHVC is to cover a wide range of driving situations. The WHVC-India cycle is a cycle that we developed 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 US and the EU. The WHVC-India cycle is identical to the WHVC for roughly the first 1,200 seconds of the cycles, and then afterwards, the speeds of the WHVC are multiplied by 0.7 to produce the speeds for the WHVC-India. The ARB Transient cycle is actually one portion of a four-mode drive cycle (the Heavy Heavy-duty Diesel Truck cycle) that was developed by the California Air Resources Board and is one of the three test cycles used to evaluate tractor trucks in the US Phase 1 and 2 fuel efficiency regulations. As the name implies, the ARB Transient cycle is meant to capture stop-and-go transient driving conditions. The final cycle, which was developed by the European Automobile Manufacturer's Association (ACEA), is meant to represent a freight truck that performs regional deliveries and spends a sizable portion of its operating time at highway speeds. Figure 2 shows the velocity profile of this cycle, and one of the key differences from the other three cycles in the presence of grade, which is shown in the brown dotted line in the figure.

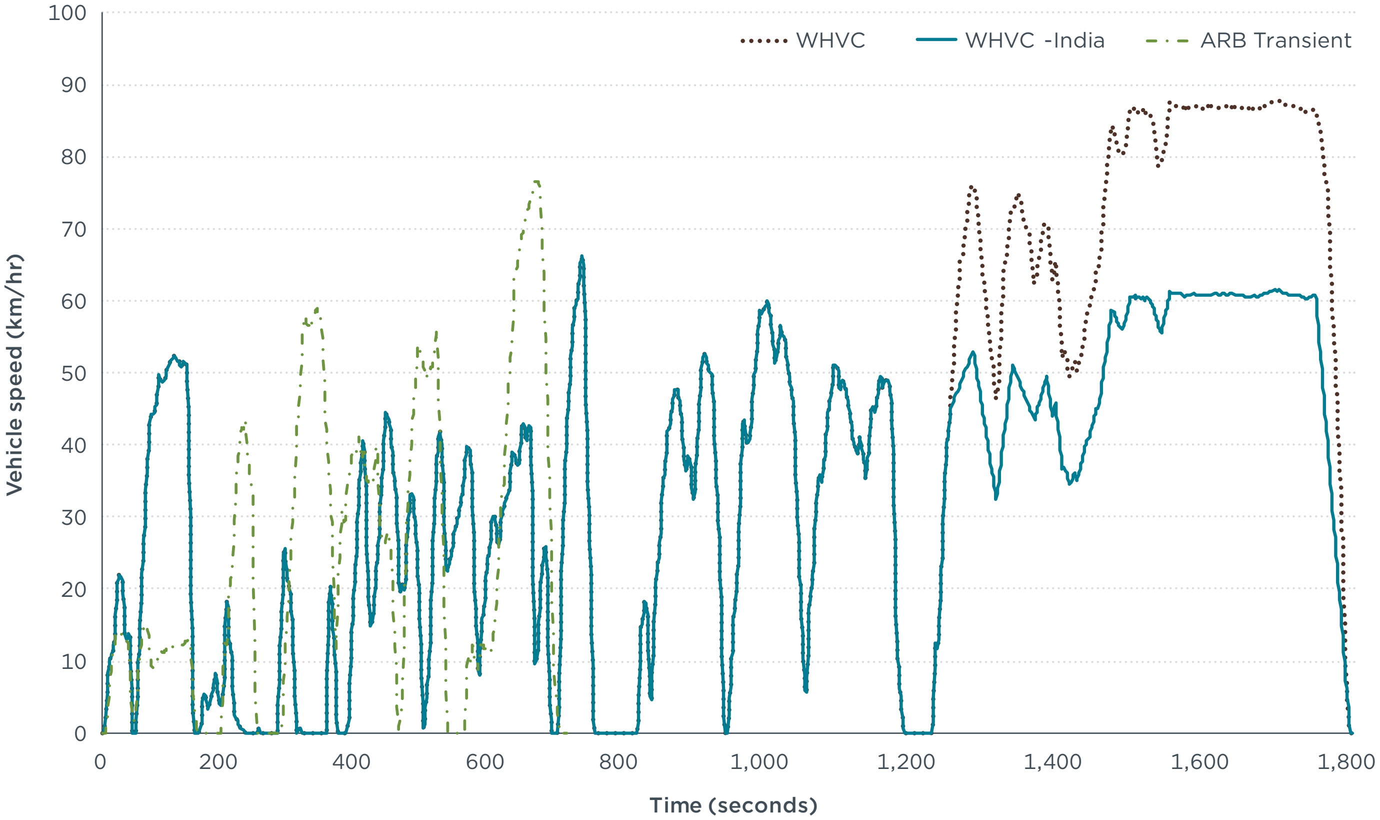

Figure 1: Vehicle speed versus time for the WHVC, WHVC-India, and ARB Transient cycles

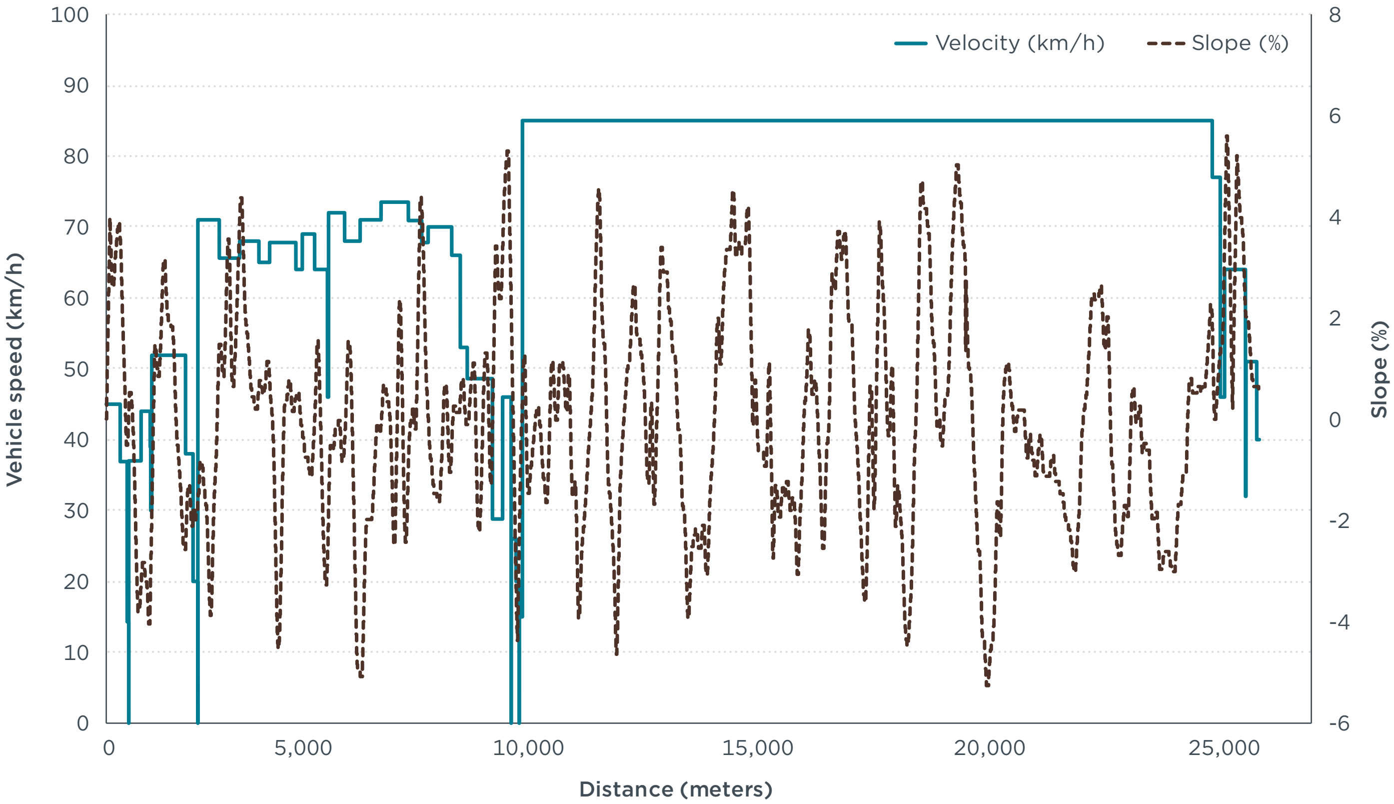

Figure 2: Vehicle speed and gradient versus distance for the ACEA Regional Delivery cycle

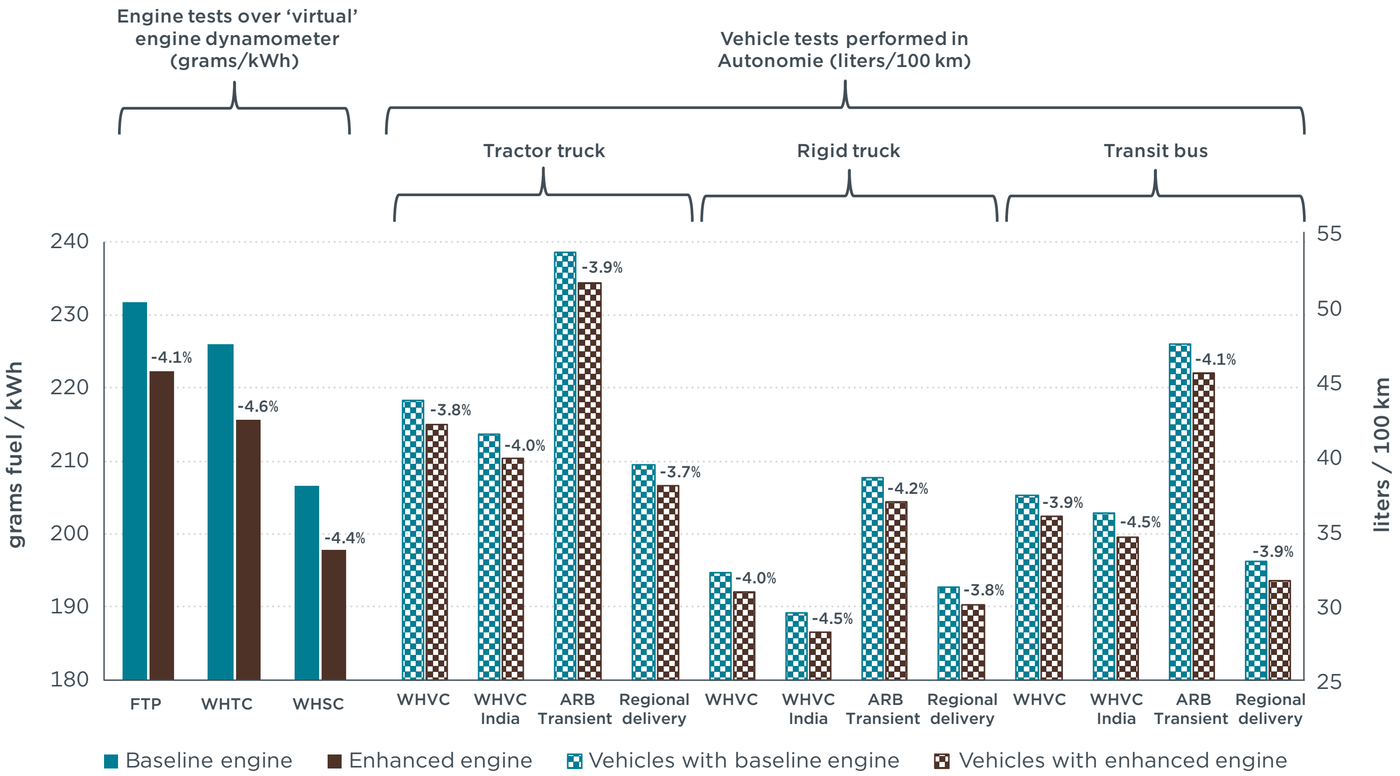

Figure 3: How efficiency improvements over engine cycles translate to vehicle cycles

As shown in the left-hand side of Figure 3 in the solid-colored columns, the more efficient engine consumed 4.1%, 4.6%, and 4.4% less fuel than the baseline engine over the FTP, WHTC, and WHSC cycles, respectively. Having established a fuel consumption benefit of between 4% and 5% on the virtual engine dynamometer for the more efficient engine, the next analytical step was to determine how these efficiency improvements would translate to vehicle drive cycles in the different vehicle platforms.

The right portion of Figure 3 with the checkered columns shows the results from the vehicle simulations. Looking at the fuel consumption benefits of the vehicles when using the more efficient engine, the fuel savings are very much consistent with the engine-based results, with values for fuel savings over the four vehicle cycles ranging from 3.8% to 4.5%. These results suggest that efficiency improvements over engine dynamometer cycles very much translate to comparable benefits across a fairly broad range of different vehicle driving conditions. The robustness of engine efficiency improvements is one of the primary reasons why the ICCT recommends that India move forward with engine-based testing as part of its initial fuel efficiency rulemaking for HDVs.

For the second research question that we explored in this study, we analyzed how reductions in aerodynamic drag and rolling resistance drag, respectively, translate to fuel savings benefits across the same three vehicle types and four vehicle drive cycles that were used in the analysis that is summarized in Figure 3. In this analysis, we reduced the coefficients of both aerodynamic drag (C_D) and rolling resistance drag (C_{RR}) by 20% while holding all of the other vehicle parameters constant to see the overall fuel savings impacts of the reductions in C_D and C_{RR}.

Figure 4 summarizes the results for all three HDV types across the four cycles. The results of the 20% C_D and C_{RR} reductions are shown in the blue and brown columns, respectively. For all 12 of the simulations, the reduction in C_{RR} was more impactful in terms of fuel consumption benefits than the reduction in C_D. On average, the percentage fuel savings from the C_{RR} reduction is 2.5 times great than the savings from the C_D reduction. These results imply that compared to aerodynamics, rolling resistance makes up a much larger portion of the overall energy losses for typical Indian HDVs. To explore the breakdown of energy losses in more detail, we performed an energy audit for one of our vehicle types.

For this energy audit, we simulated the tractor truck running over the WHVC-India drive cycle at full payload, and the Autonomie software provided us results that we post-processed to yield the percentage breakdown in energy losses shown in Figure 5. In this particular vehicle simulation, losses in the engine account for the majority of total losses (62%). Beyond the engine losses, the next

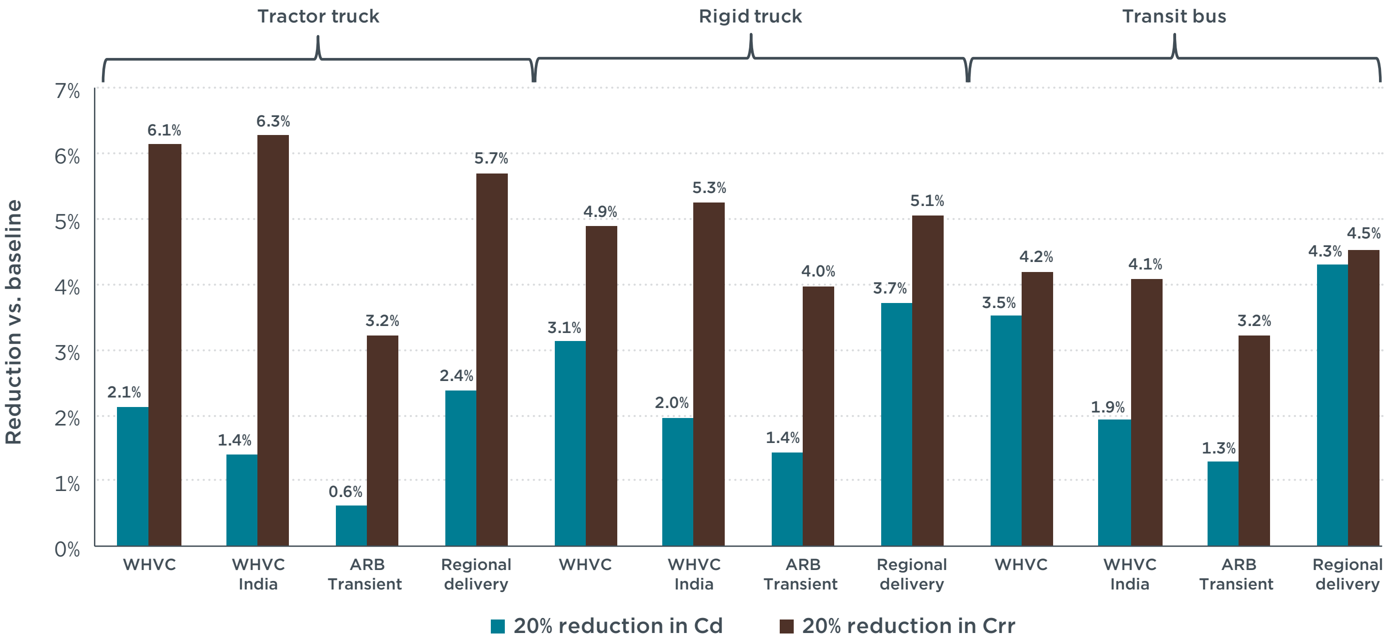

Figure 4: Fuel consumption reductions resulting from a 20% reduction in aerodynamic drag versus 20% reduction in rolling resistance

biggest loss area is tires' rolling resistance at nearly 20%. Losses from tires are almost twice as large as the next largest category, braking. Aerodynamic losses are shown in the red wedge and are actually the smallest loss area, accounting for only 2.5% of total losses. For this vehicle and drive cycle simulation, rolling resistance losses are over seven times as large as aerodynamic losses. This implies that for comparable levels of reduction in aerodynamic drag and rolling resistance drag, the resulting fuel consumption benefits are going to be much larger in the case of rolling resistance for most HDVs in India. Compared to other major markets, slower average driving speeds and a large degree of overloading make tire rolling resistance the dominant non-engine loss category for HDVs in India in most cases.

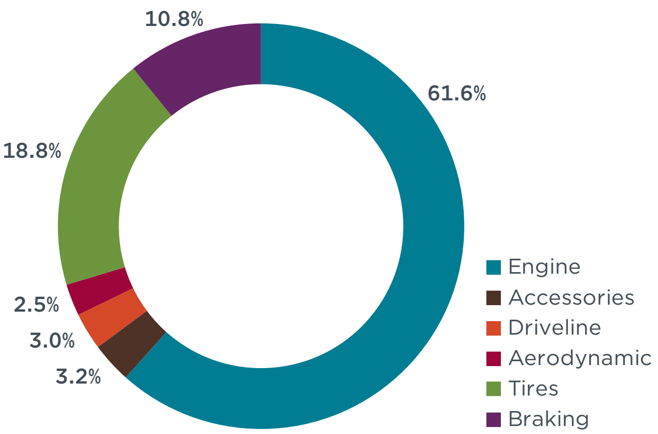

Figure 5: Breakdown of energy losses for a tractor truck operating over the WHVC-India cycle

Another way to analyze the comparative effectiveness of improvements in engines, aerodynamics, and tires is to examine the *return factors* for each parameter. Return factors (RFs), or elasticities, are the ratio of fuel consumption reduction percentage for the full vehicle to the percentage change in a given vehicle technology parameter. Thus, the higher the RF value for a given parameter, the more attractive that technology area is in terms of how improvements in that technology translates to overall fuel consumption reductions.

The average RFs (i.e., the straight average over all four vehicle cycles) for these three technology areas for each vehicle type are shown in Figure 6. The average RF for engine brake thermal efficiency (BTE) improvements for all three vehicle types is 0.96. Having a RF value so close to 1 indicates that because engines are the fuel-consuming element of the vehicle, the amount of efficiency improvements in engines almost directly translates to identical levels of efficiency gains in the full vehicle. The average RFs for tire rolling resistance and aerodynamics are 0.24 and 0.12, respectively. This implies that for the vehicle types, payloads, and drive cycles analyzed for this study, reductions in tire rolling resistance drag are roughly twice as impactful as reductions in aerodynamic drag. This means that for a percent reduction in C_{RR} and C_D, the resulting reduction is overall vehicle fuel consumption is about twice as large for tire rolling resistance improvements as for aerodynamics (i.e., 0.24% overall fuel consumption reduction from the 1% reduction in C_{RR} versus 0.12% from the 1% reduction in C_D).

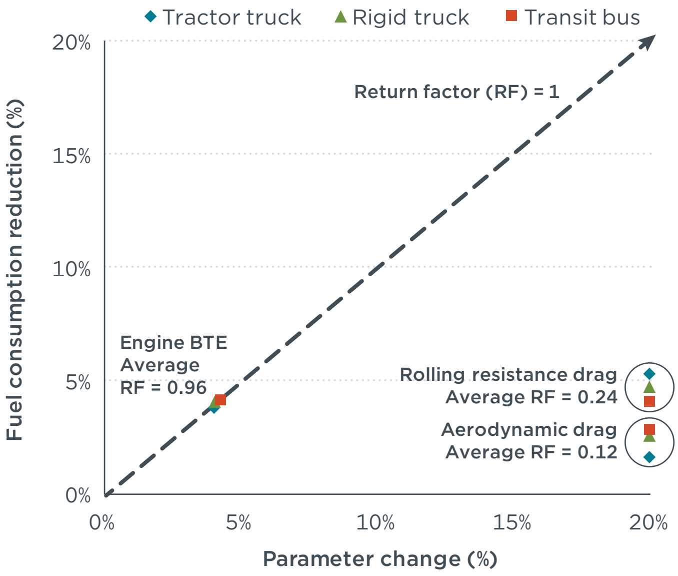

Figure 6: Average return factors for each of the three technology areas and vehicle types

Return factor = [% vehicle fuel savings] / [% change in parameter]

These results from this study strongly suggest that advancements in engines and tires are the most attractive technology areas for improvements for HDVs in India. Compared to regions such as North America and Europe, HDVs in India travel at much slower average speeds. Since aerodynamic drag forces increase with the square of vehicle velocity, our analysis indicates that for most HDV types in India, tire rolling resistance accounts for the majority of energy losses after engines, which represent well over half of total losses. Therefore, in terms of overall technology potential for fuel efficiency improvements, together, engines and tires likely represent the lion's share of opportunities.

This study supports the view that India would be best served to focus on engine and tire improvements for its first phase fuel efficiency regulation for trucks and buses. Of course, we do not discount technology advancements that are possible for areas such as aerodynamics, transmissions, and accessories. However, compared to engines and tires, we estimate that the marginal benefits from improvements in these other areas will be quite small. In future work, we will refine this analysis in terms of how the vehicles are characterized in simulation, using interviews with industry experts and data from physical testing to validate our models. In addition, we will integrate costs into the analysis so that we can develop a comprehensive assessment of the costs and benefits associated with improvements across the various technology areas. With this forthcoming cost-benefit analysis, policymakers in India will be able to best determine a regulatory design approach that will maximum efficacy in terms of technology deployments that result in fuel savings and emission reductions that will benefit the Indian commercial vehicle industry and society as a whole.