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ESTIMATING THE FUEL EFFICIENCY TECHNOLOGY POTENTIAL OF HEAVY-DUTY TRUCKS IN MAJOR MARKETS AROUND THE WORLD

Working Paper 14

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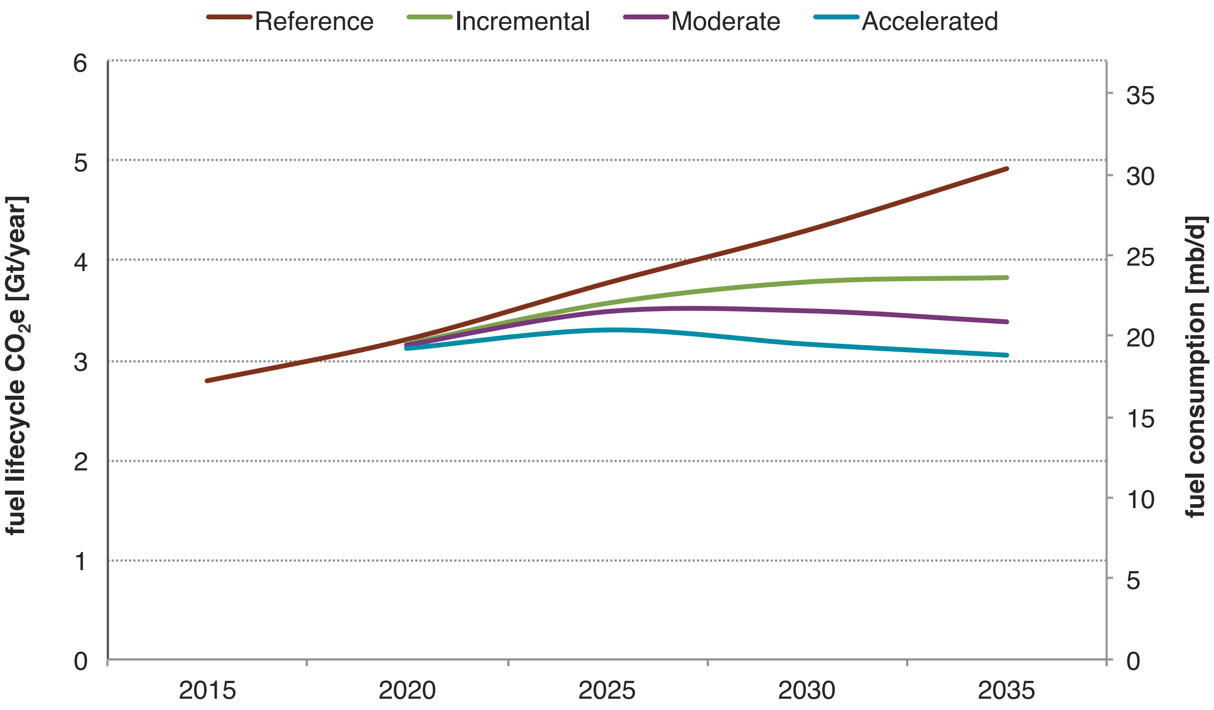
Executive Summary

As the global demand for freight transport continues to grow, improving the efficiency of on-road freight vehicles is an increasingly important step to mitigate the resulting climate impacts. Policymakers have a portfolio of possible measures to reduce the climate impact of on-road freight movement. These include both voluntary measures such as green freight programs or vehicle fuel efficiency labeling, and mandatory measures such as, fuel taxes or new vehicle efficiency standards. Policymakers in major markets are at various stages of developing and implementing efficiency standards to ensure the continued technological improvement of the new vehicle fleet.

This study investigates the potential for new freight-hauling tractor-trailers and rigid delivery trucks to improve in efficiency with the adoption of known efficiency technologies. This study develops a baseline tractor-trailer and a representative rigid delivery truck for the 2015 EU, US, Brazil, India, and China fleets. These two truck categories account for the vast majority of road freight oil use and climate emissions (ICCT 2016). The baseline fuel consumption is determined over region-specific duty cycles and payloads. Technology packages are then established that represent the most advanced applicable technologies that have been either commercialized or demonstrated to be commercially available in the 2030 timeframe. The phase-in of the technology packages into world truck markets is modeled over the 2020 through 2040 timeframe in order to determine the potential for improvement in each market. Three possible emission and fuel consumption reduction scenarios are developed to quantify the range of possible benefits over time.

Figure ES1 illustrates how full deployment of heavy-duty vehicle efficiency technology, as analyzed here, would result in energy savings of close to 9 million barrels of oil per day in the year 2035. This would be equivalent to almost 2 billion tonnes of carbon dioxide emissions avoided per year in 2035. China and India each represent about one quarter of these potential long-term oil savings and climate benefits due to their growing freight activity. These two markets are followed by the US, Europe, and Brazil in terms of having the most potential energy and carbon savings from realizing their technology potential. The remaining potential is divided among countries in the Asia-Pacific, Middle East, Africa, and Latin America as well as smaller individual markets.



ES1. Annual GHG emissions and fuel consumption from tractor-trailers and rigid trucks worldwide by efficiency scenario, 2015-2035.

This report also contributes new analysis and information to the existing literature that may be used as a foundation for future research:

- Baseline Vehicles: This is the first known study to quantify and compare the representative baseline vehicle characteristics and operational profiles of tractor-trailers and rigid delivery trucks in the top five vehicle markets. Using the best available data, the study has found that representative baseline fuel consumption on a liters per 100 kilometers (L/100km) basis varies significantly across markets for both tractor-trailers and rigid delivery trucks. Under the assumptions made in this study, there is a 48% difference in fuel consumption between the most and least efficient baseline tractor-trailers and a 26% difference between the most and least efficient rigid trucks. Less than half of that difference (approximately 10-20%) is due to variations in vehicle technology and configuration while over half of the difference is due to variations in typical duty cycle and payload.

- Energy Audits: This study uses simulation modeling to develop energy audits of the baseline vehicles over region specific duty cycles and payloads. Energy audits are an effective means to identify and prioritize the most applicable areas for technology applications. For example, a vehicle with an energy audit that shows significant energy loss due to overcoming aerodynamic drag would benefit from aerodynamic improvement technologies, while a vehicle in which an energy audit finds significant energy loss due to braking would benefit from a hybrid regenerative braking system. The most consistent result across the energy audits developed for this study is that losses from engine inefficiencies are always greater than 50% of total energy loss. Although there exist theoretical limits to internal combustion engine efficiency, this result indicates that technologies to improve engine efficiency would have wide-ranging applicability across segments and markets.

- Region Specific HDV Technology Potential: This study simulates the effectiveness of advanced efficiency technology packages on the region-specific baseline vehicles. The technology packages consist of known technologies that are either commercially available today, or are predicted to be commercially available within the next 10-15 years. Given the different payloads and duty cycles across regions, the same technology packages result in different levels of fuel consumption reduction when applied to individual vehicles. In addition, regions with more fuel saving technology already included in their baseline fleet will have less potential for technological improvements. This study finds that there is potential for fuel consumption reduction in the range of 40%-52% for tractor-trailers and 30%-36% for rigid delivery trucks across all regions assessed, with trucks sold in the EU having the smallest potential and trucks sold in India having the largest potential in both segments.

- Associated potential benefits: Applying the technology potential as analyzed here translates to sales-weighted global targets of 31% fuel consumption reduction for new Medium HDVs and 46% fuel consumption reduction for new Heavy HDVs. Deploying this level of heavy-duty vehicle efficiency technologies could result in approximately 5-9 million barrels per day of equivalent oil savings in the 2035 timeframe.

The findings in this report present a rationale for introducing and upgrading heavy-duty vehicle efficiency standards in major markets around the world. Realizing the sort of transformation in truck technology as modeled here would require effective regulations. Long-term stringent regulations give vehicle and engine manufactures as well as component suppliers the certainty to invest in the commercialization of advanced efficiency technologies.

1. Introduction

In terms of global carbon dioxide (CO_2) emissions and fuel consumption from transportation, the heavy-duty vehicle (HDV) sector is second only to the light-duty vehicle (LDV) sector. With the projections for growing freight demand in many markets as well as the proliferation of LDV efficiency standards, the gap between the two sectors is projected to narrow and eventually close to parity by 2050 (ICCT 2016). Since the 1990s, the majority of policy-driven technological advances in the heavy-duty segment have been driven by the need to curb the emission of local air pollutants, such as nitrogen oxides (NOx) and particulate matter (PM). The major global automotive markets currently either have advanced emission control technologies in place on their heavy-duty fleets or they have well-defined pathways to attaining them. While HDV local air pollutant emissions have yet to be fully resolved, with such emission control initiatives already underway, there now exists a good opportunity to focus attention on policies that lower market barriers to the adoption of efficiency technologies, reduce fuel consumption, and address the climate impact of HDVs.

Efficiency standards for HDVs in 2016 are in much earlier stages than light-duty vehicle efficiency standards, which have been around in one form or another for more than 30 years. The first HDVs to be regulated for efficiency have only just begun to come to market in the past few years. Currently only four countries in the world have finalized HDV efficiency standards – the US, China, Japan, and Canada. Other countries that have indicated they are working toward a standard at this time include India, Mexico, and South Korea. The EU is working toward regulation to certify, monitor, and report CO_2 from HDVs. Aside from the US and Canada, which have aligned their standards, the current trend for HDV efficiency standard development has been a largely un-harmonized approach with countries developing unique stringency limits, vehicle segmentation profiles, testing and certification procedures, evaluation metrics, and technology pathways. This trend may cause a higher level of effort than necessary in the development of standards. Developing strong and effective HDV standards requires a commitment of resources to develop fleet baselines, an appropriate regulatory framework, certification protocols, and technology and cost analyses.

The HDV sector presents a number of differences from the light-duty vehicle sector and therefore requires its own strategy for improving efficiency. In terms of annual sales, HDVs are only a small part of the global automotive market, but they consume significantly more fuel per vehicle than their light-duty counterparts. In contrast to light-duty vehicles, which are mostly for personal use, HDVs are used for commercial purposes such as moving freight and passengers. HDVs typically are customized for specific uses whereas light-duty vehicles are typically mass-produced for the market. The major manufacturers, component suppliers, and key industry players in the HDV market are in many cases different from those of the light-duty vehicle market. The technologies used to improve the efficiency of HDVs also differ from those that are used for light-duty vehicles. There are significantly more relevant data available on the fuel economy for the light-duty vehicle market, whereas data for the HDV sector are lacking. There is, however, evidence of significant potential to improve the efficiency of HDVs on an annual improvement rate commensurate with what is currently being achieved for light-duty vehicles.

This paper focuses on estimating the potential for technology improvements to reduce the fuel consumption of key HDV segments in markets around the world. Vehicle simulation software was used to analyze two vehicle segments – tractor-trailer and rigid truck – in five major markets: Brazil, China, the EU, India, and the US. The results were mapped to the remaining world markets and policy scenarios were modeled using ICCT's roadmap model (ICCT, 2016). The overall motivation for this project is to take the first step in a process culminating with setting global HDV efficiency targets in a way similar to what the Global Fuel Economy Initiative has done for passenger cars (Bandivadekar et al., 2016).

The report is organized into five sections:
Section 2 provides an overview of the methodology and key assumptions.
Section 3 describes baseline vehicle characteristics, operating parameters, and fuel consumption levels.
Section 4 analyzes the technology potential for each of the two vehicle types in the five regions.
Section 5 estimates the impacts on global fuel use and CO_2 equivalent emissions of various technology scenarios.
Section 6 summarizes the conclusions of this initial analysis and discusses opportunities for future work.

2. Methodology

In this project, two representative vehicle types from the HDV sector — tractor-trailers and 10 to 12 tonne rigid trucks — form the basis of the analysis. These two vehicle types represent the vast majority of on-road freight movement and, thus, account for the largest share of HDV fuel use and emissions.

The analysis includes three broad areas: (1) determining baseline vehicle specifications, operational profiles, and fuel consumption; (2) assessing the per-vehicle technology potential to reduce fuel consumption; and (3) estimating the global fuel consumption and emission impacts of wide-scale deployment of the fuel-saving technology packages developed in this analysis. The methodology followed in each area is described in the following subsections.

2.1. Baseline vehicles

The primary analytical tool used in this study to estimate fuel consumption of the baseline vehicle and technologically advanced vehicle configurations is a vehicle simulation software program called Autonomie (UChicago Argonne LLC 2016). Autonomie was developed by Argonne National Laboratory and is a state-of-the-art vehicle-modeling tool with the structure and features required to rigorously simulate emerging heavy-duty vehicle efficiency technologies. Autonomie is commercially available, readily modifiable, and is widely used by industry and researchers. In order to simulate a vehicle in Autonomie a range of inputs are required. The input parameters that are most crucial to accurately model fuel consumption are: the engine fueling map, aerodynamic drag, tire rolling resistance, vehicle weight and payload, and the driving cycle speed and grade profile.

Ten vehicle models were developed to represent two vehicle segments in each of the five vehicle markets under consideration, specifically heavy-duty tractor-trailers and rigid trucks in Brazil, China, the EU, India, and the US. The baseline vehicles were simulated over market-specific duty cycles and with typical payloads to obtain baseline fuel consumption performance.

The baseline vehicles in each region are meant to represent typical models and configurations of 2015 model year trucks. The top-selling vehicles and the most common configurations were identified based on new vehicle sales data, literature review, and consultations with HDV experts from the given markets. The authors did not aim to exactly match specific makes and models, but rather to simulate typical configurations to obtain a representative composite which combines the most common technical attributes of the tractor-trailer and rigid truck to be analyzed for each region. We recognize there is a wide range of vehicle specifications for a given heavy-duty segment in a given market. In any given market there will be vehicles that are more technologically advanced or less technologically advanced than the vehicle selected for a baseline. By identifying the most common vehicle characteristics, we aimed to select an average vehicle to represent the fleet as a first order approximation.

One of the key challenges in this project was that some technical parameters that are very relevant to a vehicle’s fuel consumption were not readily available. For example, quantitative data on vehicle aerodynamic drag coefficients and tire rolling resistance are scarce or generally unavailable. To mitigate the effects of this missing information, we consulted with industry experts who provided qualitative and quantitative information on market-specific vehicle specifications including engine efficiency, transmission technologies, aerodynamics, tire rolling resistance, and other vehicle systems. We also worked with a consultant to acquire region-specific engine fueling maps and technology penetration rates for certain markets. Nevertheless, when data were lacking it was necessary to make assumptions about some vehicle parameters based on our best engineering judgment.

Similar to the issue of lack of publically available data on vehicle technical parameters, there is also a shortage of information about real-world duty cycles in some markets. For example, while China and the US have regulatory cycles to represent local driving conditions and the EU has developed vocation-specific duty cycles based on HDV operations in Europe, we did not have access to region-specific cycles for Brazil or India. The study team faced similar challenges in finding data on typical payloads particularly in Brazil, China, and India. These duty cycle and payload issues are discussed in more detail in Section 3.3, along with details of how they were resolved.

2.2. Technology potential

The potential for fuel consumption reduction from technology integration was estimated for each vehicle type using a combination of vehicle simulation, in-house engineering analysis, and technology effectiveness values from the available literature. The technology potential analysis aims to capture what will be technically feasible and commercially available by 2030.

A two-tiered technology deployment approach was used in each of the five regions based on the relative state of technology adoption and current fuel efficiency levels in each market. To reflect current conditions and expected developments over the next 10-15 years, the EU, US, and China were considered to be on the first tier. The US and China already have HDV efficiency regulations in place, and the EU and the US are comparatively advanced in terms of vehicle technology levels. In Brazil and India, technology deployment and regulation lag by a number of years so they are considered to be on a second tier. It should be noted that China also lags behind in efficiency levels with respect to the most advanced markets but it was classified in the first tier because it already has regulations in place and is actively working toward reducing its current efficiency gap with the US and EU fleets.

As discussed further in Section 4, the assumed technology progression out to 2030 in the US is based on the required efficiency levels of both the Phase 1 (current) and Phase 2 (proposed) HDV GHG / efficiency regulations. When combined, these would apply to new model year (MY) 2014 to 2027 vehicles (U.S. EPA, 2011; U.S. EPA, 2015). Levels of technology deployment expected through US Phase 1 and 2 regulations are reasonably well understood and have been laid out in detail in the Regulatory Impact Assessments associated with the respective regulations (U.S.EPA, 2011b; U.S. EPA, 2015b). As proposed, the US standard is currently the most progressive HDV efficiency proposal of any country and likely will be used as a model for other regions. In addition, the US SuperTruck research and vehicle demonstration program provides a very useful preview of the technologies that can be commercially deployed to advance efficiency levels beyond what is expected to be achieved through the Phase 2 regulation (Delgado & Lutsey, 2014; U.S. Department of Energy: Office of Energy Efficiency and Renewable Energy, 2014). US SuperTruck technology levels and US Phase 2 technology levels were used as technology “end points” for the tier one and tier two regions, respectively.

In estimating the technology potential for tractor-trailers and rigid trucks in the five regions of interest, it is important to note that the study team made a number of assumptions, approximations, and simplifications. All of these methodological notes are documented in Sections 3, 4, and 5. More thorough region-specific evaluations of technology applicability and deployment rates require further analysis. A key assumption used in this study was that there was no change to the basic configuration of the vehicle (such as tractor layout, trailer size, and engine displacement), the payload, or the duty cycle from the baseline vehicle.

2.3. Global fuel use and emission effects

The effects of efficiency improvements to the tractor-trailer and rigid truck segments on global fuel consumption and GHG emissions were modeled using the ICCT's Global Transportation Roadmap model, which estimates worldwide transportation energy use and emissions based on specific policy and technology pathways disaggregated in 16 regions (ICCT, 2016).

The technology potentials derived for the five regions were mapped to the remaining 11 regions in the world based on market similarities (i.e., geographic proximity, current efficiency technology adoption levels, and emission standards in place). In cases where no market similarity existed, the mapping was based on the magnitude of expected potential. Three distinct scenarios were developed using different assumptions for the timing of technology deployment in each region; fuel consumption and CO_2 emission results are presented in Section 5.

3. Baseline vehicle performance

For this analysis, we used sales data, literature review, expert consultation, and internal ICCT expertise to identify representative vehicle models and specifications in each of the five regions. A wide range of data sources were used to compile the data found in this section and we are not able to give specific citations for every data point. For example, in a number of cases we found a range of information in the literature and we would then need to consult with both internal and external experts in order to make the best judgment as to which value to use in this analysis.

After specifying the baseline vehicles, we then modeled the behavior of these representative tractor-trailers and rigid trucks over region-specific payloads and duty cycles. This section describes tractor-trailer (Section 3.1) and rigid truck (Section 3.2) characteristics, typical duty cycles and payloads (Section 3.3), and baseline fuel consumption levels for the two vehicle types (tractor-trailers in Section 3.4 and rigid trucks in Section 3.5).

3.1. Tractor-trailer characteristics by region

Visually, perhaps the most significant difference among tractor-trailers in the five markets is the tractor cab design. Driven primarily by maximum overall length restrictions (16.5m for a semitrailer combination), European tractor truck manufacturers have adopted a cab-over-engine design with a flat front facade and a high floor with the engine below. China, Brazil, India, and much of the rest of the world have gravitated toward similar designs. However, length restrictions in North America are for the trailer only and not for overall combination vehicle length, so cab configurations in North America are very different, most notably the elongated front ends. In addition to cab design, a number of other features distinguish tractor-trailers in the five regions. These features vary according to market-specific topography, road infrastructure, size and weight regulations, and safety regulations, among others. Table 1 highlights the differences for some of most critical parameters that affect fuel efficiency including axle configuration, engine emission level, and maximum allowable payload.

Gross vehicle weight (GVW), which is the maximum allowable combined weight of the fully loaded tractor-trailer, as well as vehicle curb weight (i.e., the combined empty weight of the tractor plus the trailer) both vary across the different markets. This results in a range of maximum payloads[1] tractor-trailers area able to haul in the different regions. The largest maximum payload of the five regions is for tractor-trailers in India that have a 33% (7.7 tonnes) lager maximum payload than those in Brazil. The large range of engine displacements and power ratings that are used for trucks with similar payload demands reflects the differing priorities of the markets—namely the tradeoff between higher speeds and superior drivability that are enabled by larger, more powerful engines versus a greater emphasis on reducing capital costs. On this spectrum, the US and the EU represent the former, while India exemplifies the latter.

The dominant driveline configuration in the US is a three-axle (6x4)[2] tractor with a two-axle semi-trailer. The most common configuration in western, central, and southern Europe is a two-axle (4x2) tractor with a three-axle semi-trailer, while longer combination tractor-trailers (with lengths up to 25 meters, GVW up to 60 tonnes,[3] and trailers with four or more axles) may be found in northern Europe (i.e., Sweden, Finland, Netherlands, Denmark, and Norway). In this study, the 4x2 configuration was selected for EU analysis. In China, a 6x4 tractor combined with a three-axle semitrailer is the most prevalent configuration. In Brazil and India, the most familiar combinations are a 6x2 tractor with a three-axle trailer and a 4x2 tractor with a three-axle trailer, respectively. Trailers also differ among markets, with different permissible sizes and

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[1] Maximum payload = [gross vehicle weight] – [curb weight]

[2] This 6x4 terminology means that the vehicle has six wheel end positions (i.e., three axles, 6 / 2 = 3) and four wheel positions distribute power. This configuration is preferred to the 6x2, where only two wheel positions distribute power, when there is need for additional traction in icy or unpaved roads. Apart from the front steering axle on the tractor, each wheel end position on both the tractor and trailer can have two standard dual-sized tires or a single wide base tire.

[3] Tonne = metric ton = 1,000 kilograms

trailer types, which affects volume capacity as illustrated in Table 1. For example, the trailer types with the largest market shares in China, EU, and the US are stake, side curtain, and box van, respectively.

Tractor engines are very different among the markets. Different emission standards promote different technologies and engine tuning strategies. Like many countries around the world, Brazil, China, and India have crafted their HDV emission standards based on Europe's Euro pathway. Brazil, China, and India currently have emission standards equivalent to Euro V, IV, and III, respectively. The EU is currently at the Euro VI level, which, in terms of stringency, is quite similar to the US 2010 emission standard. Engine specifications also differ notably across the markets in terms of engine displacement volume and power rating. On average, the largest and most powerful engines are in the US, followed by the EU, while those in Brazil and China are somewhat smaller. India is the outlier in regards to these engine features, with an average engine size and power roughly half of the other four markets.

Manual transmissions are the preferred choice for China, India, and the US; although US market penetration of automated manual transmissions (AMTs) has been growing and is currently at about 30%. Brazil follows some of the European market trends, likely influenced by the fact that European manufacturers dominate the Brazilian HDV market. AMT adoption is a good example, with about 60% market penetration in Europe and about 50% penetration in Brazil. Having a larger number of gears adds complexity and cost to the transmissions but enables better fuel efficiency and drivability on hilly roads.

Transmission gear ratios, rear axle ratio, and tire size influence the relative value of engine speed to vehicle speed. In general, lower engine speeds (smaller ratios and larger tires) are beneficial for fuel efficiency. Tire rolling resistance, a key parameter impacting efficiency, is affected by tire size and design. In general, larger diameter tires tend to have lower rolling resistance. Bias tires allow the tire body to flex easily, providing a relatively smoother ride on rough surfaces, but this drivability characteristic also causes increased rolling resistance.

Besides the large degree of heterogeneity across the five regions, there also is diversity within each market. For example, tractor-trailer engine size ranges from below 9 liters to over 13 liters in China (Sharpe 2015). This analysis is simplified in that we are considering only one tractor-trailer vehicle profile per region to estimate technology potential for the entire market. We have designed representative tractor-trailers as a composite of the most common characteristics in each region. As previously mentioned, this assessment is a first step, and more detailed analyses would be needed for a more robust understanding of the fuel efficiency improvement opportunities worldwide.

Table 1: Baseline tractor-trailer characteristics in each region

	Brazil	China	Europe	India	US
Gross vehicle weight (tonnes)	36	40	40	40	36
Vehicle curb weight (tonnes)	16.7	15	14.5	13	14.7
Maximum payload (tonnes)	19.3	25	25.5	27	21.3
Volume capacity (m^3)	108	86	96	93	114
Axle configuration	6x2	6x4	4x2	4x2	6x4
Typical trailer type	Dry bulk	Stake	Side curtain	Platform	Box van
Trailer axle number	3	3	3	3	2
Engine Displacement (liters)	13	10	12.8	5.9	15
Engine power (kW)	324	250	350	134	340
Engine emissions standard	Proconve P7[a] (NOx limit = 2 g/kWh)	China IV[b] (NOx limit = 3.5 g/kWh)	Euro VI (NOx limit = 0.4-0.46 g/kWh)	Bharat III[c] (NOx limit = 5 g/kWh)	EPA 2010[d] (NOx limit = 0.27 g/kWh)
Vehicle fuel efficiency standard	NA	China Stage 2	NA	NA	EPA/NHTSA 2014[e]
Transmission type[f]	AMT	MT	AMT	MT	MT
Transmission gears	12	10	12	6	10
Transmission gear ratios[g]	11.32 to 1	14.8 to 1	14.9 to 1	9.19 to 1	12.8 to 0.73
Rear axle ratio	4.38	4.11	2.64	6.83	3.70
Tire type	Radial	Radial	Radial	Bias	Radial
Tire size	295/80R22.5	12R22.5	315/80R22.5	10R20	295/75R22.5

Notes: Values presented come from a combination of sources including but not limited to Polk/IHS sales databases, KGPAuto market penetration databases, publicly available literature sources, ICCT consultants' analyses, and ICCT internal expertise. [a]Equivalent to Euro V. [b]Equivalent to Euro IV. [c]Equivalent to Euro III. [d]U.S. Environmental Protection Agency. [e]National Highway Transportation Safety Administration. [f]AMT: Automated Manual Transmission, MT: Manual Transmission. [g]First gear and last gear ratios are shown.

3.2. Rigid truck characteristics by region

The rigid (or straight) truck market is more diverse than the tractor-trailer market, with an extensive range of vehicle vocations, payloads, and duty cycles. Trucks in this segment include a variety of vehicles such as delivery trucks, walk-in vans, bucket trucks, and refuse carriers that cover a wide range of mission profiles. These include operations in urban environments that are typically short trips with low average speeds and significant amounts of start-and-stop driving, as well as intercity operations that have a higher percentage of driving at highway speeds. This study is focused on rigid trucks between 10 and 12 tonnes GVW, which are equivalent to a US Class 6/7 vehicle. These trucks are mainly used to deliver freight in urban locations. Larger trucks are usually used for regional delivery or even for long haul freight transport in certain markets. As an example, the rigid truck weight segment with the most sales in Brazil and China is around 25 tonnes GVW, where some of these heavier trucks are used for mining or construction applications at very low speeds. The technologies applicable for long haul and regional haul rigid trucks would be very similar to those of the tractor-trailer segment. We opted to select urban delivery trucks as the second segment in this study in order to diversify the scope of applicable technology.

Table 2 shows the characteristics for the rigid truck vehicles analyzed in this study. Across the regions, the most uniform feature is driveline configuration; each of the representative trucks has a 4x2 axle setup. The table reveals some important differences as well, perhaps most notably the large variance in engine power and regulated emission levels.

Table 2: Baseline rigid truck characteristics in each region

	Brazil	China	Europe	India	US
Gross vehicle weight (tonnes)	9.7	12	12	12	11.6
Vehicle curb weight (tonnes)	3.2	5.8	6.5	4.0	6.3
Maximum payload (tonnes)	6.5	6.2	5.5	8.0	5.3
Axle configuration	4x2	4x2	4x2	4x2	4x2
Engine displacement (liters)	3.8	4	5.1	3.8	6.7
Engine power (kW)	119	101	185	92	201
Engine emissions standard	Proconve P7[a] (NOx limit = 2 g/kWh)	China IV[b] (NOx limit = 3.5 g/kWh)	Euro VI (NOx limit = 0.4-0.46 g/kWh)	Bharat III[c] (NOx limit = 5 g/kWh)	EPA 2010[d] (NOx limit = 0.27 g/kWh)
Vehicle fuel efficiency standard	NA	China Stage 2	NA	NA	EPA/NHTSA 2014[e]
Transmission type[f]	MT	MT	AMT	MT	AT
Transmission gears	5	6	6	5	5
Transmission gear ratios[g]	5.72-0.76	6.3-0.797	6.75-0.78	8.02-1	3.1-0.7
Rear axle ratio	4.30	5.00	4.00	5.29	4.88
Tire type	Radial	Radial	Radial	Bias	Radial
Tire size	235/75R17.5	8.25R20	305/70R22.5	8.25R20	255/70R22.5

Notes: Values presented come from a combination of sources including but not limited to Polk/IHS sales databases, KGPAuto market penetration databases, publicly available literature sources, ICCT consultants' analyses, and ICCT internal expertise.[a]Equivalent to Euro V. [b]Equivalent to Euro IV. [c]Equivalent to Euro III. [d]U.S. Environmental Protection Agency. [e]National Highway Transportation Safety Administration. [f]AMT: Automated Manual Transmission, MT: Manual Transmission, AT: Automatic Transmission. . [g]First gear and last gear ratios are shown.

3.3. Drive cycles and payloads by region

The fuel consumption performance of the two HDV types was analyzed for each region by running the vehicle models under representative market-specific operating conditions. This includes drive cycles and average payloads that capture local conditions reasonably well. Although China, the EU, and the US have well-established region-specific drive cycles that represent local driving conditions and vocation-specific duty cycles, detailed information about duty cycles and payloads in Brazil and India is generally unavailable. In those cases, the study team used its best estimates to try to reflect vehicle operations in those markets. The drive cycles used for each region are described below.

Brazil. Due to the lack of any official duty cycles specifically representing typical commercial truck operations in Brazil or elsewhere in South America, the study team elected to model tractor-trailers over the World Harmonized Vehicle Cycle (WHVC). The WHVC was developed under the United Nations Economic Commission for Europe (UNECE) World Forum for Harmonization of Vehicle Regulations (WP.29). As a collaborative development effort between stakeholders from North America, Europe, and Asia, the WHVC was based on data from trucking operations in a number of countries and is designed to cover a wide range of HDV driving situations (Heinz, 2001). The WHVC consists of three segments: an urban segment with transient stop-and-go driving, a rural segment that incorporates higher speeds, and a final motorway segment with steady state cruise driving. For this study, the authors assumed a cycle weighting of 0% urban, 10% rural and 90% motorway for Brazilian tractor-trailers. The same weighting was used for Chinese tractor-trailers as discussed below.

For rigid trucks, the multipurpose test cycle introduced in the proposed US Phase 2 HDV GHG standards was chosen. For background, in the US proposal, tractor-trailers and rigid trucks are subject to evaluation over three distinct cycles: the ARB transient, 55-mph cruise, and 65-mph cruise. The ARB transient cycle is one portion of a four-mode drive cycle, the heavy-duty diesel truck cycle, which was developed by the California Air Resources Board to capture city-based stop-and-go driving. The two cruise cycles include road grades and require steady state driving at 55 miles per hour (mph) and 65 mph. The multipurpose cycle is defined using the following percentage weighting factors for these three cycles: 70% ARB transient, 13% 55-mph cruise, and 2% 65-mph cruise. The remaining 15% of the weighting is allocated to idling, which is an important operational characteristic of many rigid trucks.

China. The cycle used for evaluating all HDVs in China on a fuel consumption basis is the WHVC-China, a slightly modified version of the WHVC. The cycle is very similar to the WHVC, although some of the original WHVC acceleration and deceleration rates are reduced to reflect Chinese HDVs, which, on average, have lower engine power-to-vehicle weight ratios than HDVs from other major markets (i.e., Europe, North America, and Japan) that were originally used to develop the WHVC (Jin, 2014). In the fuel consumption regulation for HDVs in China, tractor-trailers are evaluated over the WHVC-China cycle with weighting factors for the urban, rural, and motorway segments at 0%, 10%, and 90%, respectively. Rigid trucks are also evaluated over the WHVC-China, but the weighting factors for the urban, rural, and motorway segments are 10%, 60%, and 30%, respectively.

EU. As part of their process to establish a CO_2 certification procedure for HDVs, using a tool called VECTO, the European Commission has developed a suite of test cycles to represent various HDV mission profiles, including long haul, regional deliver, and urban delivery (Franco 2015). The long haul cycle is meant to represent typical long haul, highway-dominated driving by tractor-trailers and includes road grade. This was the cycle used for simulating the EU tractor-trailer for this study. For rigid trucks, we analyze performance using a combination of the urban delivery and regional cycles weighted at 50% each, both of which include road grade.

India. The previously developed WHVC-India cycle (Sharpe & Delgado, 2016) was used for tractor-trailers in this analysis. This India-specific cycle accounts for the fact that HDV speeds in India are typically much slower than in other major markets such as the US and the EU. Cruise speeds of 60 km/h (37 mph) or slower are common. The WHVC-India cycle is identical to the WHVC-China for roughly the first 1,200 seconds, after which the WHVC speeds are multiplied by 0.7 to produce the speeds for the WHVC-India. The ARB transient cycle was chosen for evaluating the India rigid truck.

US. As with China and the EU, we were able to utilize test cycles that already exist as part of the US GHG regulation for HDVs. As mentioned above, in the US regulatory framework, tractor-trailers and rigid trucks are subject to evaluation over three distinct cycles: the ARB transient, 55-mph cruise, and 65-mph cruise. For this analysis we use the proposed Phase 2 cycles, which have been upgraded to include road grade. For tractor-trailers, these three cycles are weighted 5%, 9%, and 86%, respectively, based on in-use data of tractor-trailer operations across the US. We used identical weighting factors of these cycles in our evaluation of the US tractor-trailers. The multipurpose cycle (i.e., 70% ARB transient, 13% 55-mph cruise, 2% 65-mph cruise, and 15% idle) was used in the analysis of the US rigid truck.

Table 3 summarizes the duty cycles used, and the average speed for each cycle. It also shows maximum allowed payload and the representative payload used for analysis. Based on anecdotal evidence and information from industry experts in each country, overloading of trucks (i.e., exceeding the maximum allowable payload) is at present a common issue in Brazil and India (as well as China). Based on that, the authors analyzed Brazil and India tractor-trailers at 100% payload. EU, US, and China tractor-trailers were analyzed at 75%, 80%, and 100% of maximum payload, respectively, which correspond to values used in the official HDV certification test protocols.

A typical urban rigid truck duty cycle usually involves starting at full (or almost full) capacity and returning empty. Based on this vocation, all the rigid trucks in this study were analyzed at full payload and at empty conditions, and the results were averaged. As a result, half payload is indicated as representative in Table 3.

Table 3: Representative duty cycles and payloads

		Duty cycle	Average speed (km/h)	Maximum Payload (tonnes)	Representative Payload (tonnes)
Tractor-trailers	Brazil	WHVC. 10% Rural, 90% Motorway	76.3	19.5	19.5
	China	WHVC-China. 10% Rural, 90% Motorway	72.7	25.0	25.0
	Europe	VECTO Long Haul	77.3	25.5	19.3
	India	WHVC-India	32.9	27.2	27.2
	US	US Phase 2 cycles. 5% ARB Transient, 9% 55-mph, 86% 65-mph	99.1	21.3	17.2
Rigid trucks	Brazil	US Phase 2 cycles. 70% ARB Transient, 13% 55-mph, 2% 65-mph, 15% idle	36.0	6.5	3.2
	China	WHVC-China. 10% Urban, 60% Rural, 30% Motorway	51.3	6.2	3.1
	Europe	VECTO cycles. 50% Urban, 50% Regional	49.0	5.5	2.7
	India	ARB Transient	24.6	8.0	4.0
	US	US Phase 2 cycles. 70% ARB Transient, 13% 55-mph, 2% 65-mph, 15% idle	36.0	5.3	2.6

3.4. Baseline tractor-trailer results

Table 4 shows fuel consumption results for the baseline tractor-trailers analyzed over their representative cycles and payloads. The baseline fuel consumption values presented in Table 4 are a product of both the vehicle specifications as well as the specific operational profile. These values are used in Section 4 as reference values to estimate technology potential.

Table 4: Tractor-trailer baseline results over market-specific duty cycles and payloads

Market	Cycle	Payload (kg)	Baseline fuel consumption (L/100km)
Brazil	WHVC	19,500	39.8
China	WHVC-China	25,000	41.6
Europe	VECTO Long Haul	19,300	33.6
India	WHVC-India	27,230	54.8
US	US Phase 2 cycles	17,237	40.4

Figure 1 shows the range of fuel consumption values for the baseline tractor-trailers analyzed over their representative cycles at empty, half, and full payload. Note that these results are not comparable among the markets because different driving cycles and payloads were used. The figure illustrates the large sensitivity of fuel consumption to payload. Depending on the vehicle, fuel consumption at full payload is about 15% to 35% higher than at half payload, and 60% to 90% higher than at zero payload.

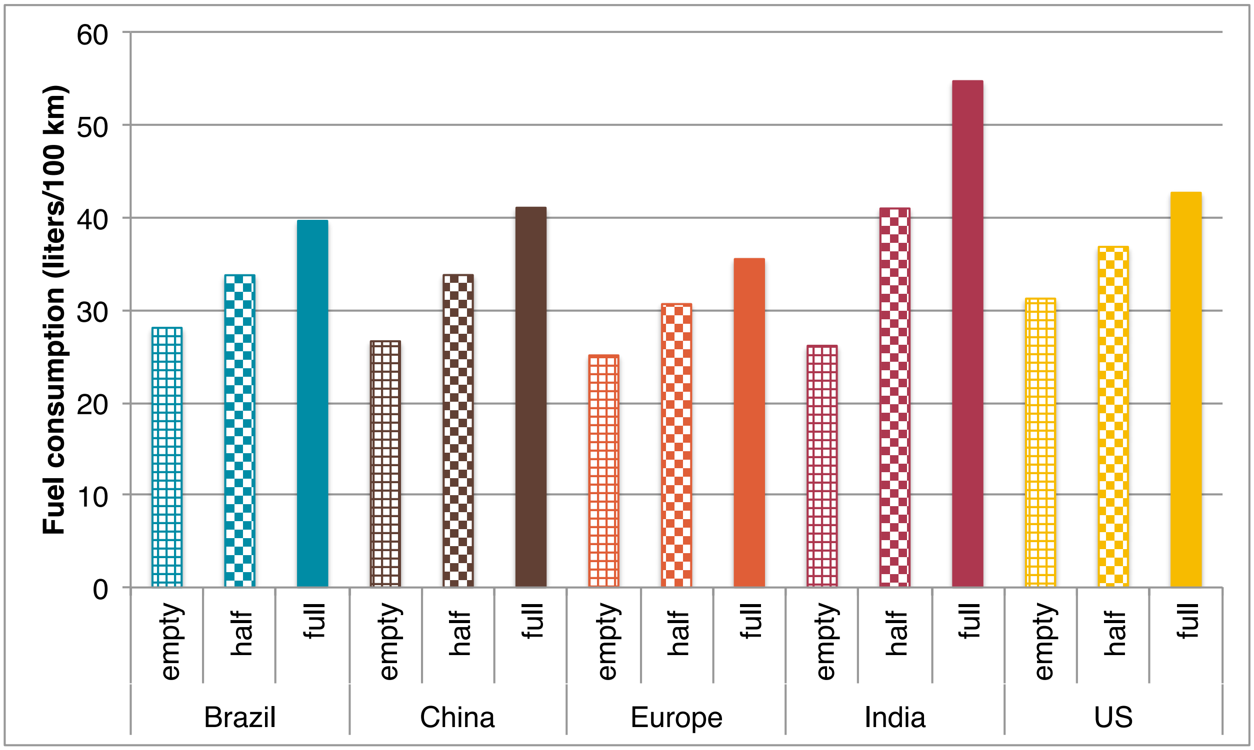


Figure 1: Fuel consumption of baseline tractor-trailers over region specific cycles at empty, half, and full allowed load.

Figure 2 shows energy audits for the five baseline tractors-trailers over their representative cycles and payloads. The figure illustrates how the energy losses differ among the different regions, allowing for identification of key technology areas to be prioritized in each market. Aerodynamic losses are more significant in the US due to the higher vehicle speeds and the fact that aerodynamic drag forces increase with the square of velocity. Tire rolling resistance losses are a larger percentage than aerodynamics for China, Brazil, and India, where the average driving speeds are relatively low compared to the US and the EU, and where there is a tendency to carry heavier payloads. India also has a large share of bias tires (currently roughly 80% of the commercial vehicle market share), which can have up to 30% higher rolling resistance coefficients than radial tires (Malik et al., 2016). Braking losses are found to be higher on vehicles driving with heavy payloads because the larger the mass, the greater the amount of energy required to decelerate to a stop. In addition, braking losses are highly related to the amount of transient behavior in a given cycle, because the amount of energy lost to braking is directly proportional to the number of stops.

At roughly 60%, engine losses are the largest energy consumer for all of these markets, suggesting that advancements in engines represent an attractive improvement area for all five regions. Although there exist theoretical limits to internal combustion engine efficiency, engine efficiency enhancements would represent fuel consumption benefits for a fairly broad range of different vehicle driving conditions (e.g., aerodynamic improvements do not offer significant fuel savings at low average speeds) and for the full lifetime of the vehicle (e.g., low rolling resistance tires might be retreaded or replaced with higher rolling resistance tires). Losses through inefficiencies in the driveline and to power accessories are a relatively smaller part of the energy audit for all markets. These audits do not include fuel consumption at extended idle (e.g., hoteling loads for driver comfort while sleeping in the tractor cab), which can be significant.

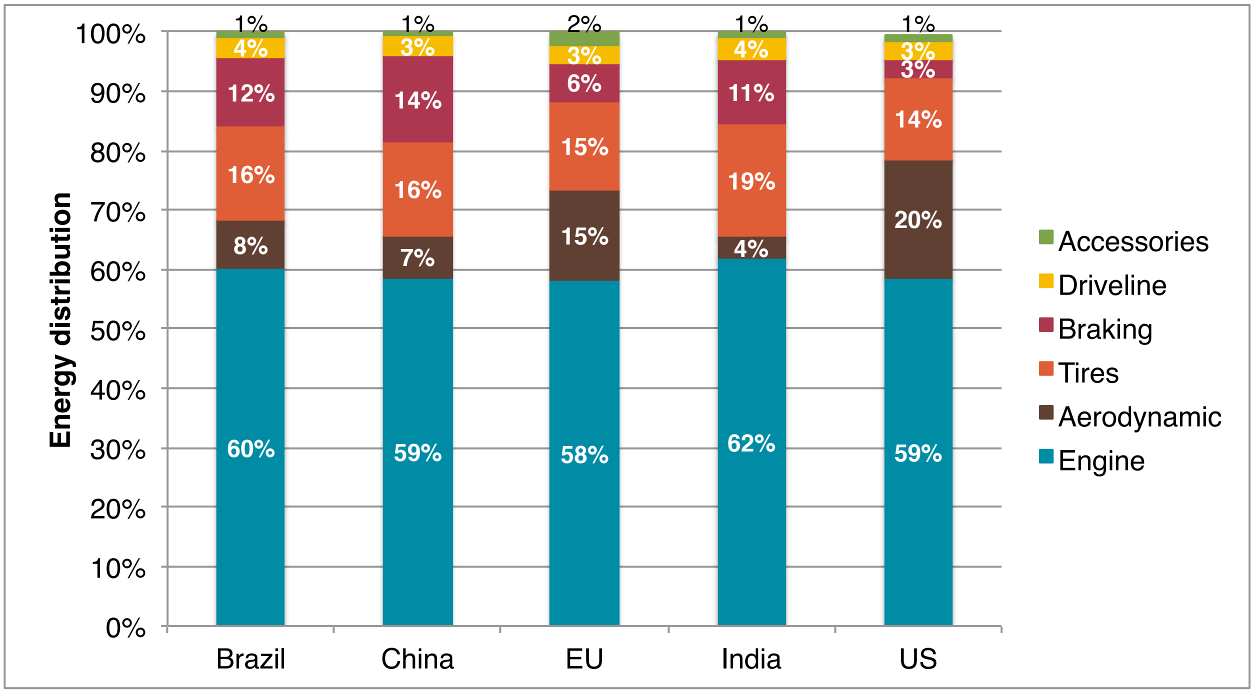


Figure 2: Tractor-trailer energy audits over representative duty cycles and payloads.

As mentioned above, direct comparison of these vehicles' baseline fuel consumption is not possible due to their different technology characteristics, payloads, and duty cycles. Even when analyzed under similar conditions there is a "productivity factor" that needs to be accounted for: Vehicles with lower power-to-weight ratios lack acceleration capabilities and are not able to follow the drive cycle as well as the higher-powered vehicles. For example, tractor-trailers in China—and even more so in India—showed large deviations from the target speed trace when fully loaded. The practical result of this is that underpowered trucks take more time to perform the same duty, their average speeds are lower, and their fuel consumption would be underestimated compared to a vehicle that was able to follow the cycle. With these caveats in mind, for illustrative purposes, the five baseline trucks were simulated over the same duty cycle over their whole range of payloads from empty to full. Figures 3, 4, and 5 illustrate the fuel consumption results of the baseline tractor-trailers simulated over the WHVC. This cycle was selected for analysis because it includes urban, rural, and highway driving, and was developed by stakeholders from North America, Europe, and Asia. Note, however, that the results presented would change if another duty cycle were used.

Figure 3 shows fuel consumption results in units of liters per 100 kilometers (L/100km). The figure suggests that European tractor-trailers have the lowest fuel consumption over this particular cycle for all payloads. China and the US appear to have similar fuel consumption levels, and Brazil and India are at higher fuel consumption levels. The comparable slope of the trendlines of the 5 vehicles indicate the average fuel consumption increase for each added 1000 kg of payload is, on average 1 L/100km over the WHVC.

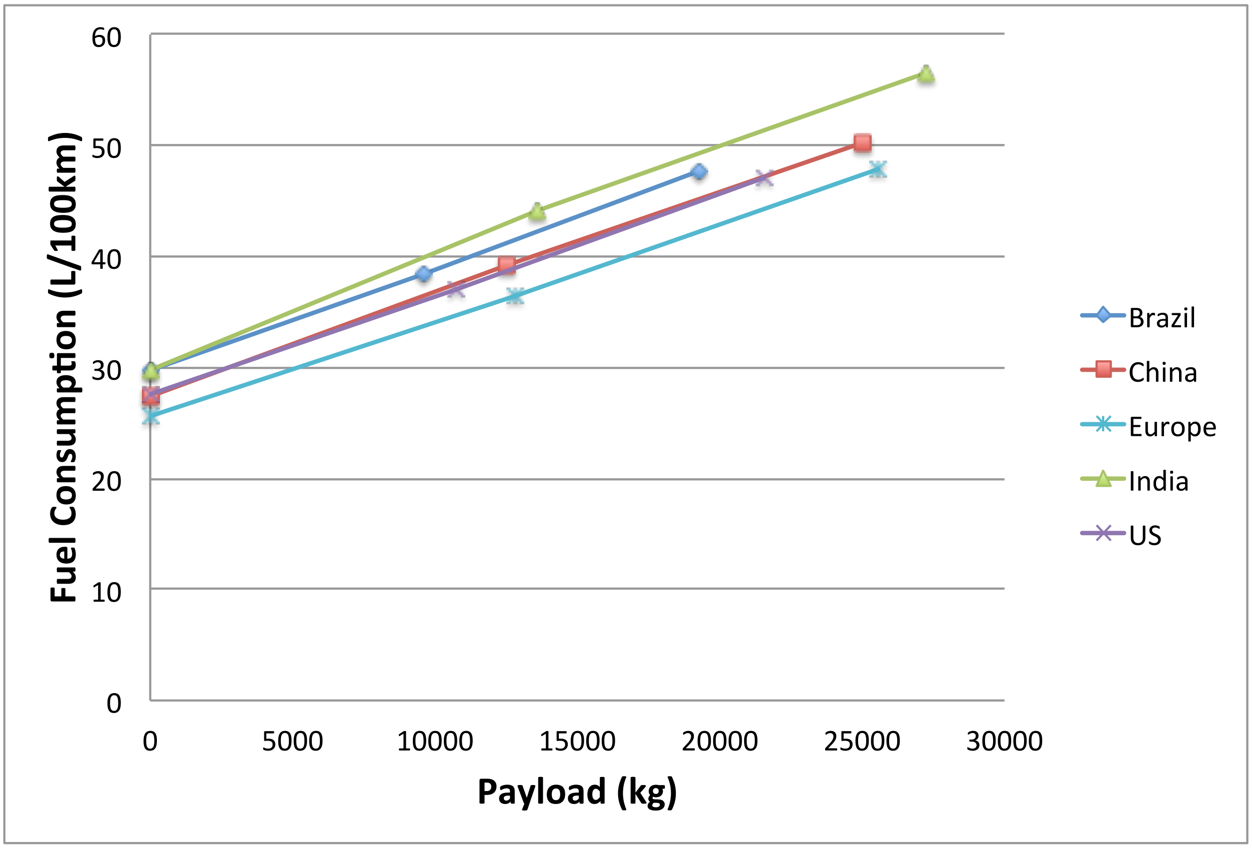


Figure 3: Fuel consumption of baseline tractor-trailers over the WHVC cycle at empty, half, and full load.

Figure 4 shows the same results as in Figure 3, but in terms of load-specific fuel consumption (LSFC), which is fuel consumption per unit of payload, in L/100 tonne-kilometer units. The figure illustrates the overall freight efficiency advantage of running vehicles at full payload, showing about 35% reduction of LSFC when running at full payload versus half payload. Logistics and operations optimization can be useful in reducing the number of empty and less-than-truckload miles to promote efficiency. The freight efficiency of vehicles operating at full payload is heavily dependent on tractor-trailer curb weight because a lower curb weight allows for a higher payload. Light weighting technologies therefore allow for additional payload to be carried, improving the LSFC values. While operating vehicles at full payload is advantageous in terms of load specific fuel efficiency, overloading (running trucks above their designed capacity) has a number of drawbacks. Overloaded trucks may cause safety issues, increased maintenance expenses, accelerated vehicle wear, and damage to road infrastructure.

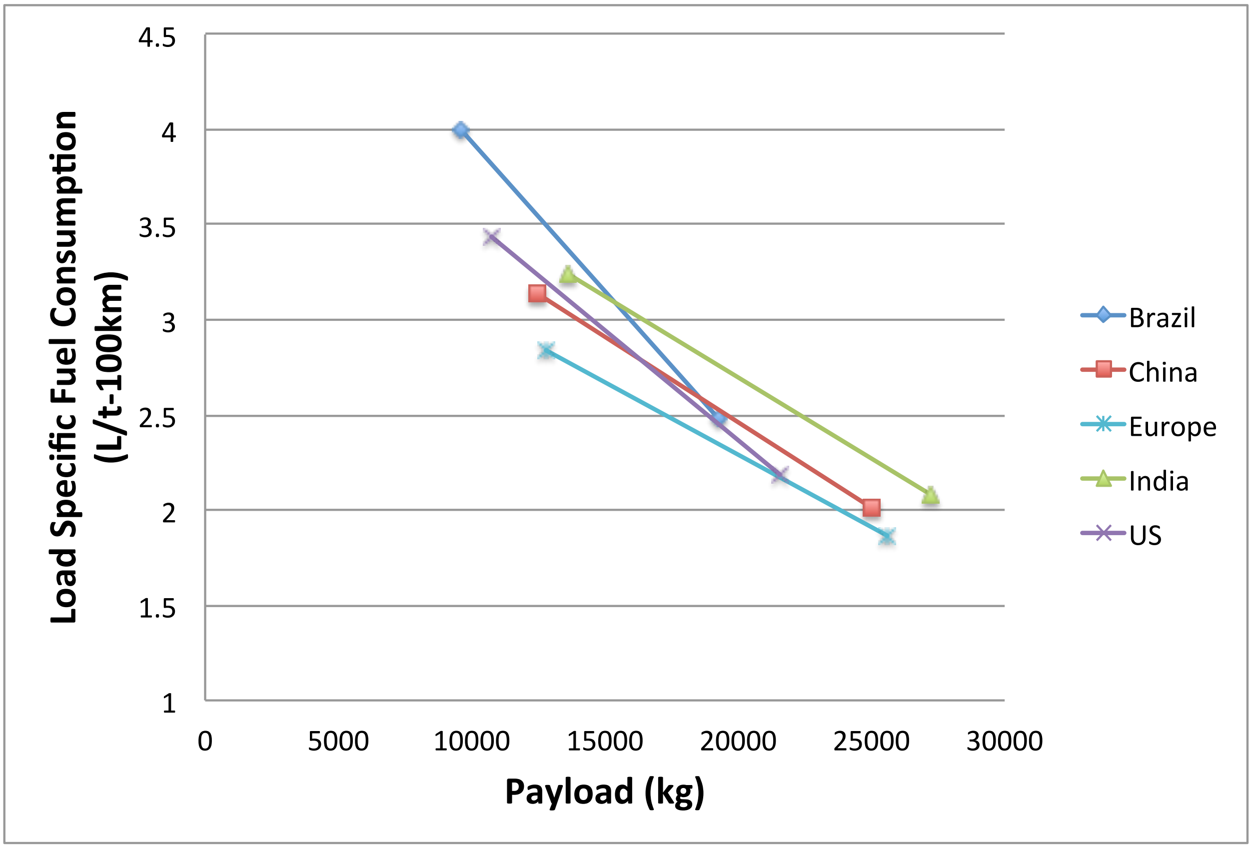


Figure 4: Load-specific fuel consumption of baseline tractor-trailers over the WHVC cycle at half and full load.

Figure 5 presents the results using a third metric, volume-specific fuel consumption (VSFC), which represents fuel consumption per unit of volume capacity, in L/100m^3-km. The results in Figure 5 were calculated assuming a freight density of 0.14 tonnes per cubic meter, the average density of US freight calculated based on average payload divided by average trailer volume (EPA 2011b). The figure illustrates that the additional volume capacity of US trucks benefits their VSFC relative to the other markets. VSFC is important to consider because many trucking operations are volume-limited rather than weight-limited, meaning that they transport relatively low-density cargo and the truck runs out of space before reaching maximum cargo weight limit. For example, in the EU the average utilized volume capacity is 82% while the average utilized weight capacity is 57% (Lumsden, 2013). Therefore, long distance transport in Europe is most sensitive to a truck's load capacity measured by volume, because trucks are less likely to be fully loaded by weight. A similar situation occurs in the US where the majority of tractor-trailers are volume-limited rather than weight-limited (EPA 2011b).

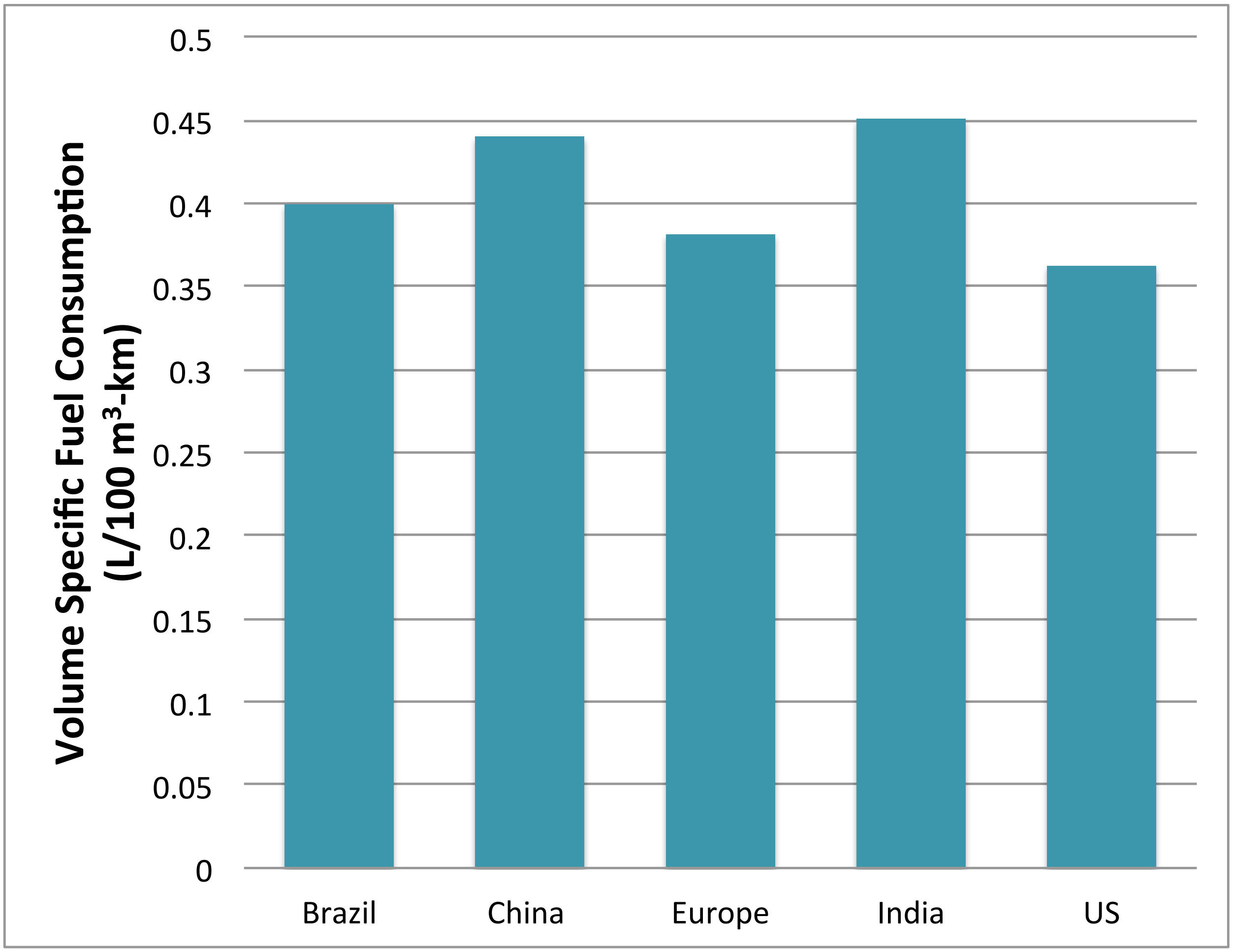


Figure 5: Volume-specific fuel consumption of baseline tractor-trailers over the WHVC cycle at a freight density of 0.14 tonnes/m^3.

Although all the aforementioned metrics are relevant to quantify efficiency, the critical element of this study is the estimation of fuel consumption reduction potential for each region, rather than the analysis of their fuel consumption absolute values. For the remainder of this study we present results in the metric of L/100km at the representative payload for the given region.

3.5. Baseline rigid truck results

Table 5 shows fuel consumption results for the baseline rigid trucks analyzed over their representative cycles and payloads. As with the tractor-trailers described in the previous section, the baseline fuel consumption values presented in Table 5 are a product of both the vehicle specifications as well as the specific operational profile. These values are used in Section 4 as reference values to estimate technology potential.

Table 5: Rigid truck baseline results over market-specific duty cycles and payloads

Market	Cycle	Payload (kg)	Baseline fuel consumption (L/100km)
Brazil	US Phase 2 cycles	3,230	23.7
China	WHVC-China	3,045	21.2
Europe	VECTO Urban/Regional	2,750	23.0
India	ARB Transient	4,000	24.9
US	US Phase 2 cycles	2,836	27.6

The energy audit analysis by region results in similar energy loss distributions for the rigid truck segment and the audit results for the 5 rigid trucks are not shown here. Instead, Figure 6 shows the results of an energy audit analysis that was conducted for a particular rigid truck (EU rigid truck) at half payload over three different duty cycles (VECTO urban, regional, and long-haul). The figure illustrates that the energy audits, and by implication the corresponding set of technologies that are most suitable to reducing fuel consumption, are influenced by duty cycle. If the rigid truck is used in an urban setting, technologies such as low rolling resistance tires and hybridization would have a substantial impact to reduce rolling resistance and braking losses, which represent 15% of the fuel energy losses. On the other hand, if the truck were used for regional or long haul transport, aerodynamic improvements would be able to impact the 18%-22% of energy losses due to overcoming air drag. A more efficient engine would consistently save fuel over all duty cycles.

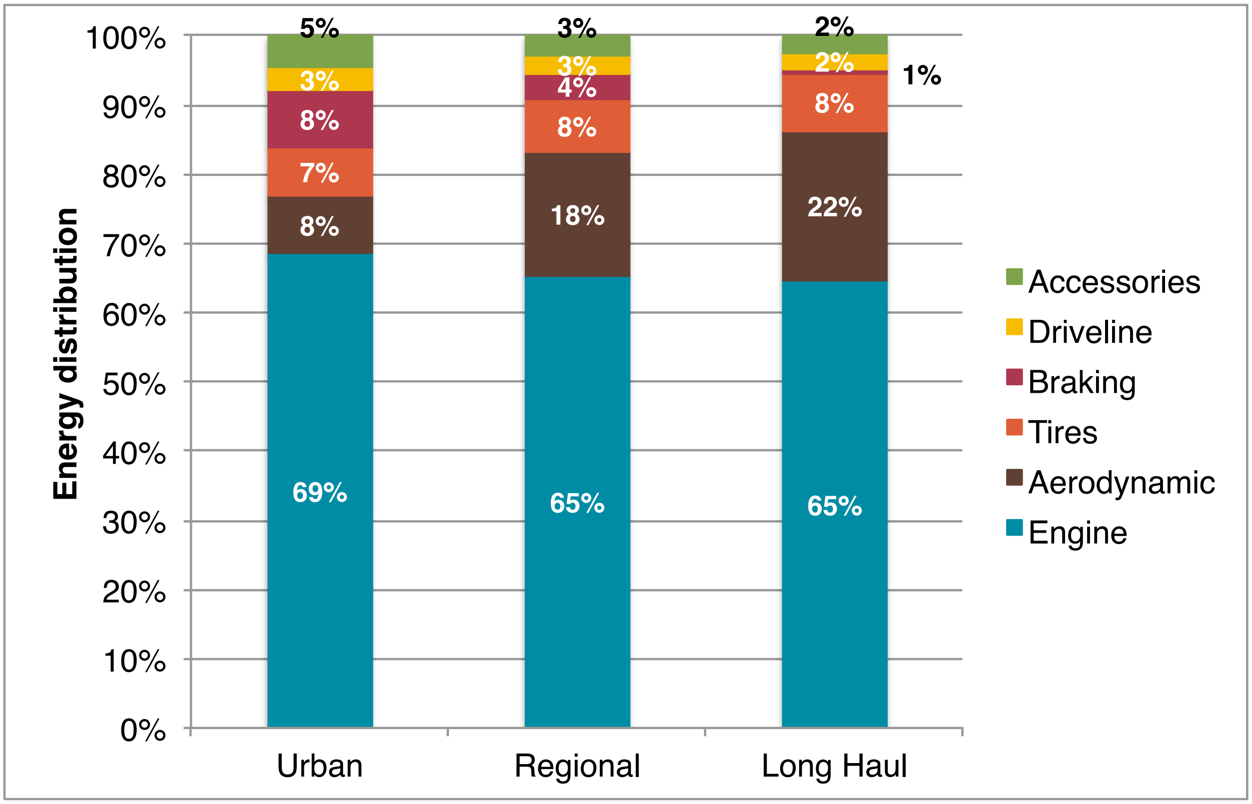


Figure 6: EU rigid truck energy audit over VECTO cycles at half payload.

4. Technology potential

The following part of the study involved estimation of potential fuel consumption reduction for each of the baseline vehicles defined in Section 3. This is an important step for setting targets. In this case we focused on the impact of applicable technologies that are predicted to be commercially available by 2030 at the latest. In order to estimate fuel consumption reduction potential, we again utilized the Autonomie vehicle simulation software to incorporate engine, transmission, and vehicle technologies into the baseline vehicles. In some cases there were technologies that could not be modeled directly in the simulation software. For those cases we adjusted the final fuel consumption number during post-processing, through the use of technology effectiveness values.

Tables 6 and 7 list the technology assumptions made to estimate technology potential for tractor-trailers and rigid trucks, respectively. Of the two sets of data in each table, the top portion corresponds to vehicle parameters used in simulation, while the bottom part presents technology effectiveness values used during post-processing to account for technologies that are not captured during simulation. These technology effectiveness values were the ones used by the US Environmental Protection Agency (EPA) in their proposed Phase 2 HDV GHG and efficiency regulation (US EPA 2015). Depending on market-specific baseline vehicle characteristics, some of these technology effectiveness values might not apply or their values would differ from those stated in the table. For example, idle reduction technology effectiveness was calculated by the US EPA based on US-specific data, but that value would not necessarily be equivalent for other markets that may have different extended idle activity. Also, depending on market-specific baseline characteristics, some of the technologies listed may already be in place. For example, for Europe and Brazil, an AMT transmission is part of the baseline technology so its effectiveness value was not applied to those vehicles. These type of market-specific considerations were taken into account during the analysis.

The tables list two potential technology steps that were previously mentioned in section 2.2. The first step corresponds to technology levels equivalent to a fleet averaged US Phase 2 (proposed) vehicle. US Phase 2 was selected as a benchmark because it represents the most advanced HDV efficiency regulation available. Step 1 technology packages for tractor-trailers are assumed to be essentially technologically equivalent to a 2027 US Phase 2 compliant Class 8 high-roof sleeper cab tractor matched with a 2027 US Phase 2 compliant trailer, but with the basic configuration and market-specific traits identified in the baseline vehicle analysis. For example, we assume no changes in the tractor cab configuration, the vehicle dimensions, or the engine displacement. For rigid trucks, the vehicles were assumed to adopt technologies equivalent to a US Phase 2 (proposed) compliant medium heavy-duty (i.e., US Class 6 and 7) multipurpose vocational vehicle.

The second step in the progression of technology adoption for tractors represents a technology package equivalent to a level of what has been demonstrated in the US SuperTruck program and best available data from EPA/NHTSA proposed rule. For the case of rigid trucks, that includes adoption of hybrid drivetrain technology along with US Phase 2 compliant engines and tires. These technology “end points” for this study were selected due to the fact that they apply technologies that are well known, have been demonstrated, and are in many cases already (or nearly) commercially available. Note that the Step 2 technology packages aim to represent maximum available technology by 2030 but not necessarily to represent the maximum that can be accomplished with incremental improvements to conventional technology. For example, rigid truck aerodynamics were not considered in this analysis, but could represent substantial fuel savings in the markets in which these trucks’ duty cycles involve high speed driving. Research also is underway to design a tractor engine with 55% brake thermal efficiency (BTE), although such advanced engine technology was not considered in this analysis (NRC, 2015). Post Step 2 technology mixes likely will start to include electrification and other zero emissions technology.

Table 6: Technology potential assumptions for tractor-trailers

	Technology	Step 1 (US Phase 2 equivalent)	Step 2 (SuperTruck/ EPA best set)
Vehicle parameters	Engine brake thermal efficiency (BTE)	~47%[d]	~50%[d]
	Tractor aerodynamics (CdA)[a]	5.3 m^2	5.1 m^2
	Trailer aerodynamics (delta CdA)	1.1 m^2	1.6 m^2
	Tire rolling resistance (RRC)[b]	5.6N/kN (steer) 5.9N/kN (drive) 4.8N/kN (trailer)	4.3N/kN (steer) 4.5N/kN (drive) 4.3N/kN (trailer)
	Transmission type	AMT	AMT/DCT[c]
	Axle configuration	6x2	6x2
	Rear axle ratio	3.2	2.3
	Weight reduction	-	Up to 1,279 kg
Technology effectiveness	AMT transmission benefit	1.8%	2.0%
	Axle configuration benefit	1.5%	2.5%
	Downspeeding	1.8%	1.8%
	Axle lubricant	0.2%	0.5%
	Predictive cruise	0.8%	2.0%
	Accessories improvement	0.3%	1.0%
	A/C improvement	0.2%	0.5%
	Automatic inflation systems (ATIS)	0.4%	1.0%
	ATIS (trailer)	1.4%	1.5%
	Direct drive	1.0%	2.0%
	Idle reduction	3.0%	5% APU[e]/ 7% other

Notes: [a]CdA is aerodynamic drag area. [b]RRC is rolling resistance coefficient. [c]DCT is dual-clutch transmission.[d]For more details on the engine technologies required to get 47% and 50%, see Delgado 2015 and EPA 2015b. [e]auxiliary Power Unit

Table 7: Technology potential assumptions for rigid trucks

	Technology	Step 1 (Phase 2 US equivalent)	Step 2 (EPA best set)
Vehicle parameters	Engine	EPA 2027[a]	EPA 2027[a]
	Tire rolling resistance	6.4N/kN (steer) 7.0N/kN (drive)	6.2N/kN (steer) 6.5N/kN (drive)
	Transmission	AMT	Hybrid
	Axle ratio	4.33	4.33
	Weight reduction	10 lbs.	400 lbs.
	Truck aerodynamics	none	none
Technology effectiveness	Two more gears (over 5-speed)	0.1%	1.7%
	DCT or AMT (over AT)	0.2%	3.4%
	Strong hybrid	4.1%[b]	22.9%
	Deep driveline integration[c]	4.4%	6.2%
	Axle lubricant	0.4%	0.5%
	Neutral idle[d]	0.7%	2.3%
	Stop-start[d]	2.7%	3.8%

[a] For more details on the engine technologies included in the EPA 2027 engine see EPA 2015b. [b] assumed 18% market penetration of hybrids. [c] includes integrated engine-transmission controls and appropriate selection of engine, transmission, and axles. [d] neutral idle and stop-start technologies are mutually exclusive, both work to minimize fuel consumption during idling

Tables 8 and 9 summarize the results of the technology potential analysis for tractor-trailers and rigid trucks, respectively, based on the assumptions in Tables 6 and 7. The fuel consumption reduction from application of US Phase 2 technology levels ranges from 20% in Europe to 36% in India. The second step of technology application would reduce fuel consumption from 40% to 52% relative to the baseline.

The representative trucks are each assumed to get to equivalent technology levels at the different steps, but their fuel consumption potential reduction and final fuel consumption values differ, due to the fact that different duty cycles and payloads were analyzed and different baseline vehicle specifications were used. As previously mentioned, an assumption used in this study is that the duty cycles and payloads are kept constant for each region. The technologies considered have fuel consumption benefits that will vary based on the duty cycle and payload. For the technologies that can be simulated, the vehicle simulation accounts for this variability (e.g., the same percent aerodynamic drag improvement applied to vehicles in China and India will show more fuel reduction in China due to the fact that the China drive cycle has higher average speeds). For technologies accounted for during post-processing (i.e., the technologies that cannot be modeled), the underlying assumption is that they affect fuel consumption independent of duty cycle or payload, which is a simplification that can be studied in more detail in future market-specific analysis. These technology potential results are used in Section 5 to analyze global fuel consumption and CO_2 emission scenarios

Table 8: Tractor-trailer technology potential results over market-specific duty cycles and payloads

Market	Cycle	Payload (kg)	Baseline fuel consumption (L/100km)	Step 1 (US Phase 2)	Step 2 (SuperTruck/ EPA best set)
Brazil	WHVC	19,500	48.0	26%	40%
China	WHVC-China	25,000	41.6	34%	52%
Europe	VECTO Long Haul	19,300	33.6	20%	40%
India	WHVC-India	27,230	54.8	36%	52%
US	US Phase 2	17,237	40.4	33%	50%

Table 9: Rigid truck technology potential results over market-specific duty cycles and payloads

Market	Cycle	Payload (kg)	Baseline fuel consumption (L/100km)	Step 1 (US Phase 2)	Step 2 (Hybrid/EPA best set)
Brazil	Multipurpose	3,230	23.7	20%	33%
China	WHVC-China	3,045	21.2	20%	33%
Europe	VECTO Urban/Regional	2,750	23.0	18%	30%
India	ARB Transient	4,000	24.2	21%	34%
US	Multipurpose	2,836	27.6	19%	31%

5. Global fuel consumption and emissions impacts

The effects of fuel efficiency improvements to tractor-trailers and rigid trucks on emissions were modeled using the ICCT’s Global Transportation Roadmap model, which estimates worldwide transportation emissions and fuel consumption based on specific policy and technology pathways in 16 regions (ICCT, 2016). Rigid trucks were modeled using the medium heavy-duty truck (MHDT) category, which includes heavy-duty trucks with a gross vehicle weight rating (GVWR) of 14,001–33,000 lbs (6.35–15 tonnes). Similarly, tractor-trailers were modeled using the heavy heavy-duty truck (HHDT) category, which includes heavy-duty trucks a GVWR greater than 33,000 lbs (15 tonnes). The cutoff of 33,000 lbs (15 tonnes) GVWR is consistent with our selected rigid trucks at around 26,000 lbs (12 tonnes) GVWR in Brazil, China, India, the US and the EU. Using the technology potential of a single vehicle configuration to represent an entire Roadmap vehicle category is a simplification that was deemed acceptable for the purpose of this study, which is a first order analysis.

5.1. Extending technology potential assumptions to other regions

As described in the previous sections, detailed fuel consumption analyses were performed for a typical rigid truck and tractor-trailer in five key regions. Specified in percentages, these estimates of technology potential were assumed to be representative on average of other vehicles in the same vehicle segment and region. To model the potential worldwide effect on emissions of improved rigid truck and tractor-trailer efficiency, the technology potentials derived for the five regions were mapped to the remaining 11 regions in the world based on market similarities, specifically geographic proximity, current efficiency technology adoption levels, and emission and fuel consumption standards in place. In cases where no natural market similarity existed, the mapping was based on expert judgment of the magnitude of technology potential.

Two distinct issues arise when considering the potential of technology to reduce fuel consumption in various regions: timing and magnitude of potential. For the region mapping, some regions are assumed to have the same timing and magnitude of technology potential as a similar target region, while other regions are assumed to have the same magnitude but reach this potential at a later time. Figure 7 summarizes the assessed magnitude of technology potential for each modeled region, while the scenarios in Section 5.2 address the time it could take for various regions to achieve this potential.

Due to past harmonization of North American standards, Canada and Mexico are assumed to follow the US technology pathway. Because Mexico has yet to adopt HDV fuel consumption standards, its attainment of this technology potential is assumed to lag five years behind the US and Canada. Based on a comparison of fuel efficiency data, Brazil is the best match for other Latin American countries. Russia is assumed to have technology potential similar to the US, but with a lag of five years because Russia has not yet adopted HDV fuel consumption standards. For rigid trucks, there is almost no difference in the assessed technology potential between the US and the EU. For tractor-trailers, however, Russia is mapped to the US potential (50%) instead of the EU (40%), since the estimated fuel consumption of Russian tractor-trailers is closer to the US and significantly higher than tractor-trailers in the EU.

Other regions that historically follow the European regulatory pathway include other countries in Europe, Australia and South Korea and are assumed to have technology potential similar to that of the EU. Japan, which already has implemented its first phase of HDV fuel consumption standards, is assumed to achieve the same technology potential as the US. Lastly, countries in other regions are assumed to have technology potential similar to other countries in Latin America, including Brazil. Assuming similar “technology potential” applies specifically to the percent reduction from 2015 technology, but it does not intend to make specific judgments about vehicle technologies, specifications, or operating conditions.

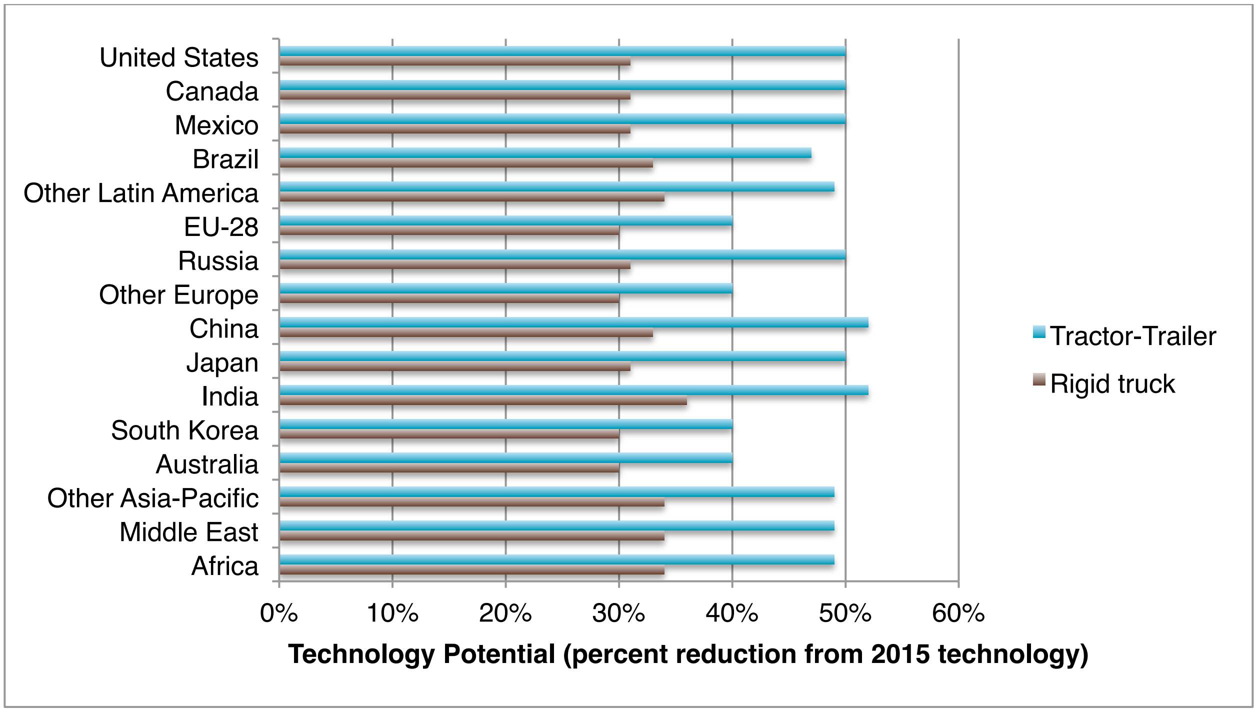


Figure 7: Technology potential assumptions by region, for technologies that are predicted to be commercially available in the 2030 timeframe or earlier.

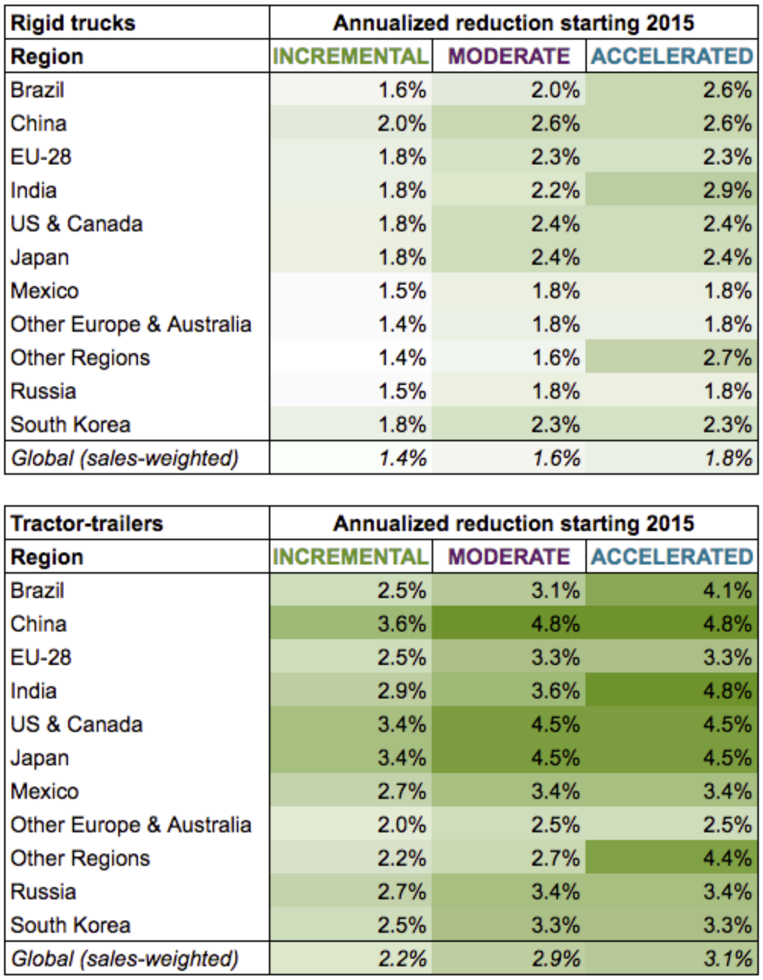
5.2. Scenario definitions

Four scenarios were developed to assess the worldwide effect on emissions of achieving the technology potential for rigid trucks and tractor-trailers:

- **Reference:** based on current policies, with no progress beyond HDV Phase 1 standards in the United States, Canada, and Japan, and HDV Stage 2 standards in China.
- **Incremental:** markets reach their efficiency potential between 2035 and 2045.
- **Moderate:** markets reach their efficiency potential between 2030 and 2040.
- **Accelerated:** markets reach their efficiency potential between 2030 and 2035.

The key difference among the three scenarios is how quickly regions are assumed to achieve their technology potential. For example, the accelerated scenario assumes that India would reach a 52% reduction in new tractor-trailer fuel consumption by 2030 at an average improvement rate of 4.8% per year compared to the incremental scenario that assumes they would reach that level by 2040 at an average improvement rate of 2.9% per year. The moderate scenario for India assumes that to reach a 52% reduction by 2035, new tractor-trailer fuel consumption would need to improve an average of 3.6% per year between 2015 and 2035. For reference, tractor-trailers under the US HDV Phase 1+2 efficiency regulations will reduce fuel consumption at a sales-weighted average rate of 3.1% per year (with the total new HDV fleet improving at 2.5% per year) (Lutsey, 2015).

Figure 8 compares the average annualized percent reduction needed for a given region to achieve its technology potential by a set year, starting in 2015. Darker fill colors indicate greater average annualized percent reductions. More detail on the annualized fuel consumption reduction assumptions, including the exact timeframe for each region, used in the scenario models can be found in the Appendix.



Rigid trucks	**Annualized reduction starting 2015**		
Region	**INCREMENTAL**	**MODERATE**	**ACCELERATED**
Brazil	1.6%	2.0%	2.6%
China	2.0%	2.6%	2.6%
EU-28	1.8%	2.3%	2.3%
India	1.8%	2.2%	2.9%
US & Canada	1.8%	2.4%	2.4%
Japan	1.8%	2.4%	2.4%
Mexico	1.5%	1.8%	1.8%
Other Europe & Australia	1.4%	1.8%	1.8%
Other Regions	1.4%	1.6%	2.7%
Russia	1.5%	1.8%	1.8%
South Korea	1.8%	2.3%	2.3%
Global (sales-weighted)	*1.4%*	*1.6%*	*1.8%*

Tractor-trailers	**Annualized reduction starting 2015**		
Region	**INCREMENTAL**	**MODERATE**	**ACCELERATED**
Brazil	2.5%	3.1%	4.1%
China	3.6%	4.8%	4.8%
EU-28	2.5%	3.3%	3.3%
India	2.9%	3.6%	4.8%
US & Canada	3.4%	4.5%	4.5%
Japan	3.4%	4.5%	4.5%
Mexico	2.7%	3.4%	3.4%
Other Europe & Australia	2.0%	2.5%	2.5%
Other Regions	2.2%	2.7%	4.4%
Russia	2.7%	3.4%	3.4%
South Korea	2.5%	3.3%	3.3%
Global (sales-weighted)	*2.2%*	*2.9%*	*3.1%*

Figure 8: Average annualized efficiency improvement from 2015 until region achieves technology potential. (Other regions include Latin America, Middle East, Africa, and Asia-Pacific)

5.2. Fuel consumption and emissions impacts

Figure 9 illustrates annual GHG emissions and fuel consumption trends for tractor-trailers and rigid trucks worldwide, measured in billion metric tons of CO_2 equivalent ($GtCO_2e$) and million barrels of oil-equivalent per day (mb/d), respectively.[4] Compared to current policies, the incremental efficiency scenario could save around 5 million barrels of oil per day in 2035 and the accelerated scenario could save an additional 4 million barrels of oil per day in that year. Figure 10 breaks down the potential worldwide fuel consumption benefit of the accelerated scenario by region, expressed as a percentage of the fuel consumption reduction in 2035. As illustrated, the top five regulated markets (China, India, US, EU, and Brazil) account for more than three quarters of the total potential fuel savings benefit. The remaining potential is divided among countries in the Asia-Pacific, Middle East, Africa, and Latin America, as well as smaller individual markets.

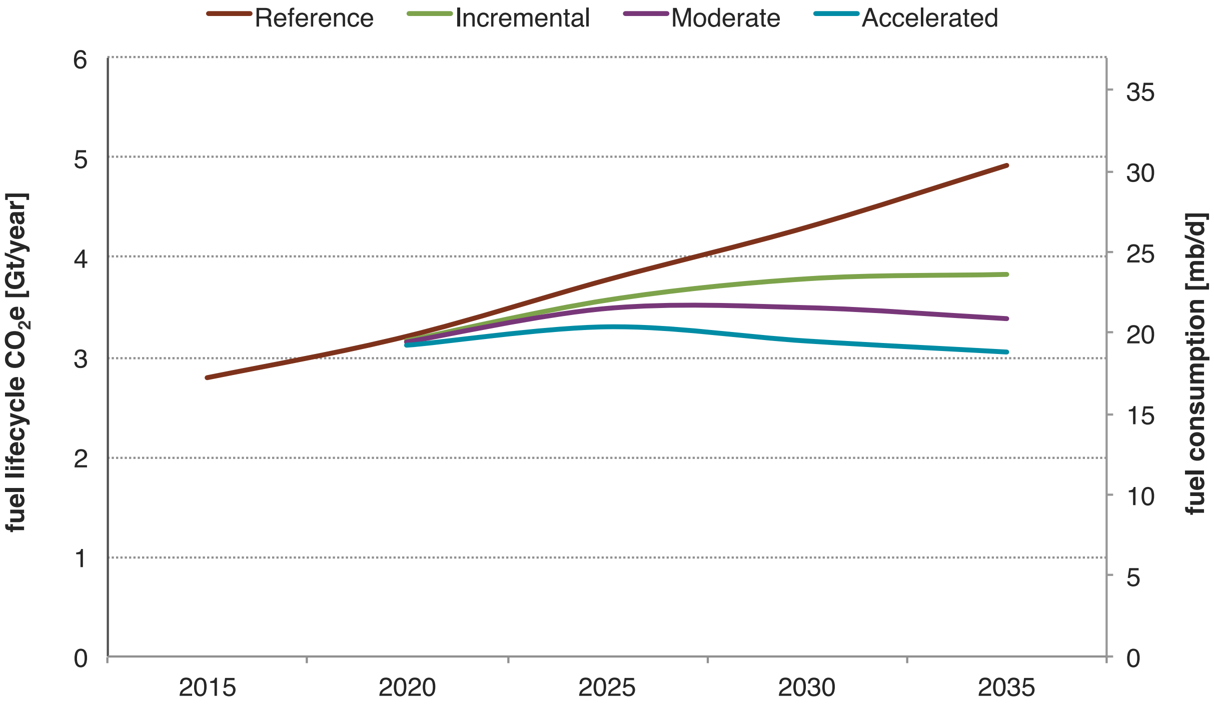


Figure 9: Annual GHG emissions and fuel consumption from tractor-trailers and rigid trucks worldwide by efficiency scenario, 2015-2035.

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[4] In the ICCT roadmap model, there are two truck categories: medium-heavy-duty truck (HDT) and heavy-HDT. While the medium- and heavy-HDT categories may include some vehicles that are not within the rigid truck or tractor-trailer categories (e.g., refuse trucks), we expect the vast majority of effects on emissions and energy consumption to be attributable to these categories.

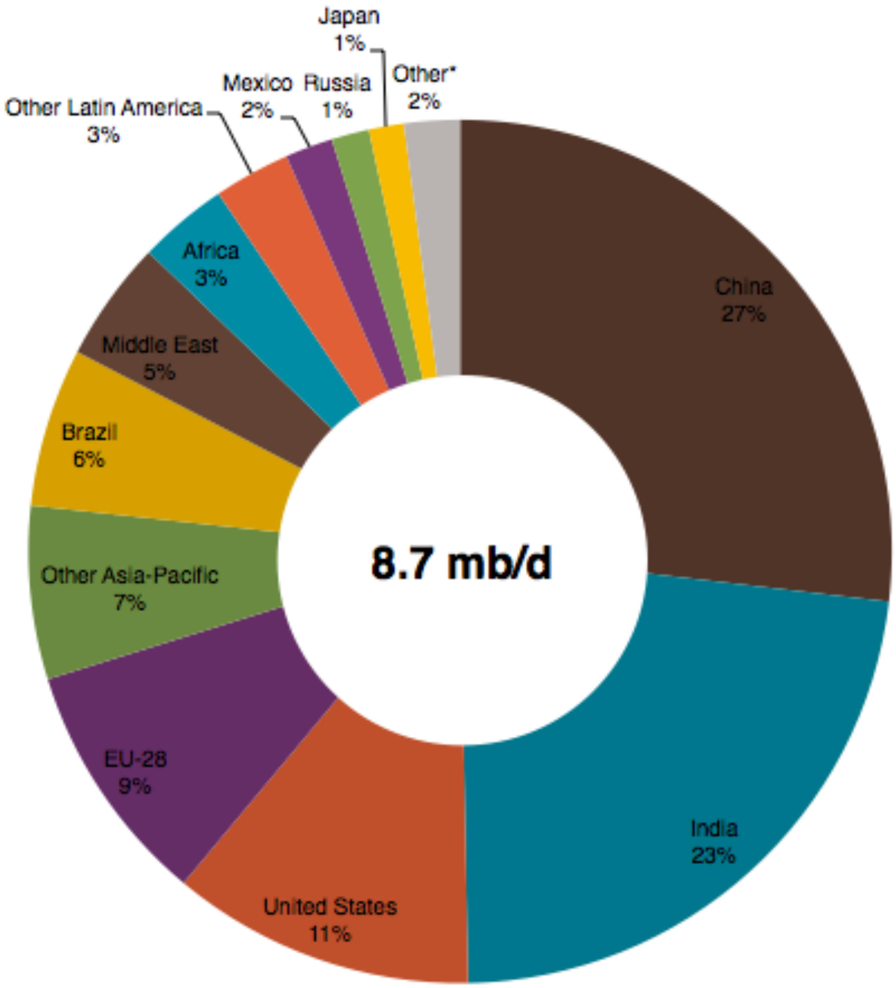

Figure 10: Share of worldwide potential fuel savings from accelerated tractor-trailer and rigid truck efficiency, 2035.[5]

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[5] Canada, Other Europe, Australia and South Korea each account for less than 1% of the potential worldwide savings.

6. Policy recommendations, conclusions, and next steps

In this report we present an initial, first order analysis of the potential benefits of technological improvement for the largest fuel consuming segments of the HDV sector. It is readily acknowledged that additional data and further analysis could help significantly to refine and improve what has been presented here. This assessment offers original analysis and findings in four key areas:

- Baseline Vehicles: This is the first known study to quantify and compare the representative baseline vehicle characteristics and operational profiles of tractor-trailers and rigid delivery trucks in the top five vehicle markets. Using the best available data, the study has found that representative baseline fuel consumption on a L/100km basis varies significantly across markets for both tractor-trailers and rigid delivery trucks. Under the assumptions made in this study, there is a 48% difference in fuel consumption between the most and least efficient baseline tractor-trailers and a 26% difference between the most and least efficient rigid trucks. Less than half of that difference (approximately 10%-20%) is due to variations in vehicle technology and configuration while over half of the difference is due to variations in typical duty cycle and payload.

- Energy Audits: This study uses simulation modeling to develop energy audits of the baseline vehicles over region-specific duty cycles and payloads. Energy audits are an effective means to identify and prioritize the most applicable areas for technology applications. For example, a vehicle with an energy audit that shows significant energy loss due to overcoming aerodynamic drag would benefit from aerodynamic improvement technologies, while a vehicle in which an energy audit finds significant energy loss due to braking would benefit from a hybrid regenerative braking system. The most consistent result across the energy audits developed for this study is that losses from engine inefficiencies are always greater than 50% of total energy loss. Although there exist theoretical limits to internal combustion engine efficiency, this result indicates that technologies to improve engine efficiency would have wide-ranging applicability across segments and markets.

- Region Specific HDV Technology Potential: This study simulates the effectiveness of advanced efficiency technology packages on the region-specific baseline vehicles. The technology packages consist of known technologies that are either commercially available today, or are predicted to be commercially available within the next 10-15 years. Given the different payloads and duty cycles across regions, the same technology packages result in different levels of fuel consumption reduction when applied to different vehicles. In addition, regions with more fuel saving technology already included in their baseline fleet will have less potential for technological improvements. This study finds that there is potential for fuel consumption reduction in the range of 40%-52% for tractor-trailers and 30%-36% for rigid delivery trucks across all regions assessed, with trucks sold in the EU having the smallest potential and trucks sold in India having the largest potential in both segments. This study assumes limited changes to vehicle configuration, and no change to engine displacement, payload or duty cycle.

- Associated potential benefits: Applying the technology potential as analyzed here translates to sales-weighted global targets of 31% fuel consumption reduction for new Medium HDVs and 46% fuel consumption reduction for new Heavy HDVs. Deploying this level of heavy-duty vehicle efficiency technologies could result in approximately 5-9 million barrels per day of equivalent oil savings in the 2035 timeframe.

This analysis has many policy implications. Strong and well-designed efficiency regulations in addition to other complimentary measures ideally would drive fuel efficiency technologies to the market and enable the potential fuel savings and GHG reduction benefits discussed above. Efficiency standards for HDVs have been successfully put in place in four markets around the world and are projected to save around 1.8 million barrels of oil per day in 2035 (ICCT 2016). The tools, resources, and research that have been developed during the process of standard setting in these markets could enable additional countries to adopt standards at an accelerated pace. Current HDV efficiency regulations cannot be directly compared because they differ in terms of testing methods, duty cycles, payloads, and evaluation metrics. The modeling effort conducted in this research allows for more direct comparisons between vehicles to determine their potential for technology improvement.

Global efficiency targets*.* As mentioned in Section 1, the overall motivation for this project is to take the first step toward setting HDV global efficiency targets in a way similar to what the GFEI has done for passenger cars. GFEI's overarching efficiency goal for passenger cars is to halve the average per vehicle fuel consumption of the on-road light-duty vehicle fleet by 2050 from a base year of 2005 (GFEI 2016). This study indicates a few potential targets that could be incorporated for freight hauling Medium and Heavy HDVs. The incremental, moderate, and accelerated scenarios defined in Section 5 would translate to the global average sales-weighted reductions listed in Table 10.

Table 10: Global sales-weighted new vehicle fuel consumption reductions by segment and scenario

Scenario	Medium HDV (6.35-15 tons)		Heavy HDV (15+ tons)	
	Annual reduction	Total reduction	Annual reduction	Total reduction
Incremental (by 2045)	1.40%	31%	2.20%	46%
Moderate (by 2040)	1.60%		2.90%	
Accelerated (by 2035)	1.80%		3.10%	

Over the short term, a few key actions would ideally be targeted to facilitate the adoption of efficiency targets around the world:

Commitment: The EU is currently the largest market in the world without efficiency standards for HDVs. The EU is extremely important, not only due to the size of its market, but also due to its global influence. The EU is headquarters to many of the world's largest heavy truck manufacturers and historically has had significant influence on the vehicles and vehicle technologies sold in markets such as India, Brazil, and China. If the EU were to make a commitment to move toward standards in the near term, the impacts would likely not only be seen in the EU fleet, but globally.

Harmonization: The above efficiency scenarios are analyzed for discrete regions, but the greatest potential benefits could accrue more quickly if more regions were moving in unison to develop and implement new policy that incentivized similar technologies into trucks across the world. Thus far, countries developing their own HDV efficiency standard have opted for a range of approaches to regulatory issues such as certification protocols, segmentation, stringency, and more (Kodjak 2015). Aligning key elements of HDV efficiency standards could have a number of benefits including lowering the cost of compliance for manufacturers and the cost of technology for end users as well as reducing the government resources required to develop standards.

Verification and compliance: As mentioned above, efficiency standards will likely be one of the key measures for realizing the adoption of technology in the proposed timeframes. One of the key elements of a well-designed standard is ensuring that the emission reductions are reflected in the real world, in other words confirming that efficiency standards directly result in the adoption of effective technology. There is significant evidence to show that there is currently a large and growing gap between light-duty vehicle CO_2 certification levels and real-world performance (Tietge 2015). There are a number of reasons for this gap and it would be important for HDV standards to include strong compliance provisions to ensure that real-world reductions are obtained.

Advanced technology roadmap: This study looks at the potential efficiency improvement of vehicles due to the adoption of known technologies that will be available by 2030. Therefore, the technology “end point” used in this study was limited to well known and commercialized, or near commercialized, technologies. Those technologies alone will not be enough to produce the reductions that are needed for full decarbonization of the transport sector. Pathways to zero- or near-zero-emissions freight transport would ideally be developed in the near term. Having these roadmaps in place will help provide incentives for technology innovators to work toward development and deployment of next-generation technologies.

Complimentary Measures: This study recommends the global adoption of new vehicle efficiency standards to drive technology adoption in the new HDV fleet. Vehicle efficiency standards represent the single largest regulatory lever that policymakers can adopt to reduce the fuel consumption of the fleet. There also exist a large number of both voluntary and mandatory complementary measures that can supplement and enhance efficiency regulations. These measures include logistics infrastructure improvements, green freight programs, technology adoption incentive programs, differentiated road tolling, fuel taxation, labeling programs, and many more. Ideally fuel efficiency standards would be considered in the context of the broader sustainable freight strategy of a given country or region.

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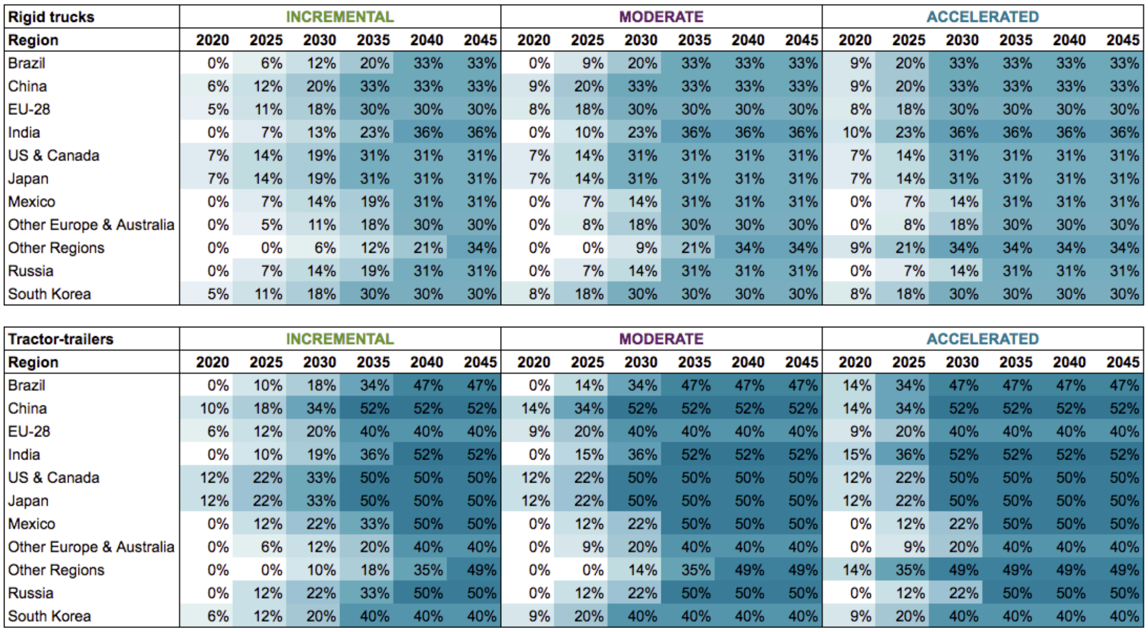
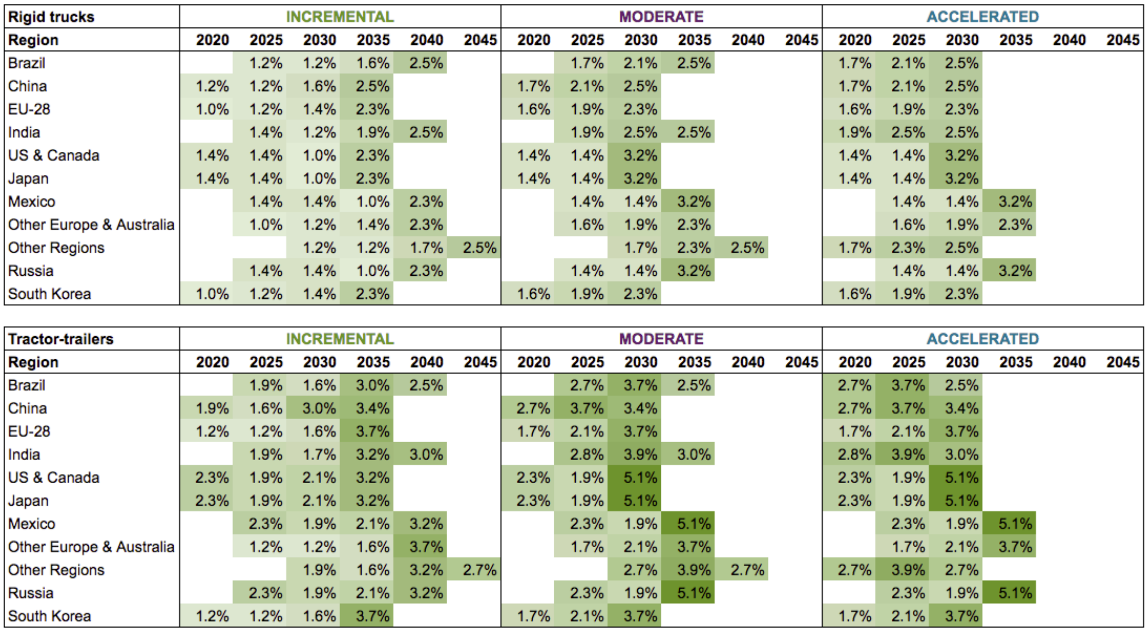
Appendix



Rigid trucks	INCREMENTAL						MODERATE						ACCELERATED					
Region	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**
Brazil	0%	6%	12%	20%	33%	33%	0%	9%	20%	33%	33%	33%	9%	20%	33%	33%	33%	33%
China	6%	12%	20%	33%	33%	33%	9%	20%	33%	33%	33%	33%	9%	20%	33%	33%	33%	33%
EU-28	5%	11%	18%	30%	30%	30%	8%	18%	30%	30%	30%	30%	8%	18%	30%	30%	30%	30%
India	0%	7%	13%	23%	36%	36%	0%	10%	23%	36%	36%	36%	10%	23%	36%	36%	36%	36%
US & Canada	7%	14%	19%	31%	31%	31%	7%	14%	31%	31%	31%	31%	7%	14%	31%	31%	31%	31%
Japan	7%	14%	19%	31%	31%	31%	7%	14%	31%	31%	31%	31%	7%	14%	31%	31%	31%	31%
Mexico	0%	7%	14%	19%	31%	31%	0%	7%	14%	31%	31%	31%	0%	7%	14%	31%	31%	31%
Other Europe & Australia	0%	5%	11%	18%	30%	30%	0%	8%	18%	30%	30%	30%	0%	8%	18%	30%	30%	30%
Other Regions	0%	0%	6%	12%	21%	34%	0%	0%	9%	21%	34%	34%	9%	21%	34%	34%	34%	34%
Russia	0%	7%	14%	19%	31%	31%	0%	7%	14%	31%	31%	31%	0%	7%	14%	31%	31%	31%
South Korea	5%	11%	18%	30%	30%	30%	8%	18%	30%	30%	30%	30%	8%	18%	30%	30%	30%	30%

Tractor-trailers	INCREMENTAL						MODERATE						ACCELERATED					
Region	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**
Brazil	0%	10%	18%	34%	47%	47%	0%	14%	34%	47%	47%	47%	14%	34%	47%	47%	47%	47%
China	10%	18%	34%	52%	52%	52%	14%	34%	52%	52%	52%	52%	14%	34%	52%	52%	52%	52%
EU-28	6%	12%	20%	40%	40%	40%	9%	20%	40%	40%	40%	40%	9%	20%	40%	40%	40%	40%
India	0%	10%	19%	36%	52%	52%	0%	15%	36%	52%	52%	52%	15%	36%	52%	52%	52%	52%
US & Canada	12%	22%	33%	50%	50%	50%	12%	22%	50%	50%	50%	50%	12%	22%	50%	50%	50%	50%
Japan	12%	22%	33%	50%	50%	50%	12%	22%	50%	50%	50%	50%	12%	22%	50%	50%	50%	50%
Mexico	0%	12%	22%	33%	50%	50%	0%	12%	22%	50%	50%	50%	0%	12%	22%	50%	50%	50%
Other Europe & Australia	0%	6%	12%	20%	40%	40%	0%	9%	20%	40%	40%	40%	0%	9%	20%	40%	40%	40%
Other Regions	0%	0%	10%	18%	35%	49%	0%	0%	14%	35%	49%	49%	14%	35%	49%	49%	49%	49%
Russia	0%	12%	22%	33%	50%	50%	0%	12%	22%	50%	50%	50%	0%	12%	22%	50%	50%	50%
South Korea	6%	12%	20%	40%	40%	40%	9%	20%	40%	40%	40%	40%	9%	20%	40%	40%	40%	40%

A1. Rigid truck and tractor-trailer efficiency improvements relative to 2015 by scenario and region (darker fill colors indicate larger reductions).



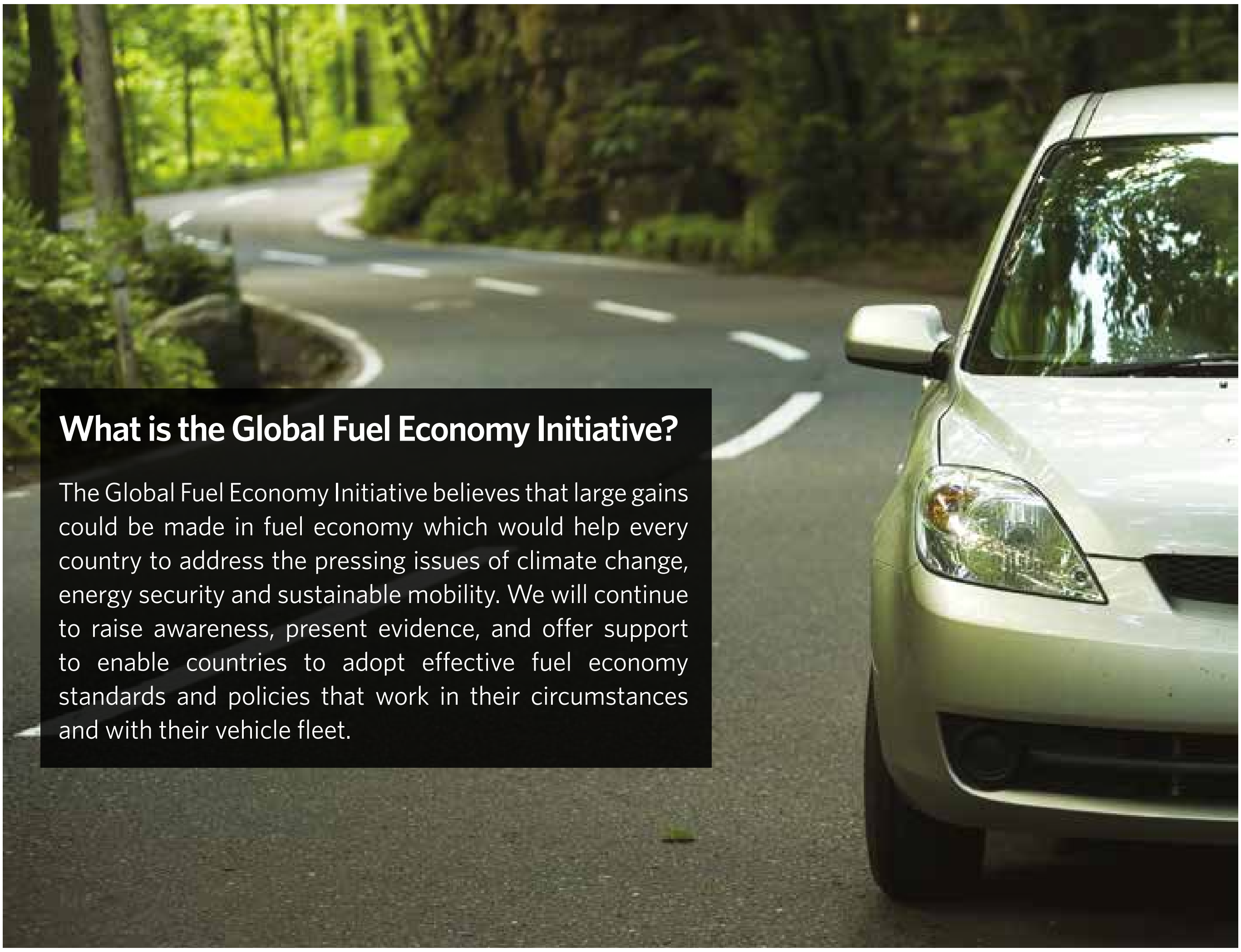
Rigid trucks	INCREMENTAL						MODERATE						ACCELERATED					
Region	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**
Brazil		1.2%	1.2%	1.6%	2.5%			1.7%	2.1%	2.5%			1.7%	2.1%	2.5%			
China	1.2%	1.2%	1.6%	2.5%			1.7%	2.1%	2.5%				1.7%	2.1%	2.5%			
EU-28	1.0%	1.2%	1.4%	2.3%			1.6%	1.9%	2.3%				1.6%	1.9%	2.3%			
India		1.4%	1.2%	1.9%	2.5%			1.9%	2.5%	2.5%			1.9%	2.5%	2.5%			
US & Canada	1.4%	1.4%	1.0%	2.3%			1.4%	1.4%	3.2%				1.4%	1.4%	3.2%			
Japan	1.4%	1.4%	1.0%	2.3%			1.4%	1.4%	3.2%				1.4%	1.4%	3.2%			
Mexico		1.4%	1.4%	1.0%	2.3%			1.4%	1.4%	3.2%				1.4%	1.4%	3.2%		
Other Europe & Australia		1.0%	1.2%	1.4%	2.3%			1.6%	1.9%	2.3%				1.6%	1.9%	2.3%		
Other Regions			1.2%	1.2%	1.7%	2.5%			1.7%	2.3%	2.5%		1.7%	2.3%	2.5%			
Russia		1.4%	1.4%	1.0%	2.3%			1.4%	1.4%	3.2%				1.4%	1.4%	3.2%		
South Korea	1.0%	1.2%	1.4%	2.3%			1.6%	1.9%	2.3%				1.6%	1.9%	2.3%			

Tractor-trailers	INCREMENTAL						MODERATE						ACCELERATED					
Region	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**
Brazil		1.9%	1.6%	3.0%	2.5%			2.7%	3.7%	2.5%			2.7%	3.7%	2.5%			
China	1.9%	1.6%	3.0%	3.4%			2.7%	3.7%	3.4%				2.7%	3.7%	3.4%			
EU-28	1.2%	1.2%	1.6%	3.7%			1.7%	2.1%	3.7%				1.7%	2.1%	3.7%			
India		1.9%	1.7%	3.2%	3.0%			2.8%	3.9%	3.0%			2.8%	3.9%	3.0%			
US & Canada	2.3%	1.9%	2.1%	3.2%			2.3%	1.9%	5.1%				2.3%	1.9%	5.1%			
Japan	2.3%	1.9%	2.1%	3.2%			2.3%	1.9%	5.1%				2.3%	1.9%	5.1%			
Mexico		2.3%	1.9%	2.1%	3.2%			2.3%	1.9%	5.1%				2.3%	1.9%	5.1%		
Other Europe & Australia		1.2%	1.2%	1.6%	3.7%			1.7%	2.1%	3.7%				1.7%	2.1%	3.7%		
Other Regions			1.9%	1.6%	3.2%	2.7%			2.7%	3.9%	2.7%		2.7%	3.9%	2.7%			
Russia		2.3%	1.9%	2.1%	3.2%			2.3%	1.9%	5.1%				2.3%	1.9%	5.1%		
South Korea	1.2%	1.2%	1.6%	3.7%			1.7%	2.1%	3.7%				1.7%	2.1%	3.7%			

A2. Rigid truck and tractor-trailer annualized efficiency improvements by scenario and region (darker fill colors indicate larger reductions).

GFEI
GLOBAL FUEL ECONOMY INITIATIVE

50BY50
GLOBAL FUEL ECONOMY INITIATIVE



What is the Global Fuel Economy Initiative?

The Global Fuel Economy Initiative believes that large gains could be made in fuel economy which would help every country to address the pressing issues of climate change, energy security and sustainable mobility. We will continue to raise awareness, present evidence, and offer support to enable countries to adopt effective fuel economy standards and policies that work in their circumstances and with their vehicle fleet.

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