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The Future of Trucks

Implications for energy and the environment

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INTERNATIONAL ENERGY AGENCY

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Acknowledgements

This report was prepared in the Directorate of Sustainability, Technology and Outlooks (STO) of the International Energy Agency (IEA), under the Direction of Kamel Ben Naceur. Pierpaolo Cazzola and Timur Gül led this activity. The report was written by Jacob Teter, Pierpaolo Cazzola and Timur Gül, with significant contributions from Eamonn Mulholland. Other IEA contributors include Pharoah Le Feuvre (biofuels); Simon Bennett (market and policies); Paul Hugues (biofuels cost assessment and energy and emissions decompositions); Zoe Lagarde (distance-based pricing); Volker Kraayvanger and Pedro Cespedes Ruiz (natural gas); Tyler Bryant and Sacha Scheffer (fuel economy standards and high-capacity vehicles); and Emanuele Bianco (Power-to-X fuels). Zane McDonald and Erik Mahoney also contributed to the analysis.

External reviewers include Alan McKinnon (Kuehne Logistics University), Wolfgang Schade (M-Five), Manfred Schuckert (Daimler), Magnus Lindgren (Swedish Transport Administration), Buddy Polovick (US Environmental Protection Agency), Dave Mullaney (Rocky Mountain Institute), Florian Kleiner (German Aerospace Center), Gian Gomes Marques (Volkswagen AG), Guillaume de Smedt (Air Liquide), Jon Stenning (Cambridge Econometrics), Jacques Leonardi (University of Westminster), Nils-Olof Nylund (Technical Research Centre of Finland [VTT]), Oscar Delgado (International Council on Clean Transportation [ICCT]), Andrew Palmer (Heriot-Watt University), Herbert Fabian (UN Environment), Mark Schipper (Energy Information Administration of the United States), Patrik Akerman (Siemens), Pia Agatep (Clean Air Asia), Raimonds Aronietis (International Transport Forum [ITF]), Sophie Punte (Smart Freight Centre), Sudhir Gota (SLoCaT Secretariat), Todd Onderdonk (ExxonMobil), Urs Ruth (Bosch), William Todts (Transport & Environment), Jacques Marmy (International Road Transport Union [IRU]), Tiziana Frongia, Nikolaus Steininger and Juan-Nicolas Ibanez (European Commission), Per Hanarp (Volvo Trucks), Patrice Nogues (EDF), Anant D. Vyas (Argonne National Laboratory), Takanori Shiina (Honda), and Alvin Meija (Clean Air Asia). External reviewers from the following bodies provided comment to the biofuels section of the report: European Biogas Association (EBA), Neste Oy (Anselm Eisentraut), Energiforsk – the Swedish Energy Research Centre (Mattias Svensson), Helmholtz Centre for Environmental Research – UFZ(Eric Billig). The Advanced Motor Fuels and the Bioenergy IEA Technology Collaboration Programmes also contributed to the review.

The report benefited from a joint workshop organised by the Joint Research Centre of the European Commission and the IEA on the future of trucks for energy and environment, held on 8 November 2016 and attended by several stakeholders, including representatives of truck manufacturers (Daimler, Scania, Volkswagen, Volvo Trucks), energy companies (Shell, ExxonMobil), other industries (Arconic, Bosch, BorgWarner, Eaton, Michelin, Siemens, Wabco), industry associations (European Automobile Manufacturers Association [ACEA], European Liaison Committee of Common Market Forwarders [CLECAT], IRU, World Business Council for Sustainable Development [WBCSD]), intergovernmental organisations (UN Environment), non-governmental and non-profit organisations (Clean Air Asia, Connekt, ICCT, Smart Freight Centre, The Energy and Resources Institute [TERI], Transport & Environment), governmental bodies (European Commission, South African National Energy Development Institute), academic and research institutions (Fraunhofer Institute for Material Flow and

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Logistics, German Aerospace Center, Heriot Watt University, IFSTTAR, KAPSARC, Netherlands Organisation for Applied Scientific Research [TNO], Kuehne Logistics University, Rensselaer Polytechnic Institute, University of Cambridge, University of Gothenburg, University of Westminster, VTT) and consultancy firms (Ricardo Energy & Environment , CE Delft, M-FIVE). The agenda, the presentations and the summary of the workshop are available on the IEA web site:

www.iea.org/workshops/the-future-role-of-trucks-for-energy-and-environment.html.

IEA reviewers included Rebecca Gaghen, Kamel Ben Naceur and Jean-Francois Gagné.

The report was edited by Adam Majoe.

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Executive summary

Road freight vehicles are a key enabler of global economic activity and play an essential role in delivering all types of goods or commodities from their points of production to the factories and industries that use or transform them, or to their final points of sale. Economic growth is closely associated with growth in road freight activity (measured in tonne-kilometres [tkm]). Many types of road vehicles deliver goods, including trucks of all sizes. But about 65% of freight activity is accomplished by heavy-freight trucks – a mix of rigid body and articulated trucks with a gross vehicle weight of greater than 15 tonnes. Although heavy-freight trucks are the most efficient for hauling cargo, their large annual mileage means that they consume half of the oil in the road freight sector.

Road freight vehicles are a central source of global oil demand today: at around 17 million barrels per day (mb/d), oil demand from road freight vehicles accounts for around one-fifth of global oil demand – equivalent to the current oil production of the United States and Canada combined. Oil demand from road freight vehicles is roughly equal to that of the entire industry sector and is outstripped only by passenger cars, which account for around one-quarter of total oil demand. Oil demand growth from road freight transport has outpaced that of all other sectors from 2000 onward. While oil use of passenger cars has begun to plateau and decline in many industrialised countries, oil use from road freight vehicles continues to rise. Road freight transport relies primarily on diesel, which accounts for more than 80% of its oil use. Road freight vehicles alone accounted for about 80% of the global net increase in diesel demand since 2000, and make up about half of global diesel demand today. As a result, road freight today accounts for more than 35% of transport-related carbon dioxide (CO_2) emissions, and around 7% of total energy-related CO_2 emissions.

Road freight transport is set to continue to drive global oil demand growth

Without further policy efforts, oil demand from road freight vehicles is set to rise by 5 mb/d to 2050. In the Reference Scenario, global road freight activity is expected to increase by a factor 2.4, driven by robust GDP growth, bringing up oil demand. Emerging and developing countries in Asia, in particular the People's Republic of China (hereafter, "China") and India, account for about 90% of the net increase in road freight oil demand over the projection period, equivalent to around 30% of total oil demand growth from all sectors. The energy intensity (measured by unit of tkm) falls by nearly 40% below today's level, as road freight vehicles become increasingly more efficient. Efficiency improvements are driven by Canada, China, Japan and the United States, the only countries with heavy-duty fuel economy standards in place already today (although the European Union, Mexico, India and Korea are looking to introduce them). Oil-based fuels, in particular diesel, remain the primary fuel in the Reference Scenario, at around 85% of road freight transport fuel use by 2050. Biofuels and natural gas together account for the majority of the remainder. The consequence is that direct CO_2 emissions grow to 3.4 gigatonnes (Gt) of CO_2 in 2050, one-third above today's level. The increase in oil demand and CO_2 emissions in the Reference Scenario means that the importance of road freight transport for key energy policy goals, such as energy security and environmental protection, is likely to grow moving forward.

Reducing future growth of oil demand from road freight vehicles is a challenging, but possible task; opportunities arise from three main areas. Systemic improvements in road freight operations and logistics can reduce growth in road freight trucking activity and improve the on-road efficiency of truck operations. Near-term examples include using Global Positioning System to optimise truck routing; driver training and the use of on-board, real-time feedback devices that monitor the on-road fuel economy of trucks; and a wide range of measures to

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improve the utilisation of vehicles to maximise load. Other measures, including autonomous trucks or the "physical Internet" – an open, shared and modular system wherein all physical assets used in goods delivery are shared across companies – could transform the road freight operations entirely, but face higher barriers to implementation. Similarly, many vehicle efficiency technologies pay back their higher capital costs through fuel savings within only a few years. For the existing stock of trucks, aerodynamic retrofits can reduce the drag coefficient and lead to reductions in road load; and low rolling resistance tyres can translate into immediate improvements in fuel economy. For new trucks, additional technologies exist for reducing idling and for improving vehicle efficiency, such as the use of lightweight materials and improvements to truck engines, transmissions and drivetrains. However, some of these opportunities have longer payback times than operators tend to consider when purchasing new trucks. Finally, the use of alternative fuels and alternative fuel trucks could help achieve key energy and environmental policy goals, such as diversifying the fuel supply of road freight and reducing CO_2 and air pollutant emissions. Natural gas, biofuels, electricity and hydrogen are the main alternatives to oil, but they differ in the extent to which they can contribute to policy objectives.

A vision for modernising road freight transport

In the Modern Truck Scenario, targeted efforts to modernise road freight transport reduces oil demand from road freight vehicles by nearly 16 mb/d by 2050, relative to the Reference Scenario, with benefits for environmental goals. The Modern Truck Scenario sets out a plausible, yet ambitious, vision to modernise road freight transport. It capitalises on the opportunities for systemic improvements in operations and logistics across all aspects of road freight, vehicle efficiency improvements and support for the use of alternative fuels. In the Modern Truck Scenario, the energy intensity of vehicle operations (in energy used per tkm) drops by more than one-third in 2050, relative to the Reference Scenario. Improvements to logistics and road freight operations reduce tkm by 13% in 2050 and total vehicle activity (measured in vehicle-kilometres) by more than 20%. Energy efficiency and alternative fuels, including electrification, lead to a reduction in energy intensity, relative to the Reference Scenario, of 34% in 2050. The result is that direct CO_2 emissions from road freight transport decline by 2.5 Gt in 2050, or 75%, relative to the Reference Technology Scenario.

Not all elements of the Modern Truck Scenario are easily implemented, but there are three key enablers that present important near-term energy policy opportunities. Tightening fuel economy standards and expanding their geographic coverage can accelerate fuel economy improvements over the coming decades. Standards can be supported by differentiated vehicle taxation to incentivise the purchase and operation of efficient trucks. Care must be taken to ensure that test procedures reflect real-world operations and that simulation tools rely on accurate component testing. Data availability and data sharing are key prerequisites to realising some of the potential that underlies systemic improvements in freight logistics, capitalising on the advancement of digital technologies and their application across all aspects of road freight, including supply chain and fleet management, collaboration across shippers, and the optimisation of vehicle operations. The rules of data exchange must be multilaterally defined and transparent for everyone, and confidentiality safeguarded. Some of the potential for systemic improvements can be realised by individual operators alone, but the better the system is designed (i.e. the more operators and other stakeholders that are included), the more effective its implementation. Support for alternative fuels and vehicles needs to cover four main areas: RD&D, market uptake of alternative fuel vehicles, adequate access to charging or refuelling infrastructure and the availability of alternative energy carriers. A focus on low- or zero-emitting fuels not only at the point of use but also across the entire supply chain, both with regards to air pollutant and greenhouse gas emissions, can help ensure the pursuit of multiple energy policy goals at the same time.

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Introduction

The relevance of transport for the global energy sector cannot be overstated. Transport accounts for more than half of global oil demand, at around 52 million barrels of oil per day (mb/d). Oil demand from the second-largest consumer, the industry sector (including feedstocks), is only one-third that of transport, at 17 mb/d. Sectoral oil demand is growing rapidly: at 1.9% per year, transport oil demand has grown faster than all other energy demand sectors since 2000 and has contributed 80% to total global oil demand growth between 2000 and 2015. With its heavy reliance on oil products, the transport sector is also a key contributor to climate change and emitted 7.8 Gt of carbon dioxide (CO_2) in 2015, about 22% of the global total energy-related CO_2 emissions.

The transport sector spans a wide range of different purposes and modes. Transport activity can be split into two broad categories, one being passenger movements and the other being the movement of goods and services. The possible means to satisfy such demands differ widely, as do the modes of transport, which range from different types of road vehicles to railways, ships and airplanes. The choice of the appropriate mode for each type of activity depends on a range of factors, including speed, costs and convenience of access. In the case of the movement of goods, a central pillar of global economic activity, road freight vehicles are often the mode of choice and range from pickups and vans to large long-haul trucks. Road freight vehicles constitute a key segment of global oil demand: at close to 17 mb/d, road freight oil use is second to that of passenger vehicles (which consume around 23 mb/d) and nearly as high as all oil use by the industry sector.[1] As a result, road freight transport alone was responsible for 2.6 Gt of energy-related CO_2 emissions in 2015, or about 7% of total global energy-related CO_2 emissions.

Table 1 • The road freight sector in 2015 at a glance

Share of total	All energy sectors	Transport	Freight
Oil use (primary energy) / energy consumption (final energy)	**18%** / 9%	**32%** / 32%	**75%** / 75%
Carbon dioxide emissions	7%	33%	75%
Freight activity (in tonne-kilometres)	--	--	20%
Number of on-road vehicles (**including** / excluding light-duty trucks)*	--	**16%** / 5%	--

Sources: IEA (2017a), Mobility Model, June 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport.
*excludes motorised 2- and 3-wheelers.

In the developed world, even as the oil consumption and energy use of road passenger vehicle fleets have begun to plateau and decline, oil use by road freight continued to increase. Even in developing and emerging countries, where demand for passenger transport means that oil demand growth has been and will continue to increase rapidly, the pace of oil demand growth by the road freight sector has in the decade begun to outstrip that of passenger modes in many key countries, such as India. In the People's Republic of China (hereafter, "China"), the pace of oil demand growth by road freight is expected to surpass that of all passenger road modes in the coming five years.

Despite its relevance for global oil use and CO_2 emissions, road freight transport has not received the same policy attention as passenger cars. Although policies to curb air pollutant emissions

[1] The assessment of historical energy demand from light commercial vehicles, medium- and heavy-freight trucks carried out for the purpose of this report is based on the IEA Mobility Model. It combines and calibrates parameters from multiple sources, including vehicle sales, stocks, mileage, energy use per vehicle-kilometre, loads and activity (in tonne-kilometres). The resulting historical diesel and gasoline demand from this assessment may differ slightly from that reported in IEA energy balances or in other IEA publications.

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from road freight vehicles exist in many countries, only four countries in the world – Canada, China, Japan, and the United States – have regulations in place for fuel economy standards for heavy-duty vehicles (including trucks), and all but Japan's emerged only in the past decade. In 2015, while more than 80% of global light-duty vehicle sales were covered by fuel economy standards, the four countries constituted about 50% of new heavy-duty vehicles sales. In the absence of further regulatory efforts, road freight transport is expected to be a key source of global oil demand and CO_2 emissions growth over the next couple of decades (IEA, 2016a). In recognition of the potential relevance for achieving energy security and environmental goals, the International Energy Agency (IEA) has devoted this report to the future role of trucks.

This report is composed of three main chapters:

- **Chapter 1: The role of trucks in the energy sector** aims to provide a concise primer on road freight transport, reviewing in detail the current contribution of road freight transport to energy demand, CO_2 emissions and air pollution. It covers the historical drivers of freight activity, the main features of the global truck market, and the current policy landscape.
- **Chapter 2: Opportunities to reduce energy and emissions growth** aims to provide an overview of all relevant technological and system-wide measures to curb future oil demand and emissions growth from road freight transport. It reviews the status and prospects of alternative fuels, including natural gas, biofuels, electricity and hydrogen, and discusses the possible ways and extent to which the average fuel consumption of different types of road freight vehicles can be reduced. It also assesses the potential of systemic improvements, such as better logistics, for contributing to lower fuel demand growth from the sector.
- **Chapter 3: Long-term outlook and policy insights** first presents two alternative outlooks for road freight transport to mid-century through the analysis of two key scenarios. In the Reference Scenario, the outlook for future energy demand and CO_2 emissions growth to 2050 is presented on the basis of all policies that are currently in place or have already been announced. This scenario is not a normative scenario that the IEA deems desirable or one that energy stakeholders should try to bring about. Based on the analyses presented in Chapters 1 and 2, it is the basis for expectations for the future in the absence of further policy efforts and serves as an invitation for improvement should the outcome be deemed suboptimal or even unacceptable. The Modern Truck Scenario (MTS) presents an improved course of action. Drawing on the review of technological and system-wide measures to reduce future energy and emissions growth from road freight transport in Chapter 2, it identifies key policies, actions and technologies that could spur the modernisation of road freight transport, and discusses the likely co-benefits for selected primary energy policy objectives. Based on a comparison of the two policy scenarios, Chapter 3 next provides a concise overview of the lessons learned and derives recommendations for policy makers. These policy insights explore options to reduce the road freight sector's energy and emissions growth while improving the efficiency with which it can foster global economic activity and contribute to essential policy goals, such as energy security, climate change and air pollution.

The analysis of past, present and future road freight transport trends conducted in this report uses the IEA's Mobility Model (MoMo), the primary transport model of the IEA's *Energy Technology Perspectives* series (IEA, 2017b). The historical database of the model is the culmination of more than a decade of efforts from numerous researchers to build an internally consistent international database of transport vehicle stocks, sales, activities, energy use and emissions, drawing largely on publically available data sources. Using IEA statistics on energy use by fuel in road transport and reports that monitor vehicle efficiency trends across specific vehicle

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operations in key regions (GFEI, 2016), MoMo enables a comprehensive and detailed global and regional overview of road freight operations and their implications for energy use and emissions.

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The role of trucks in the energy system

Road freight vehicles are a key enabler of global economic activity. There is no one single definition of what road freight vehicles actually are, given the wide range of activities that fall under the broad category. One of the essential roles of road freight vehicles is to deliver goods from their points of production to the factories and industries that use or transform them, or to their final points of sale. However, the purposes vary depending on the good in question, and so do the freight vehicles to support them. For example, road freight vehicles link coal mines with coal-fired power plants or industrial boilers, as well as agricultural food production with warehouses and supermarkets or the textile industry with clothes stores. But they also facilitate many other elements of global economic activity. Road freight vans and trucks are used, for example, to deliver mail or to bring building materials to construction sites and also encompass garbage trucks and firefighting trucks (Box 1).

Besides their active role in supporting global economic activity, road freight vehicles also play a key role as consumers of energy, in particular, refined products of oil, and as emitters of air pollutants and greenhouse gas (GHG) emissions. This first chapter intends to establish the place of road freight vehicles in the global energy landscape. It does so by first laying out the contribution of road freight vehicles to global energy demand as well as emissions. It then discusses the factors behind these trends by analysing the role of various drivers of road freight activity, discussing road freight vehicles and markets, and assessing current road freight vehicle fuel intensities and policy framework.

Box 1 • Definitions for road freight vehicles used in this report

Road freight transport encompasses all activities that are linked to the movement of goods, including everything from raw materials to foodstuffs and electronics. There is a wide variety of different vehicle types that can fulfil this function,* but, for the purpose of this report, road freight vehicles are broadly classified into three main categories, each of them containing a wide and heterogeneous population of vehicles suited to their particular range of operations:

Heavy-freight trucks (HFTs) are commercial vehicles with a gross vehicle weight (GVW) greater than 15 tonnes (t). They typically serve long-haul delivery of goods, have from two to four or more axles and a power rating of between 200 and 600 kW. The heaviest HFTs are operated essentially year-round, often covering more than 100 000 kilometres (km) per year and in some instances twice this distance. HFTs account for the majority (about 70%) of road freight activity and about 50% of truck energy use. This category also includes road trains: multiple trailers pulled by a single tractor unit.

Medium-freight trucks (MFTs) are commercial vehicles with a GVW from 3.5 t to 15 t. They include small lorries, rigid trucks and tractor-trailers as well as large vans. They tend to perform regional operations but also include public and commercial service vehicles, such as garbage trucks or fire-fighting trucks. In countries with a less-developed highway network infrastructure, the function of some MFTs mimics that of HFTs: they are used in long-haul operations and for transporting goods from central distribution hubs (warehouses and ports) to their final destinations, such as retail firms, or for transporting bulk building materials and resources. Together, HFTs and MFTs comprise heavy-duty trucks.

Light commercial vehicles (LCVs) are pickups, vans and small trucks with a GVW of less than 3.5 t. LCVs are one of two classes of light-duty vehicles (the other being passenger light-duty vehicles) and are used for the transportation of goods. In general, the LCV fleet consists of vans, chassis cab-style vehicles, small open lorries and pickup trucks. They are used for a variety of tasks, including small-scale 'last-mile' deliveries, such as a postal or commercial delivery services, and for transporting industrial goods and building materials to and from work sites. They are also used to

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provide services, such as repairs, plumbing and heating, and office support.

The functions of these trucks vary depending on their size, weight and horsepower as well as on regional factors, including the level of economic development, geography and the shares of various sectors (such as forestry, agriculture, mining, manufacturing, resource extraction, light- and heavy-industry, and services) in the economy. Truck classification schemes vary from country to country and are generally far more detailed than the three broad categories used in this report (Table 2).

* In addition to the activities of the three categories of trucks discussed at length in this report, two- and three-wheeled freight vehicles also transport small but significant shares of goods in certain countries. For instance, in the People's Republic of China (hereafter, "China"), Chinese rural vehicles, small two- and three-wheeled vehicles, are used in agriculture and industry as well as for transporting goods more generally (Sperling, Lin and Hamilton, 2004). In Japan, motorcycles are a popular and widespread mode of urban delivery. Motorcycles and even electric two- and three-wheelers will continue to be part of the on-road freight modal mix, but their relevance in terms of energy and emissions is relatively small and has been shrinking. Moreover, with the exception of certain urban delivery contexts (e.g. last-mile delivery), their role is marginal and is likely to diminish in the coming decades.

Table 2 • Truck classification schemes in the United States, European Union, China and Japan

United States		European Union				China				Japan			
Vehicle Category	Weight (t)**	Vehicle Category	Weight (t)*	Trailers & semitrailers	Weight (t)	Trucks	Weight (t)	Tractors	Weight (t)	Trucks Category	Weight (t)	Tractors Category	Weight (t)
		N1	< 3.5										
2b	3.86 - 4.54	N2	3.5 - 12	*O1*	< 0.75	3.5 - 4.5		3.5 - 18		1-4	3.5 - 7.5	1	< 20
3	4.54 - 6.35					4.5 - 5.5							
4	6.35 - 7.26			*O2*	0.75 - 3.5	5.5 - 7							
5	7.26 - 8.85					7 - 8.5				5	7.5 - 8		
6	8.85 - 11.79					8.5 - 10.5				6	8 - 10		
7	11.79 - 14.97			*O3*	3.5 - 10	10.5 - 12.5				7	10 - 12		
8a	14.97 - 27.22	N3	> 12			12.5 - 16				8	12 - 14		
						16 - 20		18 - 27		9	14 - 16		
						20 - 25				10	16 - 20	2	> 20
8b	> 27.22			*O4*	> 10	25 - 31		27 - 35		11	> 20		
						> 31		35 - 40					
								40 - 43					
								43 - 46					
								46 - 49					
								> 49					

* In the European Union, vehicle categories N1 and N2 are defined in Annex II of Directive 2007/46/EC as vehicles for goods transport with a reference mass (i.e. without payload) exceeding 2 610 kg.

** The weight classes for the United States and Canada are rounded to the nearest hundredth t. In the United States and Canada, classifications for all trucks are independent of vehicle design (though with the advent of Phase II regulations, trailers will be classified and regulated). In the European Union, trucks and trailers/semitrailers are classified (and regulated) separately. In China and Japan, (single unit) trucks and tractors are classified and regulated separately. Classification schemes in other countries and global regions differ from those shown above.

Notes: The weights shown are the gross vehicle weight (GVW) (the weight of the vehicle plus the maximum intended payload) for the European Union and Japan, the maximum design weight for the People's Republic of China and the gross vehicle weight rating (GVWR) (the maximum recommended operating weight of a vehicle as specified by the manufacturer) for the United States and Canada. These all refer to essentially the same thing: the maximum designed weight of the vehicle plus its payload. The single exception is tractors, which may carry trailers that have weights exceeding the maximum weights.

Sources: Transportpolicy.net; US EPA, 2016a; EC, 2007; ECCJ, 2005.

Energy use and emissions from road freight vehicles

Energy use

Globally, road freight transport energy consumption has grown by more than 50% over the past one-and-a-half decades, from around 23 exajoules (EJ) in 2000 to 36 EJ in 2015. Today, road freight transport makes up 32% of total transport-related energy demand. Road freight transport

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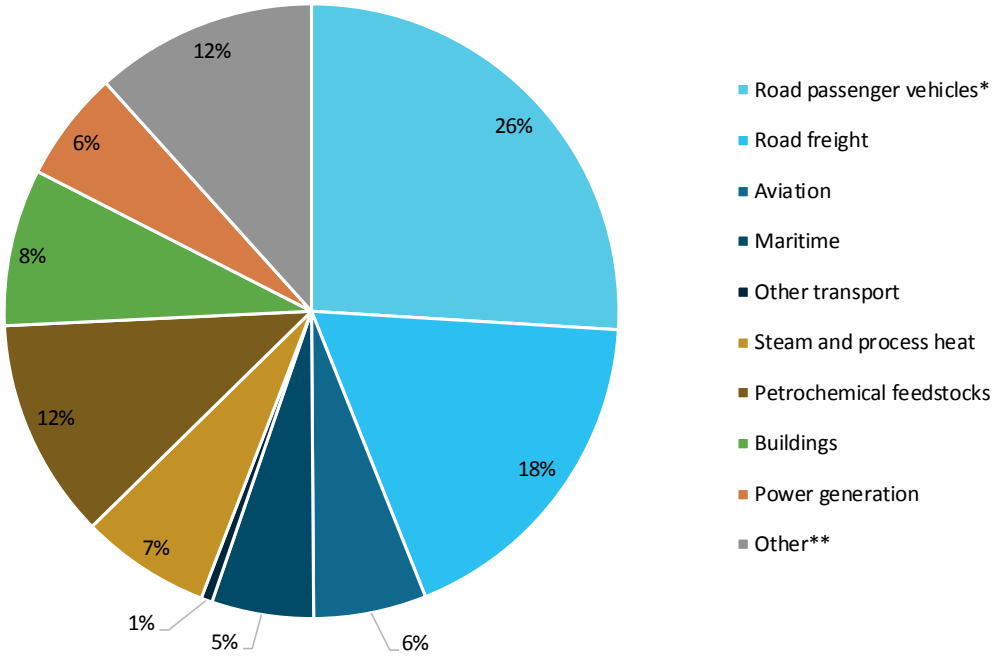
fuel demand primarily takes the form of petroleum-derived fuels, which account for more than 97% of sectoral final energy. This makes road freight transport an important contributor to global oil demand growth: since 2000, oil use from road freight vehicles has grown by nearly 6 million barrel per day (mb/d) to close to 17 mb/d in 2015, accounting for more than 35% of the net increase in global oil demand over that period. Today, oil demand from global road freight transport is roughly equivalent to that of the global industry sector (which is 17 mb/d when including feedstocks) and three-quarters the total oil demand from passenger light-duty vehicles (PLDVs) (Figure 1). Road freight transport is the primary user of diesel among all energy sectors: 84% (or 14 mb/d) of all oil products used in the sector are diesel fuels, which means that about half of global diesel demand is from road freight transport. Road freight transport alone accounted for 80% of the global net increase in diesel demand since 2000.

Figure 1 • Sectoral consumption of oil in 2015 (mb/d, primary energy)



* Passenger vehicles include buses and two- and three-wheelers.

** Includes agriculture, transformation and other non-energy use (mainly bitumen and lubricants).

Note: The percentages show the shares of oil consumption in 2015.

Source: IEA (2016a).

The use of gasoline plays a much smaller role in road freight transport and is largely confined to light commercial vehicles (LCVs); about two-thirds of gasoline use in road freight vehicles is linked to this segment. At 2.6 mb/d, gasoline demand from road freight vehicles constitutes 13% of global automotive gasoline demand. The share of gasoline use in road freight oil demand gets smaller as the size of the trucks increases. For HFTs, nearly all oil use is diesel-based due to the higher energy density of the fuel and the efficiency of diesel engines in heavy-duty applications.

Among countries, the United States is by some distance the largest market for road freight oil use, consuming around 3.3 mb/d of oil-based fuels for road freight transport, about one-fifth of the global total. Around 73% of US road freight oil use is diesel. The share of gasoline in Canada, Mexico and the United States, which is higher in each of these countries than one-quarter, is disproportionally high compared with that of most other industrialised European and Asian countries (where the shares range from less than 1% to 23% in Japan), reflecting these countries' large LCV fleets. The European Union uses about 2.1 mb/d (13% of the global total), practically all

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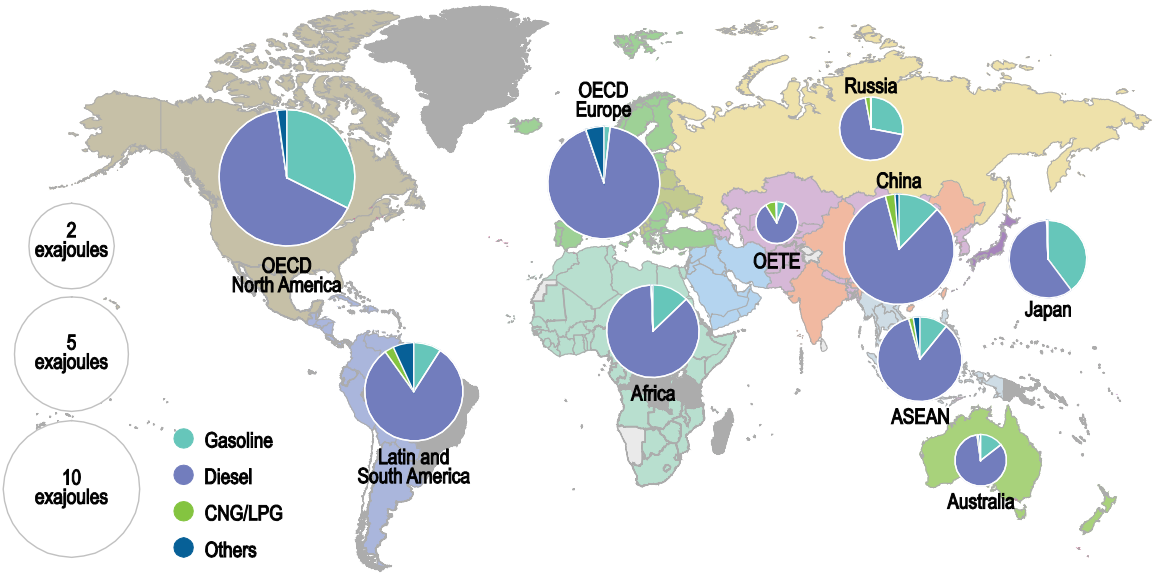
of which is diesel. At 2.1 mb/d, China's oil demand is nearly equal to the European Union's, though about 10% of this comes in the form of gasoline. India's oil demand for road freight transport has seen the largest growth among all countries since 2000, growing by a more than a factor of three. Road transport oil use in India and the Middle East has tripled since 2000 as well. Latin America and the Middle East each consumed about 1.4 mb/d in 2015, around 90% and 85% of which was diesel in each region, respectively. In Africa, the ASEAN countries and Brazil, road freight oil use has more doubled since 2000. Brazil's consumption now totals about 0.7 mb/d (about 95% diesel), while it is 0.8 mb/d in India (and nearly all diesel).

Alternative fuels so far play a minor role in supplying energy to road freight vehicles. Biofuels contribute 2.2% of final energy to road freight transport in shares that roughly mirror those of the petroleum-based fuels they substitute: biodiesel, 1.6%; ethanol, 0.6%; and biomethane, less than 0.01%. The United States and Brazil are the world's largest producers of fuel ethanol, and the two countries account for more than 80% of global fuel ethanol consumption in road freight vehicles. Biodiesel is used as a road freight transport fuel in more countries than ethanol and is most commonly used in ASEAN countries, Brazil, China, the European Union, India and the United States. Natural gas supplies the remaining 1.2% of energy to trucking. This primarily goes to dual-fuel trucks but also includes a small but growing share of trucks with engines designed to run on compressed natural gas (CNG) and liquefied natural gas (LNG). Figure 2 shows the energy consumption of gasoline and diesel in key global regions.

Figure 2 • Energy consumption of road freight vehicles, 2015



This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries, and to the name of any territory, city or area.

Note: ASEAN = Association of Southeast Asian Nations; OECD = Organisation for Economic Co-operation and Development; OETE = other European Transition Economies.

Source: IEA (2017a), Mobility Model, June 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

Carbon dioxide emissions

With its heavy reliance on oil products, road freight transport is an important contributor to global energy-related CO_2 emissions. At 2.6 Gt in 2015, direct CO_2 emissions from road freight vehicles were equivalent to more than 40% of road transport-related CO_2 emissions, around one-third of total transport-related CO_2 emissions, and about 7% of total CO_2 emissions from

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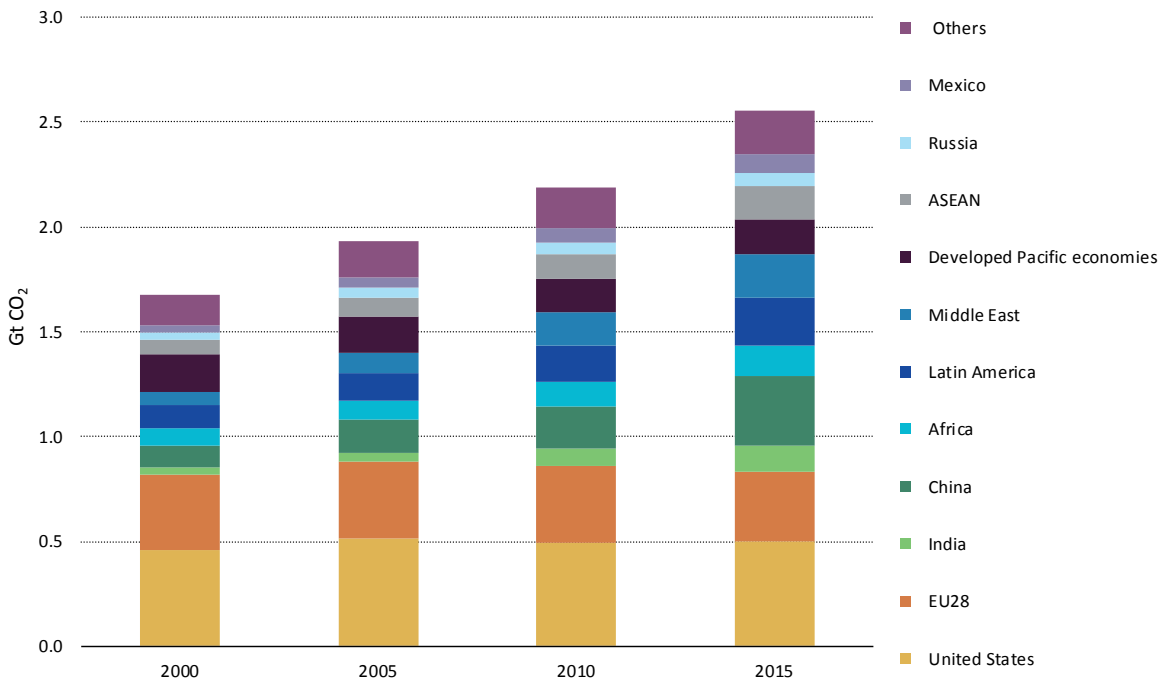
energy production and use. Road freight further accounts for 75% of all freight transport CO_2 emissions.

Over the period 2000-15, emissions from road freight vehicles rose in line with oil demand: in 2000, CO_2 emissions from road freight vehicles were only 1.7 Gt. CO_2 emissions attributable to road freight vehicles rose by 2.8% per year since 2000, and contributed to more than 40% of CO_2 emissions growth from transport and around 10% from the entire energy sector over that period. More than 90% of global emissions growth from road freight vehicles was in emerging economies, led by China (around 25%), and this growth was in parallel with their contribution to global economic growth over that period.

CO_2 emissions from road freight vehicles have grown in most countries since 2000. But their contribution to total emissions growth varies by region. In industrialised countries, road freight vehicles were the main contributor to transport-related emissions growth and bucked the wider energy trend of declining CO_2 emissions in many, but not all, of these countries. In the United States (where emissions from road freight grew by more than 50 Mt CO_2) emissions growth from road freight vehicles more than offset the decline in emissions from passenger vehicles. The rising trend of road freight vehicle emissions in the United States marks a sharp contrast to the efforts to reduce the total CO_2 emissions from fuel combustion, which fell by around 650 Mt over the same period. In developing and transition economies, emissions generally grew across all parts of the energy sector, given the economies' need to fuel economic growth and lift their populations out of poverty. Since 2000, road freight transport has contributed to 40% of the growth in CO_2 emissions from road transport in these countries and 8% to the overall growth of CO_2 emissions form fuel combustion.

Figure 3 • Tailpipe CO_2 emissions from road freight transport by region, 2000-15



Note : EU28 = European Union. Developed Pacific economies = Australia, Japan, Korea and New Zealand.
Source: IEA (2017a), Mobility Model, June 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

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The majority of the growth in direct CO_2 emissions[2] from road freight vehicles since 2000 is attributable to large trucks. HFTs contributed some 600 megatonnes (Mt) (or 65%) to global CO_2 emissions growth from road freight vehicles, and MFTs another 300 Mt (33%), partly owing to their importance in transporting goods and commodities over large distances, a key facilitator of economic activity. Although the stock of such vehicles is generally much smaller than that of LCVs (see Figure 11), their average emissions per km and annual usage tend to be higher. As a global average, the on-road emissions of HFTs are around 1 080 grammes of CO_2 per kilometre (g CO_2/km) and for MFTs some 690 g CO_2/km, while LCVs emit only around 260 g CO_2/km.

Air pollutant emissions

Air pollution is a major public health problem, and many of its root causes can be found in the energy sector. Around 6.5 million deaths are attributed each year to poor air quality, making it the world's fourth-largest threat to human health behind high blood pressure, dietary risks and smoking (IEA, 2016b). The transport sector is an important contributor, given its high reliance on the combustion of petroleum-derived fuels. For example, the transport sector contributed to more than half of global energy-related emissions of nitrogen oxides (NO_x), 12% of sulphur dioxide (SO_2), and 7% of total fine particulate matter ($PM_{2.5}$) in 2015. Road transport-related emissions of $PM_{2.5}$ are particularly detrimental to human health due to people's direct proximity and exposure to road traffic. They result both from the combustion of petroleum-derived fuels and from abrasion from the wearing and corrosion of vehicle components, road materials and safety barriers.

Road freight transport is a major contributor to transport-related pollutant emissions.[3] In the case of NO_x, road freight vehicles contribute more than one-third of total transport-related emissions. For $PM_{2.5}$ emissions, they account for nearly half of total transport-related emissions. For SO_2, the share is much lower, at 4% of transport-related emissions, largely because fuel quality standards for automotive diesel fuel mandate low concentrations of sulphur in most countries and because emissions from international shipping are much larger. In addition to the fact that diesel engine exhaust emissions are recognised as carcinogenic (IARC, 2012), emissions from diesel-powered transport refrigeration units (including both fresh and cryogenic cold storage) on trucks are often unregulated and in many cases (such as in the European Union) make up a high share of particulate emissions.

Policy makers in many countries have been active in limiting air pollutant emissions from heavy-duty as well as light-duty vehicles (Figure 4). If implemented, the most stringent standards (including those adopted by the European Union, Japan or the United States) can substantially reduce combustion-related air pollutant emissions from road freight transport, with potential spillovers for other energy policy goals.

[2] In this introductory chapter, all reported CO2 emissions are from vehicle tailpipes emitted as a result of fuel combustion. These emissions are also called "tank-to-wheel" (TTW) emissions. In Chapter 2, well-to-tank (WTT) emissions are included in the analysis of the life cycle emissions of various alternative transport fuels.

[3] Despite its significance in terms of absolute emissions, the link between the amount of air pollutant emissions from road freight transport and human health is not clear-cut. For example, although HFTs and MFTs are the largest contributors to road freight pollutant emissions, the majority of their travel occurs outside densely populated urban areas, which means that human exposure is more limited than in the case of passenger cars. Nevertheless, in many regions where population density is high even outside of major cities or along main freight corridors, the health impacts of truck pollutant emissions are severe.

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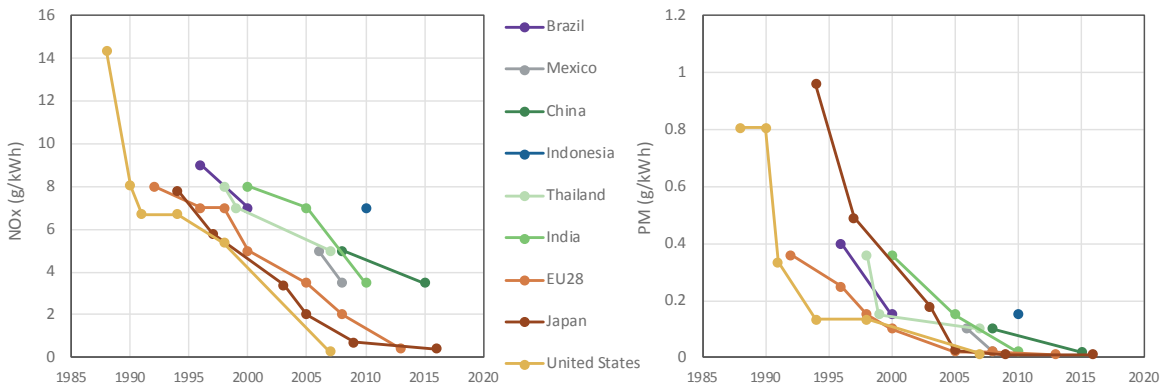
Figure 4 • Tightening of selected emission standards on trucks, by country



Note: Other countries with pollutant emission standards for trucks in the range of those shown here include Argentina, Australia, Chile and Korea.

Source: ICCT and DieselNet (2016).

Drivers of road freight activity

The activity of road freight transport is broadly linked to economic growth, given the sector's critical role for economic activity. But it also relates to a number of other factors, such as the relative quality and availability of road, rail and shipping infrastructure, which impact the costs and ease of using each of these modes. For the purpose of this report, the IEA has undertaken a major effort to review and extend its database of these drivers (Box 2). In the following section, we present and discuss some of the main findings.

Road freight activity and economic growth

The activity of on-road freight vehicles is typically measured in tonne-kilometres (tkm).[4] Activity has increased rapidly over the past few decades in many countries. In the United States, for example, on-road freight goods movement nearly doubled between 1980 and 2010 (Bureau of Transportation Statistics, 2016). In the European Union, road freight activity has grown nearly four-fold over the past three decades. Meanwhile in India, according to official data, activity increased by more than ten-fold over the same period (Ministry of Road Transport and Highways, 2009, 2016). In China, estimated activity growth of more than thirty-fold occurred between 1975 and 2015.[5] Figure 5 shows the estimates of total road freight activity (including LCVs, MFTs and HFTs) derived in the Mobility Model from 1990 to 2015.

[4] A tonne-kilometre (or tonne-mile) is the standard unit of measure for freight activity and is the transport of 1 t of cargo (which typically includes pallets and packaging as well as products) over 1 km.

[5] These are the values reported by national statistical agencies. The surveys used to collect these values have been periodically updated to improve the coverage and reliability of freight activity, and so values from earlier years are more likely to be inaccurate or biased compared with more recent published values.

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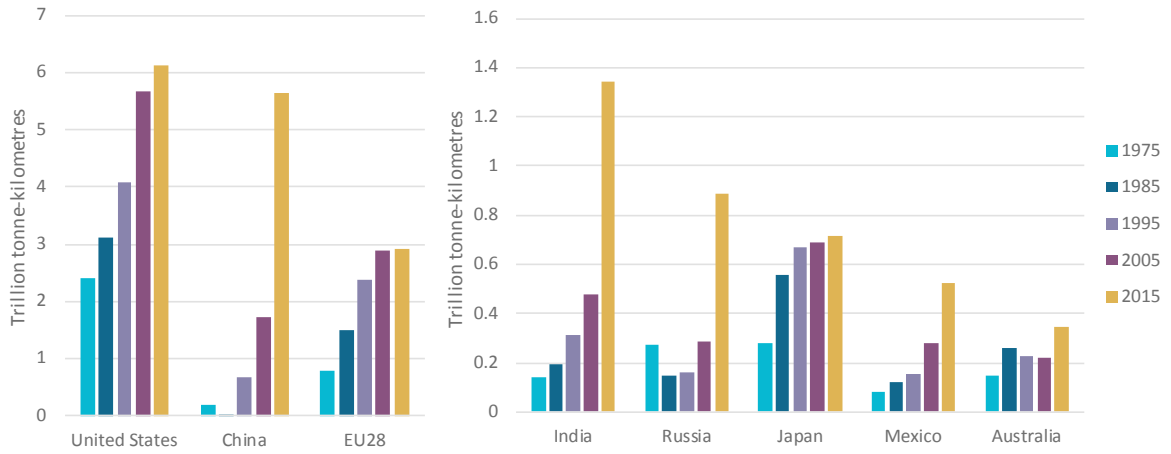
Figure 5 • Road freight activity in selected countries and regions, 1990-2015.



Note: Road freight activity is extrapolated based on national and regional data sources and calibrated using the IEA Mobility Model. The calibration is based primarily using data on vehicle sales, stocks, mileage, energy use per vkm and total energy demand, complemented by information on loads (including empty runs and laden trips with partial capacity utilisation). Vehicle mileages are the parameter with the greatest uncertainty in terms of data quality and reliability. This bottom-up approach, mainly focused on vehicles and energy, leads to estimations of total tkm that differ substantially from official statistics, especially in China, where official statistics report higher tkm values, and in the European Union, where Eurostat data provide lower tkm estimates.

Sources: IEA (2017a), Mobility Model, June 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport; analysis and elaboration based on national and regional data sources: Department of Infrastructure and Regional Development, Australia (2013); National Bureau of Statistics, China (2015); Ministry of Road Transport and Highways, India (2016); Japan Statistics Bureau (2014); FSSS, Russia, (2016); Bureau of Transportation Statistics, United States (2016); Eurostat, EU28 (2016).

In emerging countries in particular, growth in on-road freight activity accelerated as demand for consumer and industrial goods increased. A number of factors drove the impressive acceleration observed in China and India (and also across the ASEAN region) in the past decade. The main ones are summarised below:

- the globalisation of production activities and supply chains, closely interlinked with the rapid industrialisation and economic development that took place in South and East Asia
- the global nature of raw material markets and their uneven geographical distribution, requiring the transportation of goods to and from ports located along the coasts and clusters of industrial and economic development (often located near metropolitan areas)
- the strong export-oriented nature of the economic growth in these countries, which required the movement of goods to ports and other infrastructures serving global trade.

The above factors will continue to influence future activity demand for the services provided by the road freight sector. Overall, the nexus between goods movement on one hand and economic development on the other is corroborated by the fact that increases in road freight activity appear to be closely linked with economic growth in all major economies (Figure 6).

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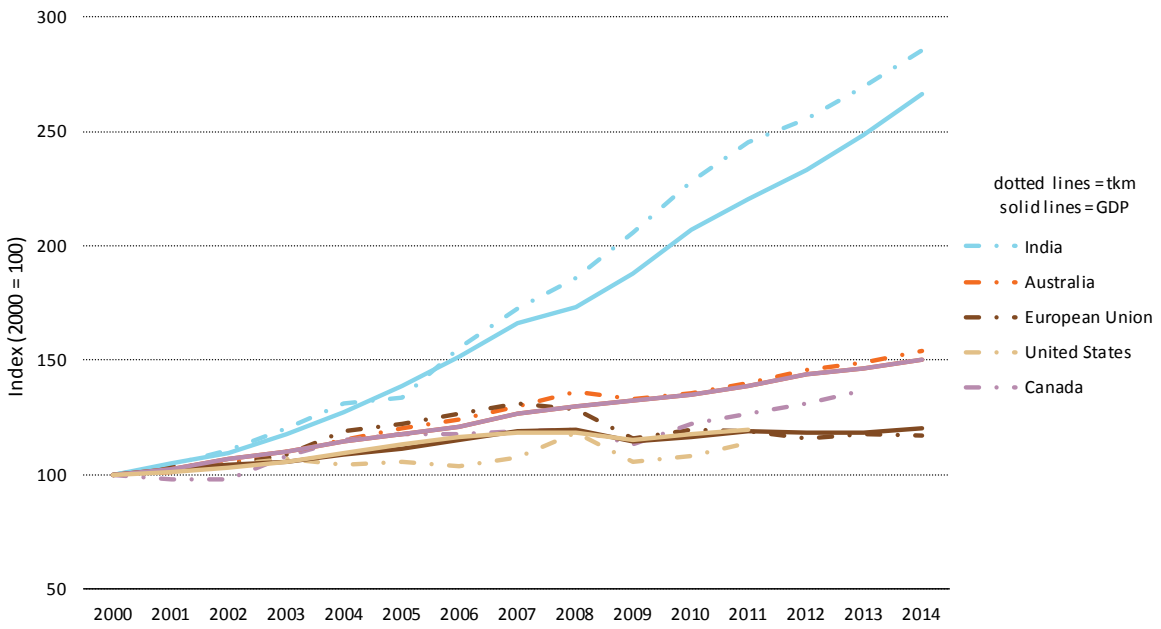
Figure 6 • Indexed evolution of road freight activity versus gross domestic product in selected regions

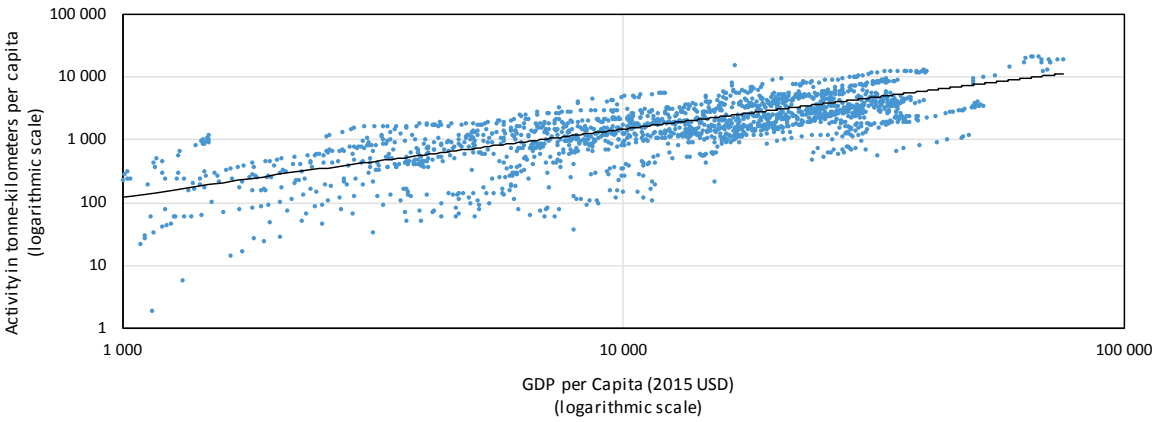


Note: GDP = gross domestic product.

Sources: Department of Infrastructure and Regional Development (2013); NATS (2016); Eurostat (2016); Japan Statistics Bureau (2014); Bureau of Transportation Statistics (2016); Ministry of Road Transport & Highways (2016); World Bank (2016); OECD (2016); IEA (2016c).

Regressions of country- and regional-level GDP per capita with per capita levels of the road freight activity of heavy-duty trucks (i.e. HFTs and MFTs) measured in tkm show that the global long-run elasticity of per capita freight activity to GDP per capita (shown in Figure 7),[6] is slightly above unity (1.07), meaning that for every 1% increase in GDP per capita, tkm per capita increases by 1.07% on average.

Figure 7 • Road freight activity (tkm per capita) plotted against GDP per capita



Sources: National Bureau of Statistics China (2015); Ministry of Road Transport & Highways (2016); Japan Statistics Bureau (2014); North American Transportation Statistics; Federal State Statistics Service; Bureau of Transportation Statistics (2016); Eurostat (2015); OECD (2016); The World Bank (2016); Afghanistan Ministry of Transport and Civil Aviation; Australia Department of Infrastructure and Transport (2011); Inter-American Development Bank (2015); General Statistics Office of Viet Nam (2016); Lao Statistics Bureau (2015); Department of Infrastructure and Transport (2011).

[6] This result is based upon observations covering the period 1971 to 2014 and countries specified in the sources of the figure.

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There is growing attention to the possibility that road freight activity might sooner or later start to decouple from economic growth. This suggests that at high income levels, economic growth might not require commensurate growth in freight activity, but that activity might instead level off or decrease at high levels of GDP per capita. Indeed, there are a few cases that seem to indicate that this decoupling might have begun in some developed countries.

- In *Japan*, for example, actually declined between 2005 and 2015 (Japan Statistical Yearbook, 2011, 2017). This was partly due to stagnating economic growth during the mid-1990s following the economic collapse but was also attributable to improvements in domestic logistics and operations. Road networks were designed to simplify the procedural routine of issuing passage permits for large-sized vehicles, and smart logistics management was promoted to improve freight logistics (Ministry of Land, Infrastructure, Transport and Tourism, 2015, cited in Taniguchi, 2015). Furthermore, the modal share of rail increased slightly over the period following privatisation of the rail network.
- Between 2005 and 2015, official statistics indicate a potential decoupling across various *member states of the European Union* (Eurostat, 2016). In certain countries (including France, Germany and the United Kingdom) over some periods, tkm has stagnated or declined even as GDP has continued to grow. Due to the low rates of GDP growth and brief periods of tkm decline, detailed statistical analysis of national trends and their causes is needed to provide further evidence of decoupling.
- In the *United Kingdom*, there is evidence that freight activity remained flat from 1997-2004 while the economy grew (McKinnon, 2007). Most of this apparent decoupling could be attributed to the growing presence of foreign firms in the United Kingdom's road freight, a decline in road freight's share of overall freight activity (i.e. a modal shift) and increasing prices for road freight services. Other possible factors include the shift in the share of gross value added to overall GDP from manufacturing to services, off-shoring to Eastern Europe and Asia, and the shift to larger vehicles (including double-deck trailers). Sorrell et al. (2012) additionally suggest that the decoupling of road freight energy use and emissions (not activity) during 1989-2004 was the result of logistics improvements that resulted in more efficient operations, and they emphasise the fact that economic trends rather than government policy were the primary causes.
- *Spain* and the *United States* also witnessed a decoupling of economic growth and road freight activity (Alises, Vassalo and Guzmán, 2014; Caid, 2004). Just as in the United Kingdom, the decoupling can mainly be attributed to the growth in the share of services to value added, although, in the case of Spain, decoupling was found to be less pronounced due to less marked improvements in logistics and supply chain management than in the United Kingdom.
- On a global scale, and looking at historical developments, this report does not find strong evidence that decoupling is occurring, corroborating the findings of Eom et al. (2012) and DeJong (2016). Despite this finding, the projections adopted here do take into account a slight degree of decoupling, occurring only at high-income levels, in order to reflect the growth of economic output imputable to services and the declining share in value added of freight transport-intensive economic sectors like industry and agriculture.[7] This is also consistent with policy efforts that aim to facilitate such decoupling. The European Union, for example, set the objective of decoupling freight activity from GDP in its transport and environment integration strategy in the late 1990s as a means of promoting a more efficient

[7] This takes into account the fact that the sectors of the economies primarily focused on the exchange of goods – such as agriculture, mining, construction or industrial manufacturing – demand more tonne-kilometres in their production processes than economic activities focused on the exchange of services.

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mechanism for freight transportation. More recently, the European Union adopted long-term targets to shift 30% of road freight goods movements over 300 km to other modes by 2030 and 50% by 2050 (EC, 2011).

Vehicle activity, loads and mileages

Vehicle movements must accommodate the increasing demand for the movement of goods on road networks. These are typically measured in vehicle-kilometres (vkm), a metric that measures the total annual distance covered by a given fleet.

Given the limited availability of vkm statistics (the subset of countries that report annual vkm data is much smaller than those that report tkm), vehicle activity is more difficult to estimate at a global level. Despite data availability limitations, regressions of vkm per capita and GDP per capita clearly confirm that vehicle activity grows with rising incomes.

Assumptions and estimations help to overcome some of the data limitations. Vehicle activity at the country and regional levels was evaluated here based on the ratio of tkm and average vehicle load (expressed in tkm/vkm), building on the available statistics on tkm and on an assessment of the representative loads for each truck category (LCVs, MFTs and HFTs). All representative loads include empty running (when the vehicle is travelling without any payload):

- LCVs, primarily used for last-mile deliveries, are assumed to operate with an average load of 0.5 t. This is consistent with load carrying capacities in the range of 1 t to 2 t, shares of empty running in the 40% to 60% range and capacity utilisation rates on laden trips in the 50% to 60% range.
- MFT loads are assumed to range between 4 t and 10 t and to decline with increasing income (Figure 8, left). This assessment builds on indications derived from surveys that focus on truck loads in developing regions (Grütter, 2016) and statistics on loads and gross vehicle weight published for OECD countries, including data for the United States (BTS, 2016) and countries in the European Union (Eurostat, 2016).
- Loads for HFTs are assumed to fall in the 12 t to 16 t range. These loads are also assumed to rise with income, reflecting the evolution of gross vehicle weights with income growth observed in the European Union (Figure 8, right, right, based on Eurostat [2016]). This is consistent with a shift to tractor-trailers and combination trucks in high-income countries (over rigid trucks), the relaxation of constraints on longer and heavier vehicles, and road network improvements.[8]

[8] The growing relevance of HFTs with income growth (as discussed in the section on vehicle stocks) and the assumptions used for HFTs (as discussed in the following bullet) suggest that these observations do not conflict with the decline in empty running or the increasing average payload weight on laden trips that have been observed in European statistics (IEA, 2009). On the other hand, growth in just-in-time delivery has resulted in lower vehicle load factors in many freight subsectors. Moreover, average load factors must account for the differences in the average density of the product mixes transported as vehicle utilisation is typically measured solely in terms of weight rather than volume.

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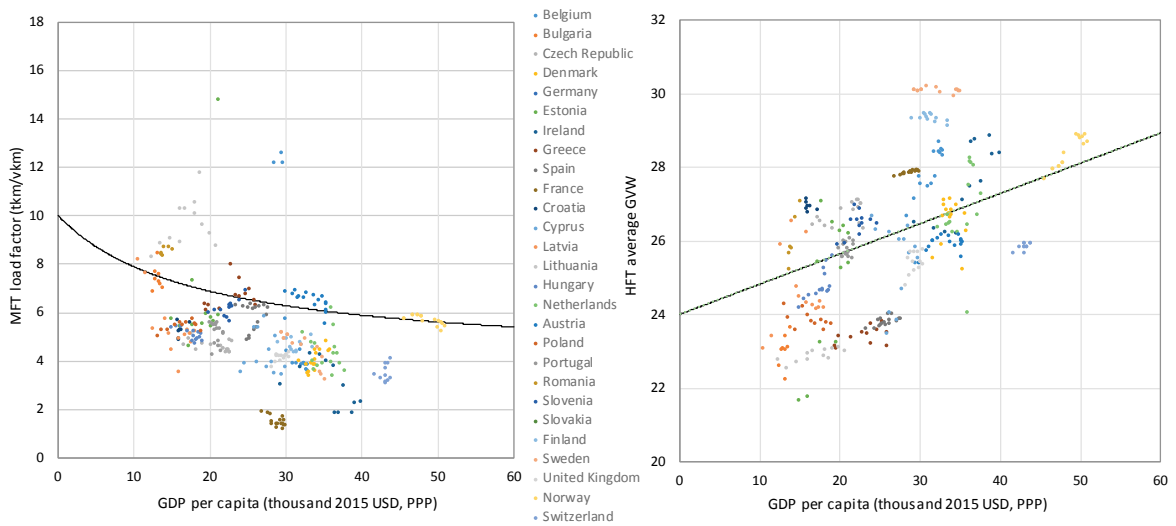
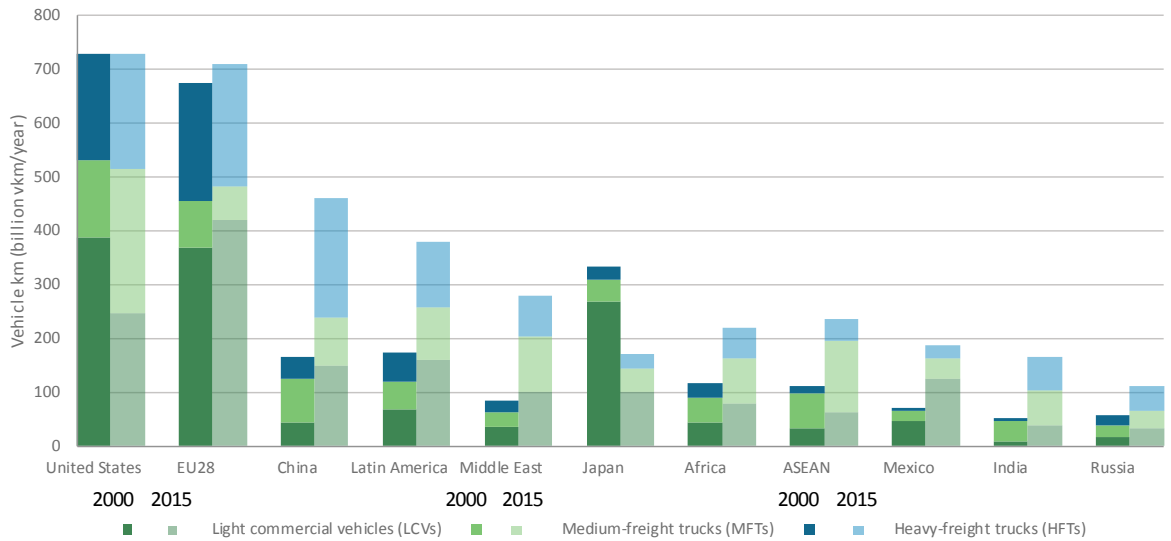
Figure 8 • Evolution of MFT loads and the gross vehicle weight of HFTs versus income in selected countries



Sources: Grütter (2016); BTS (2016); Eurostat (2016).

Figure 9 provides an overview of the resulting vkm across the main global regions and modes. In 2015, the United States, the European Union and China were the regions with most road freight vehicle activity (in order of decreasing activity), followed by Latin America and a cluster of other regions.

Figure 9 • Evolution of annual vkm by mode in the main global regions, 2000-15



Source: IEA (2017a), Mobility Model, June 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport.

All regions that experienced strong economic growth over the past 15 years also saw their vehicle activity increase significantly. The strongest growth took place in China, where the increase in vkm from 2000 to 2015 exceeded the total vehicle activity of the Middle East in 2015. Other regions with remarkable increases in road freight vkm include Latin America, the Middle East, ASEAN, Mexico, India and Africa (in order of decreasing total activity increase over the 15 year

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period). In all of these regions, the increase in road freight vkm between 2000 and 2015 exceeded the total vkm of the Russian Federation (hereafter, "Russia") in 2015.

LCVs are the most relevant vehicle category when looking at modal shares of vkm activity due to their large share in the global road freight vehicle stock (for a more detailed discussion of this, see the vehicle stock section). LCVs account for large shares in terms of both stock and vkm, particularly in developed global regions, including Japan, the European Union and the United States. HFTs also account for sizeable shares of vehicle activity, despite much lower shares in the global vehicle fleet, primarily because of their much greater frequency of use in regional and long-haul missions and the higher mileages resulting from this usage pattern.

Vehicle activity also reflects differences in average annual vehicle mileages across all regions. The mileage estimates used here result from an effort to rationalise and calibrate national and regional data. Links between (bottom-up) vehicle sales and (top-down) energy use are established through survival rates, stocks, mileages, vkm and fuel economies, and with (top-down) tkm (linked to vkm by the share of empty running and average load on laden trips), further detailed in Box 2.

Box 2 • Creating a coherent global dataset of historical road freight activity

For the purpose of this report, data and projections related to road freight activity in the IEA Mobility Model (MoMo) were revised and updated. The update uses official estimates and other publicly available statistics on road freight transport activity (expressed in tkm and vkm as well as vehicle stock and sales (the latter of which are collected, checked for internal consistency and harmonised with MoMo definitions annually).

Data were collected from a wide range of publicly available sources to construct a global dataset of historical road freight activity across as many regions as possible. However, there is a lack of publicly available data on freight activity across most developing regions, especially for Africa, the Middle East, and the non-European Union Eastern Europe/Eurasia region. Although OECD members and other countries report estimates of domestic activity in tkm on an annual basis, the methods for estimating road freight activity are not uniform across countries and are subject to revision. China, for example, substantially revised the methods and coverage of its on-road freight survey in 1985 and again in 2008, as is evident in the periodic jumps in those years (Figure 5).

The disaggregation of tkm data by truck size class (either on a kerb-weight or gross vehicle weight [GVW] basis), as well as by commodity, is reported only in the European Union, the United States and a few other countries. The availability of national data on vehicle stocks, annual average mileage and the product of the two (vkm) is even more limited than tkm data.

Data availability limitations required the use of estimations for determining the key parameters for the information flow that links vehicle sales with energy use (through survival rates, stocks, mileages, vkm and fuel economies) and tkm (linked to vkm by the share of empty running and average load on laden trips). Estimations of the fuel economies for LCVs, MFTs and HFTs relied primarily on research on tested and real-world specific fuel consumption under various drive cycles, vehicle loads and mission profiles, largely leveraging on the analysis recently developed by the ICCT for the Global Fuel Economy Initiative (GFEI, 2016), complemented by information on the fuel consumption of vehicles reported by communities of vehicle users, such as those reviewed by Tietge et al. (2015) in the case of cars. Surveys focused on developing regions (Grütter, 2016) and available data points from the United States (BTS, 2016) and the European Union (Eurostat, 2016) were also reviewed to estimate gross vehicle weights and average truck loads within each truck segment by country, region and across varying income ranges. This information was then used as the basis for defining the average loads of medium- and heavy-freight trucks as functions of income and used to estimate the loads.

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Table 3 • Average mileages in thousand kilometres of annual travel for the main road freight vehicle categories in selected global regions, 2015

Country/Region	LCVs	MFTs	HFTs
Africa	9	18	29
ASEAN	11	39	47
China	8	25	36
EU28	18	51	73
India	9	29	38
Japan	9	31	43
Latin America	11	30	51
Mexico	17	50	69
Middle East	15	47	59
Russia	12	36	50
United States	20	63	90
World average	***13***	***37***	***52***

Notes: Average mileages are estimated on the basis of calibration across many variables, including national automotive gasoline and diesel consumption as estimated in the IEA Energy Balances (IEA, 2017b) as well as national and regional statistics on truck stocks, sales and road freight activity (vkm and tkm). The resulting estimates are for the average mileage of each truck category over its entire lifetime and, as such, are lower than the mileages in the first two to five years of operation (especially for HFTs).

Source: IEA (2017a), Mobility Model, June 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport.

Despite the need for some degree of adjustment in each region and road freight vehicle category to calibrate between bottom-up and top-down (namely, fuel use and tkm) parameters, this assessment broadly reflects the influence of road network conditions and regional characteristics in determining the distance between the origin and destination of hauls, and hence on average mileage. Key reasons for these dependencies include:

- Road quality and the degree of development of highway networks influence travel speed. Travel time constraints for each vehicle class are unlikely to vary significantly across regions (except for differences due to the average length of haul, discussed in the next bullet, vehicles performing similar missions need to be loaded and unloaded for similar amounts of time across all global regions, and travel mostly during day time). As a result, countries with poorer road quality and less developed highway networks are likely to have lower truck mileages.
- The distance between the origin and destination of hauls is typically longer in large countries with long distances between cities and agricultural and industrial regions, in regions with lower population densities, and in regions where there are limited opportunities to substitute road transport with rail (e.g. because of the lack of a developed railway network), pipelines or shipping (e.g. in landlocked countries). Longer travel distances generally imply a decrease in the ratio of loading and unloading time relative to the times that a vehicle is being driven – this is especially relevant for HFTs, which are most frequently used for long-haul deliveries. Despite some differences in average speeds due to the nature of the road network, this increased time on the road implies higher mileages.

Regions with long freight transport hauls also tend to apply lower fuel taxes: in most middle- and high-income countries, low fuel taxes are coherent with expectations of higher mileages. Figure 10 compares mileage estimates across a cluster of major high-income countries (Australia, Canada, France, Germany, Italy, Japan, Korea, the United Kingdom and the United States) for

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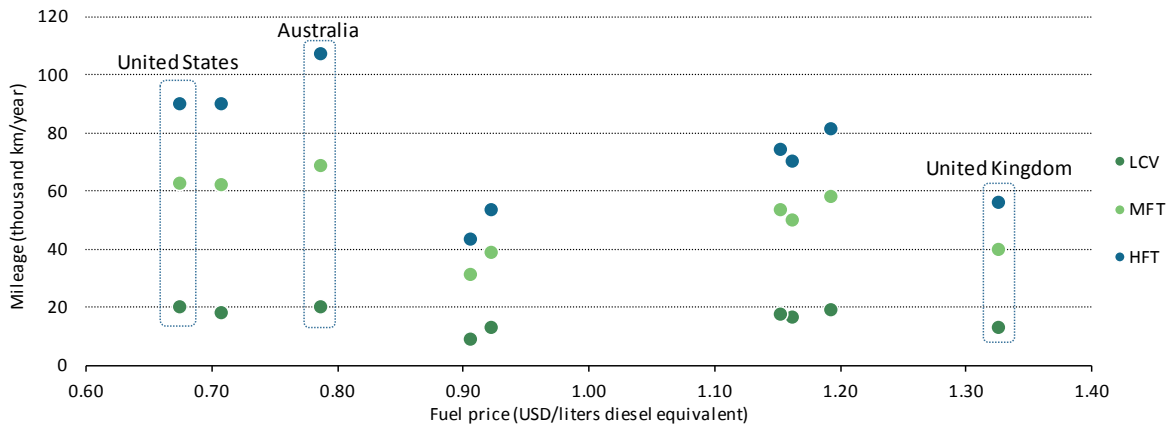
LCVs, MFTs and HFTs, together with the associated average fuel prices (which tend to depend in a large part on the fuel taxation regime).

Figure 10 • Mileage by truck category versus fuel price for high-income countries, 2015

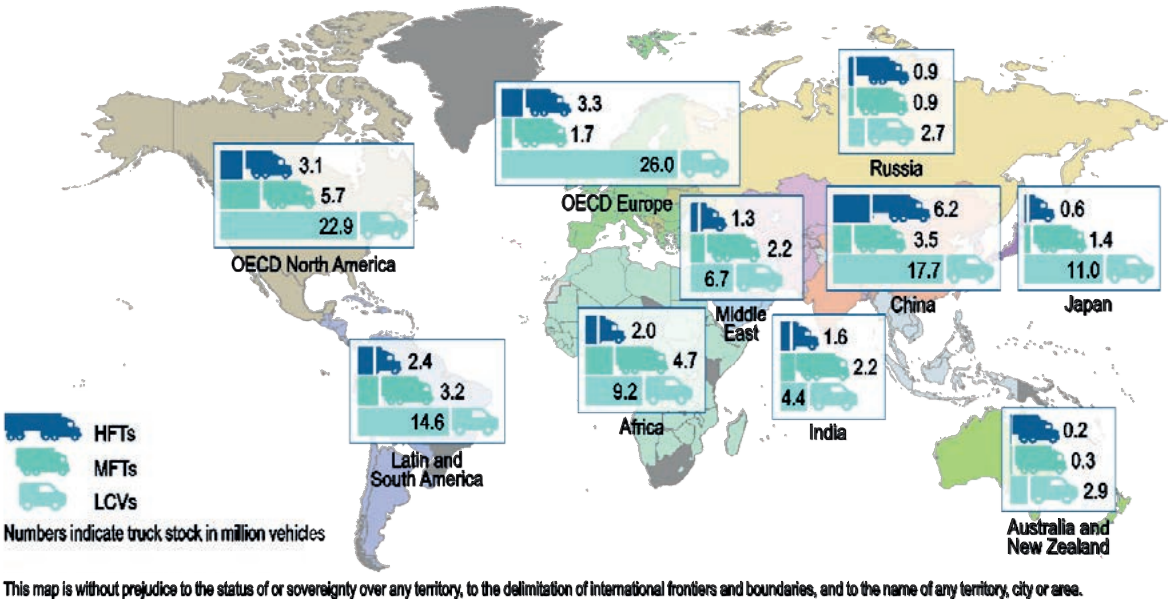


Source: IEA (2017a), Mobility Model, June 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport.

Vehicle stocks

The global fleet of trucks operating in 2015 was dominated by LCVs, which, at more than 130 million vehicles, made up 70% of the truck stock. MFTs totalled nearly 32 million vehicles (17% of the fleet), and 24 million HFTs comprised the remaining 13% of trucks. Comparing stock sizes across the main global regions shows that in 2015, the European Union had the largest truck fleet, with nearly 28 million trucks. The next biggest fleets were in China (more than 27 million trucks), the United States (19 million trucks) and Japan (13 million trucks) (Figure 11).

Figure 11 • Global stock of road freight vehicles, 2015



Source: IEA (2017a), Mobility Model, June 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

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Truck stock shares by category do not vary uniformly across income levels:

- LCV ownership is lowest at incomes lower than United States dollars 10 000 (USD) per capita, grows with increasing income, and tends to stabilise, once incomes exceed USD 30 000 per capita, at ownership rates around one-tenth of those observed for passenger light-duty vehicles (PLDVs).
- MFT shares in total HDV truck stocks (which include MFTs and HFTs) are highest in low-income countries where LCV ownership is very low, and the quality of the road network constrains the use of heavy-duty trucks except for very specific routes (e.g. highways and main trunk roads) and services. In low-income countries in the early stages of industrialisation (such as many African countries), the use of road vehicles starts from heavy-duty trucks (i.e. MFTs and HFTs) for heavy industry, often oriented towards the export market (e.g. mining, raw material and energy resource extraction). Consequently, the stock share of LCVs in such countries is very low.
- MFT shares tend to decline once the average income ranges between USD 10 000 to USD 30 000 per capita, at levels that correspond with the rise of LCV ownership (partly displacing activities that were delivered by MFTs). Both the development of highway networks and the development of logistics allow for a greater reliance on HFTs.
- HFT stock shares remain low, compared with LCV and MFT stocks, across all income levels, but HFT stock shares grow marginally with rising income. As economies develop, so do the quality of their highway networks and supply chain and logistic systems. This increases the potential to rely on rigid trucks and tractor-trailers for regional and long-haul goods transport as well as a shift within the HFT segment from rigid to articulated trucks (tractor-trailers).
- In addition, many other factors influence the size and distribution of truck stocks. These include: geography; population density and distance among many centres of raw material production, industrial processing and consumption; the level and rate of urbanisation; country size; the share of light and heavy industry, services, and agriculture in the economy; the development of the railway sector; and regulations and restrictions on trucking, rail and inland freight.

Regional differences also suggest that global regions with higher urbanisation rates and high densities (such as Japan) tend to rely more on LCVs than MFTs. LCV shares are also higher in countries with large numbers of pick-up trucks in their vehicle fleet (such as the United States), partly because of classification issues. Figure 12 shows stock shares of LCVs, MFTs and HFTs in a selection of countries across a wide spectrum of income levels and illustrates the observations outlined above.

Over the past 15 years, MFT and HFT stocks have grown rapidly in Africa, ASEAN, China, India, Latin America and the Middle East, accompanying rising GDP in these countries and regions. The growth was more significant for MFTs in China, ASEAN member countries, and in Africa.

Truck stocks grew more moderately in developed countries. In Canada and the European Union, the HFT stock grew more than the MFT stock, while in Japan and the United States, the number of MFTs and HFTs on the road increased very little between 2000 and 2015.

Overall, the expansion of road freight activity that accompanied rapid economic growth led to rapid growth in HDV truck stocks. In those countries with a lower availability of high-quality road infrastructure, much of the growth in heavy-duty stocks was in MFTs.

The average scrappage age of trucks is generally higher in developing regions than in developed regions, reflecting constrained access to finance – which implies the sale of cheaper vehicles with reduced performance in terms of durability, power and fuel economy – in a highly fragmented

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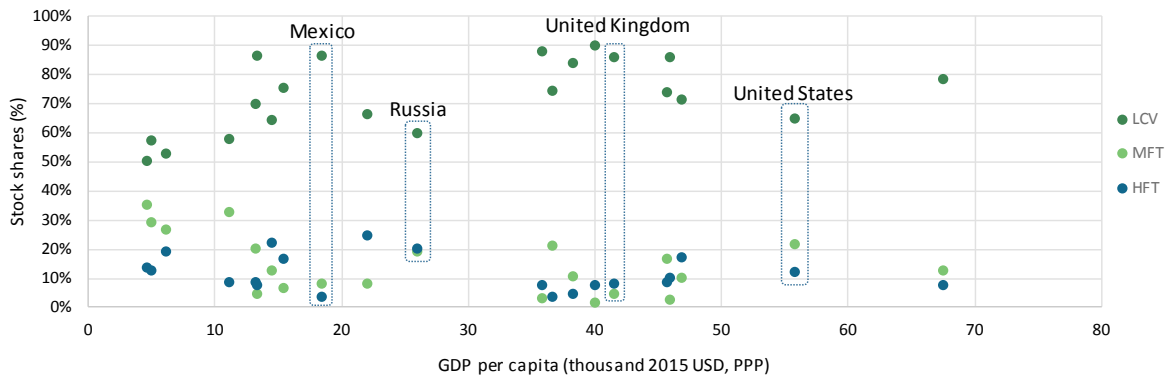
industry. Despite this, the average age of the vehicle stock may, however, be lower in developing regions due to the rapid increases in annual sales over time.

Figure 12 • Stock shares of LCVs, MFTs and HFTs in selected countries and regions, plotted against income



Source: IEA (2017a), Mobility Model, June 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport.

Vehicle stock distributions also reflect different vehicle usage cycles. In regions with greater access to borrowed capital, the typical usage distribution profile foresees the prioritisation of fairly new trucks (up to five years old) for long-distance operations (and therefore coupled with higher mileages). These vehicles are then typically sold to second owners for regional operations and are operated at decreasing annual mileages over time. Older trucks are also sometimes exported to nearby markets in emerging and developing countries. The main second-hand vehicle trade flows occur between the United States and Mexico, Japan and other countries in Asia and Africa that drive on the left-hand side of the road, across Europe (from west to east and from north to south) and from the European Union to African countries and countries in the Middle East that drive on the right.

Sales of new heavy-duty trucks

Globally, sales of small trucks (LCVs) are more than twice those of heavy-duty trucks (MFTs and HFTs) combined. Between MFTs and HFTs, global sales shares are roughly evenly distributed, but with substantial variation at the national and regional levels. In 2015, MFTs constituted about one-fifth of heavy-duty trucks sold in the EU market; in the United States, the split was 50:50; and across the ASEAN member states the MFT sales share in heavy-duty trucks (MFTs and HFTs) was about three-quarters of total sales. Due to the differences in national and regional classification frameworks (see Box 1) as well as the fact that MFTs and HFTs make up the largest share of road freight activity and energy use, this section focuses only on heavy-duty (i.e. MFT and HFT) truck sales.

Global registrations of heavy-duty trucks, including both new vehicle sales and second-hand imports, have grown by about 60% since the turn of the century, from 2.7 million units sold in 2000 to nearly 4.4 million in 2015 (Figure 13). Global sales dropped by 10% during the financial crisis but rebounded sharply in the subsequent two years. China surpassed the United States and European Union as the largest global sales markets for heavy-duty trucks in 2009; indeed, while global sales decreased, China's sales grew by 75% between 2008 and 2009. In the subsequent years, China's market share continued to grow rapidly; by 2015 it accounted for 20% of new heavy-duty truck sales globally. In the European Union, new truck sales grew moderately through 2008 before plunging more than 40%; as of 2015, they had not returned to their 2000 level. While sales in the United States also plummeted by 40% during the economic crisis, rapid sales

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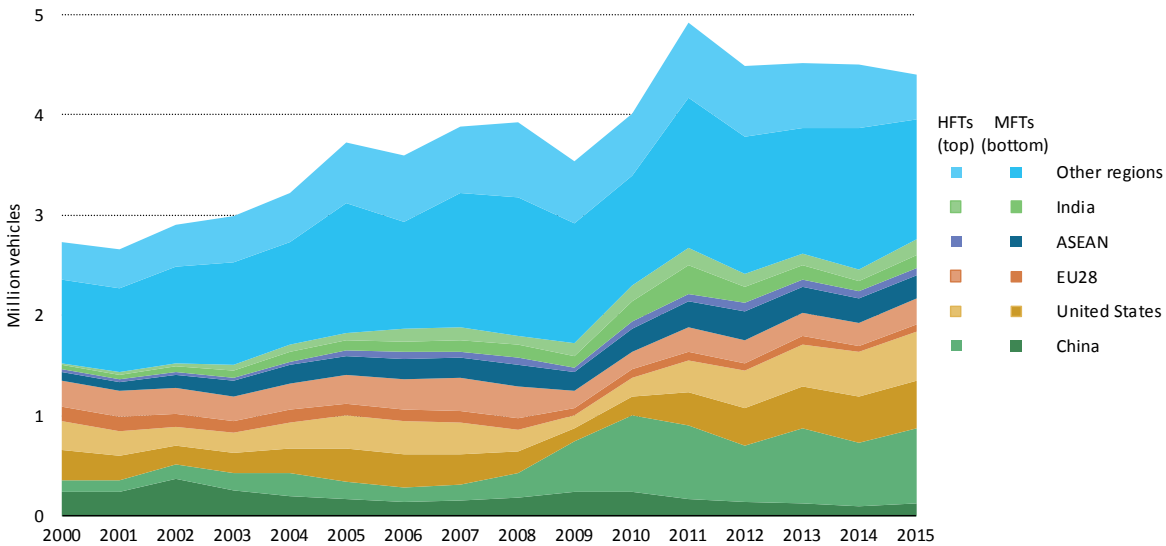
growth from around 2010 onwards led to the United States rivalling China as the world's leading heavy-duty truck market from 2012 onwards; by 2014, it had regained the title of the world's largest truck market, and in 2015 it represented about 22% of global MFT and HFT sales.

Figure 13 • Global sales of new and second-hand imported heavy-duty trucks, 2000-15



Notes: The figure includes registrations of both new vehicles and second-hand imports. Among the regions shown in the figure, imports of heavy-duty trucks are most relevant in developing and emerging countries, such as in African countries, where they made up more than three-quarters of truck sales, and Russia, where they accounted for nearly half of total truck sales in 2015.

Source: Mobility Model, June 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport/ .

By pushing strongly into the global market, particularly in emerging nations, Chinese and Indian original equipment manufacturers (OEMs) are likely to be taking a major step toward becoming globalised manufacturers. OEMs from both countries have solid positions in their domestic markets and will be able to exploit market growth in the Middle East, Africa, selected Asian countries, and Latin America. The particular focus of this expansion is on budget and "good enough" trucks.

A defining feature of the market for trucks is its regionalisation. Despite the example of the handful of manufacturers that sell heavy-duty trucks in both the North American and EU markets, to a far greater degree than in the light-duty passenger vehicle market, the dominant manufacturers are national or regional.

In the case of rigid trucks and, to a lesser extent, tractor-trailers, only one or two vehicle platforms tend to dominate the sales for each manufacturer. The engines, powertrains and other components (e.g. the axle configuration and, in the case of tractors, the trailer type) of these vehicles are then customised to meet the demands of the customer, which means that for any given vehicle platform, "hundreds or even thousands of individual variants" (Muncrief and Sharpe, 2015) operate according to specific mission profiles and applications. All major truck OEMs either source from suppliers or jointly or directly manufacture their own proprietary engines, transmissions and axles, which they then sell through contracted retailers, which offer financing and sales support (Roeth et al., 2013). In less-consolidated markets, where many smaller OEMs make trucks, the share of non-proprietary core components (including engines and powertrains) sourced directly from component suppliers is higher (Sharpe, 2015).

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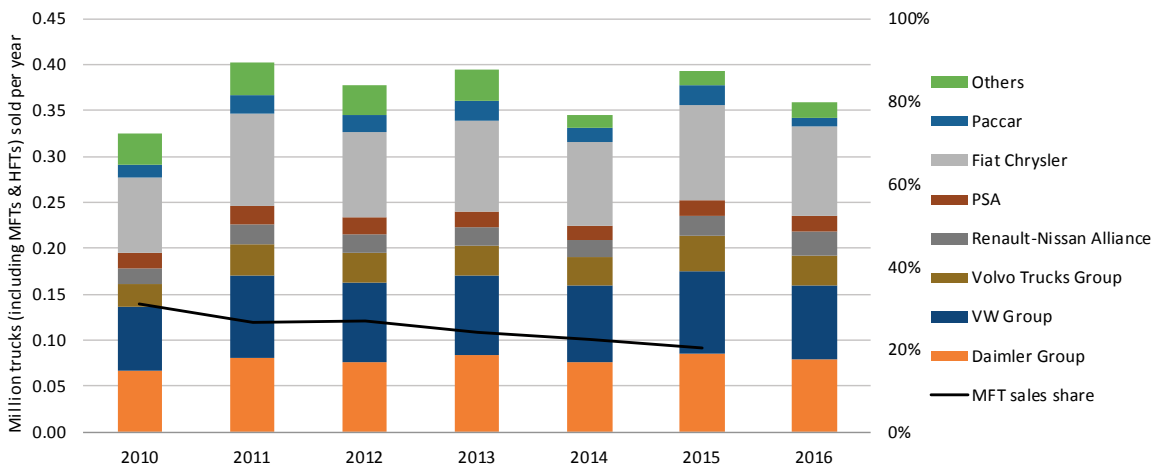
New pollutant emission and fuel economy regulations have led to an influx of new entrants, including research institutions, into the components market for car and truck manufacturing. In the trucking industry, these suppliers offer new products, including aerodynamic, advanced engine and powertrain controls, emission control and after-treatment devices, and operational telematics (Roeth et al., 2013).

Regional trends

In the *European Union*, the truck market has continued to consolidate since 2010. Four manufacturers (Daimler, VW Group, Volvo, and Renault-Nissan Alliance) made up more than 60% of the market in 2016 (Figure 14).[9] While Germany has the largest market for new truck sales, the main growth areas for road haulage are Poland and other new European Union member states (Muncrief and Sharpe, 2015).

Among HFTs, the market is split between tractor-trailers[10] and rigid trucks (also known as "straight" trucks), with annual sales of each of around 100 000 units (Muncrief and Sharpe, 2015). The greater heterogeneity in vehicle design and the range of missions of rigid trucks than tractor-trailers reflects the wider range of applications for this vehicle type. This vehicle segment accounted in 2008 for 38.5% of heavy-duty vehicle sales in the European Union (Hill et al. 2011). Sales data for tractor-trailers and rigid trucks (which constitute the two top-selling HDV vehicle segments) show a clear trend from as early as 1995 toward heavier trucks with larger and more powerful engines, converging on models similar to those sold in the United States (Hill et al. 2011).

Figure 14 • Truck sales by manufacturer in the European Union, 2010-16



Note: Sales volumes are taken from MoMo; are shares taken from Marklines vehicle sales database and include only heavy-duty trucks (buses have been removed). The Marklines database does not include sales in Croatia or Iceland. Sales for 2016 are estimates based on 2015 sales from MoMo and the sales trend between 2015 and 2016 given in Marklines. The line indicates the sales share of MFTs, which has declined slightly from 31% to 20% over the first half of this decade.

Sources: Marklines (2017); IEA (2017a), Mobility Model, June 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

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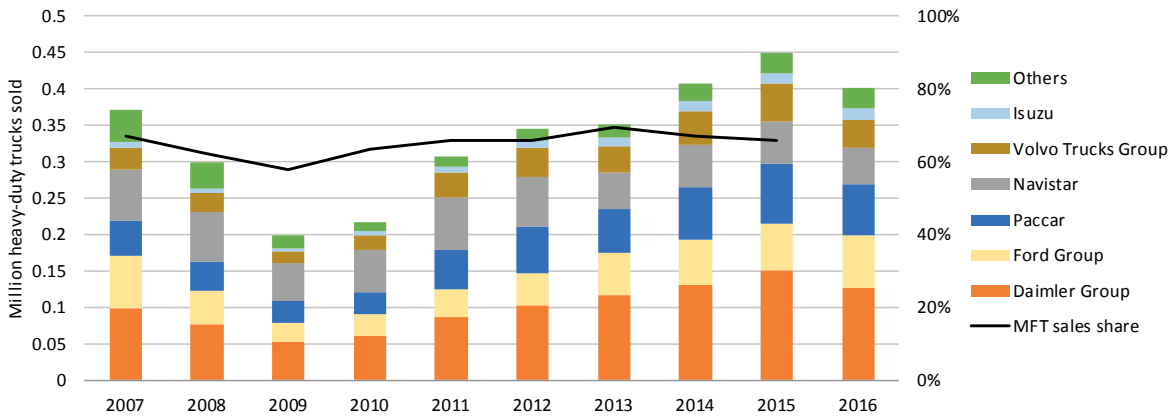
[9] Note that the country where a vehicle is sold and registered is not necessarily the same as the country where it was manufactured.

[10] Of the various tractor-trailer configurations, each of which is tailored to a specific mission type, the most common in Europe is the side-trailer curtain (Hill et al. 2011).

The United States new truck market is even more consolidated than the European Union's, although a direct comparison is difficult given the different vehicle categories. Across the wider heavy-duty truck market, many of the same manufacturers (including Daimler, Paccar and Volvo) operate both in the United States and the European Union. The market share of these three OEMs is roughly similar in the United States and in the EU, in 2016, they accounted about 40% sales in the United States, and about 35% of sales in the European Union.

In the US, medium trucks, with a GWV of 6 351 kg to 14 969 kg (classes 4-7), make up around half of total heavy-duty truck sales. The majority of HFTs (broadly the US class 8 category, i.e. trucks with a GVW of 14 969 kg) are tractor-trailers.[11] In 2014, sales of tractor-trailers (also called semis, or 18-wheelers) equalled around 139 000 units (Muncrief and Sharpe, 2015). Sales of rigid trucks in the United States are typically only slightly lower than those of tractor-trailers (Muncrief and Sharpe, 2015). In their initial years of operation, class 8 trucks are driven for long mileages of up to around 240 000 km. Thereafter, they may operate for up to 20 or more years, typically at much shorter mileages in regional operations.

Figure 15 • Sales of new medium (class 4-7) and heavy trucks (class 8) by manufacturer in the United States, 2007-16



Note: Shares are taken from Marklines vehicle sales database and include only heavy-duty trucks (buses have been removed). The US medium truck category includes only a subset of the MFT category (GVW from about 6.35-15 tonnes). By the US classification, sales shares of medium trucks dipped from 67% to 58% during the economic crisis, but have since returned to 66%.

Source: Marklines (2017).

In China, the truck manufacturing sector is far less consolidated than in the United States and the European Union, with small OEMs making up more than one-third of the market for domestically made trucks in 2016. No single manufacturer controls more than 12% of the market, and the market leaders (China FAW, China National Heavy-Duty Truck Group, Lifan Industry Group, Shaanxi Automobile Group, Dongfeng Motors and Anhui Jianghuai Automotive Group) each make up between 5% and 12% of total heavy-duty truck sales. China's sales grew fastest during the construction spurt from around 2007 to 2011 (Figure 16). The share of MFTs in China's truck sales dropped rapidly over the first decade of the 20th century and decreased from over 50% to about 15% over the past decade.

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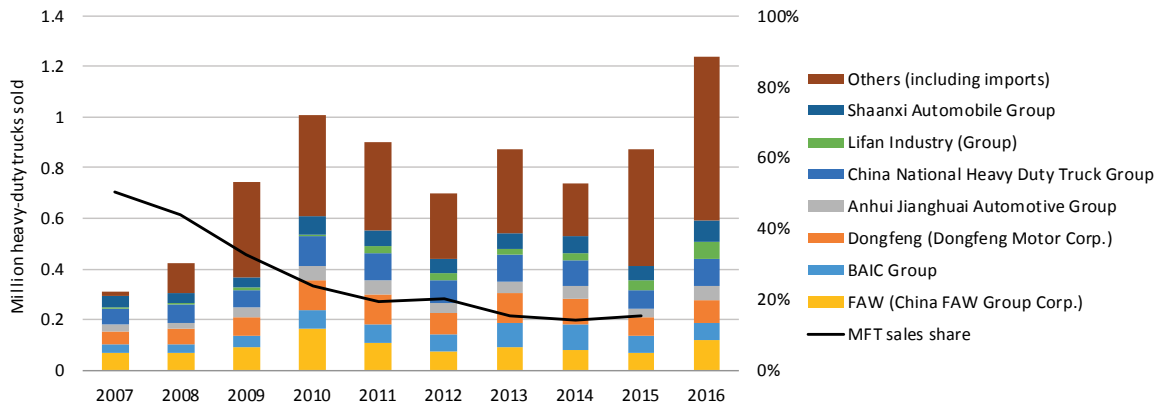
[11] Some tractor-trailers in the United States also fall into category 7. Tractor configurations differ between markets in the European Union and the United States. Differences include the axle configuration and number, cab design, weight and length. The regulatory and operational conditions in which tractor-trailers operate are also different (e.g. speed restrictions, weight limitations and duty cycles), making a direct comparison of fuel efficiency difficult (Sharpe, 2015).

Figure 16 • Truck sales by manufacturer in China, 2007-16

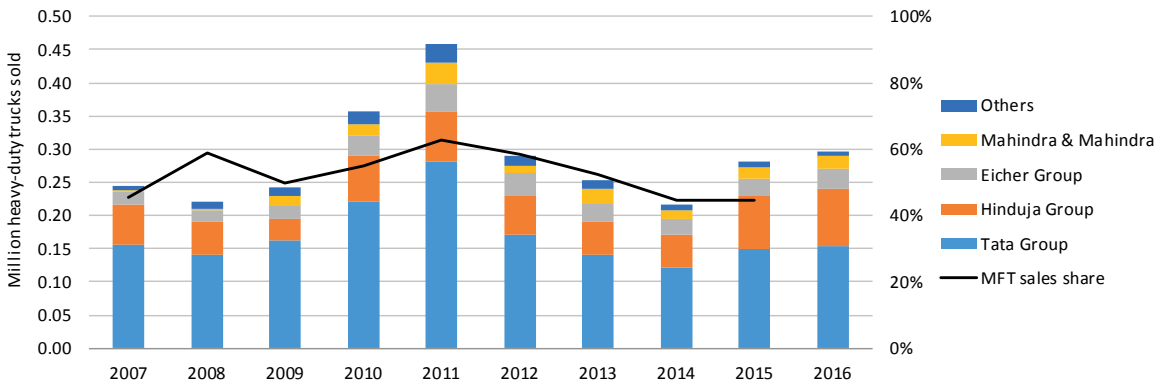


Notes: The Marklines database includes only domestically manufactured vehicles and heavy-duty trucks (buses have been removed). Sales volumes are taken from MoMo; shares are taken from the Marklines vehicle sales database under the assumption that sales tracked in MoMo but not in Marklines are either made by small domestic manufacturers or are imports. Sales for 2016 are estimates based on the 2015 sales from MoMo, and the sales trend between 2015 and 2016 are given in Marklines. The line indicates the sales share of MFTs, which has steadily declined since 2007 from 50% to 15% in 2015.

Sources: Marklines (2017); IEA (2017a), Mobility Model, June 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport.

In India, industry consolidation is more pronounced than in any of the markets considered above. The top four manufacturers account for more than 95% of heavy-duty truck sales (including MFTs and HFTs) (Figure 17). More than 50% of heavy-duty trucks sold in 2016 were made by Tata Group, down from 64% in 2007. Tata is the only OEM in India that sources about half of their engines from the independent engine supplier Cummins; as Tata dominates the truck market and supplies not only Tata but also other OEMs, this means that Cummins engines account for more than one-third of heavy-duty truck engine sales in India (Sharpe, 2015).

Figure 17 • Truck sales by manufacturer in India, 2007-16



Notes: The Marklines database includes only heavy-duty trucks (buses have been removed). Sales volumes are taken from MoMo; shares are taken from the Marklines vehicle sales database. Sales for 2016 are estimates based on the 2015 sales from MoMo, and the sales trend between 2015 and 2016 are given in Marklines. The line indicates the sales share of MFTs, which has fluctuated over the past decade between 45% and 65%.

Sources: Marklines (2017); IEA (2017a), Mobility Model, June 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

Within HFTs, the share of rigid trucks is much higher in India than in any of the other three markets, and the share of tractor-trailers is only around 15%, in stark contrast to the United States and the European Union, in particular. Heavy-freight trucks in India are equipped with

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smaller engines; most engines are less than 9 litres, whereas, in the United States and the European Union, nearly all HFT engines are greater than 9 litres in size (Sharpe, 2015).

The market for logistics services

The global logistics and delivery sector makes up about 15% of the world's GDP (Wible, Mervis and Wigginton, 2014). On average, about 7-8% of a product's cost reflects its delivery costs, and transport constitutes about 40% of these costs, although of course there is wide variation in this percentage by product. A number of firms with distinct but sometimes overlapping functions co-ordinate and compete at various levels of the supply chain.

Shippers are typically large, multinational corporations that generate freight movement and are the customers of carriers, small and medium-sized enterprises that operate truck fleets. The objective of shippers is, hence, to deliver commodities within designated time constraints, maximising reliability and minimising costs. For their part, carriers, which operate in a highly competitive marketplace, aim to maximise profits by minimising the costs of meeting shippers' demands. Over the past few decades, logistics service providers (LSPs) have emerged in certain national and regional markets (such as the European Union and the United States) to co-ordinate efficient deliveries given contractual constraints between shippers and carriers. LSPs include both third-party logistics (3PL) services and *brokers* (also known as fourth-party logistics [4PL] services), the difference between the two being that brokers tend to focus on individual contracts between shippers and carriers and do not have physical assets. In general, LSPs tend to have more extensive human, technology and/or physical assets (including fleets and drivers) and are more strategic in their operations. This entails matching cargo and capacity, negotiating prices, reaching a contract, stipulating liability and insurance, tracking cargo and final payments upon delivery, and, in some cases, also managing fleets. Given their role in co-ordinating shipments across various companies, LSPs are well-placed to leverage various efficiency-improving logistics options, including intermodal deliveries, routing, load sharing and co-loading (see the section on systemic improvements in Chapter 2) (Roeth et al., 2013). Most LSPs also operate their own truck fleets.

Truck fleets are typically small, and carrier markets are highly fragmented, even in developed countries, such as the United States and the European Union.[12] In Asia, the trucking sector is even more markedly unconsolidated: nearly 90% of trucks are owned by individual drivers, and only 0.1% are owned by companies with more than 100 trucks (GFA, 2016). Individual owner-operators and larger carriers alike may choose to buy or lease their vehicles, and their operations may be concentrated in one of many subsectors (e.g. food, construction materials or raw materials), geographies or environments (e.g. urban, rural or both).

Between the early 1980s and 2010, the total cost of domestic freight in the United States as a share of GDP was cut in half (from 18% to 9%). Improved logistics were among the drivers that led to this dramatic improvement in the sector's efficiency (Roeth et al., 2013). Surveys and other annual data collection efforts provide evidence of a more than 20% improvement in vehicle capacity utilisation in the United States from about 2003 to 2015 (ACT Research, 2017; ATA, 2017), a trend that has been attributed to better pallet packaging and loading, more backhauling (see Chapter 2), improved telematics and the maturation of third-party logistics.

The volume of the road freight market alone is about USD 725 billion in the United States and USD 395 billion in the European Union (Srinivasan and Leveque, 2016). Both markets are highly fragmented; in the United States, the top five firms account for less than 20% of total revenue.

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[12] In the United States, for instance, 97% of truck fleets operate 20 or fewer trucks, and 90% operate six or fewer trucks.

In many countries, truck drivers constitute a substantial share of blue-collar employment. In the United States, there are just under 2 million heavy and tractor-trailer truck drivers, and in the European Union, there are about 2.5 million truck drivers – in both cases, this accounts for about 1% of total jobs. The various literature points to the high rates of job dissatisfaction and subsequent absenteeism and attrition as major contributors to operational inefficiencies among road freight carriers (Sternberg and Harispuru, 2017; Prockl and Sternberg 2015; Saldanha, Hunt and Mello 2013). For instance, uncertainties in drivers' availability reduce scheduling efficiency, and high turnover means that drivers are not familiar with the best routes and schedules, resulting in suboptimal routing and vehicle utilisation. Across many developed countries, the average age of truck drivers has increased in recent decades, posing a current and continuing risk of labour shortages, which can also lead to increases in the price of labour for trucking.

Road freight fuel intensity and policy frameworks

Fuel intensity of road freight transport

As outlined above, there is a large variety of road freight vehicles that cater to very different purposes. They vary in size and weight and, depending on their load, may have widely varying specific fuel consumption. For example, within the HFT category used in the IEA analysis, a modern, empty long-haul truck with a trailer and a maximum payload of 20-25 tonnes consumes on average around 25 litres of diesel equivalent per 100 kilometres (lde/100 km), although fuel consumption can exceed 40 lde/100 km when running at full load. A modern long-haul tractor with semi-trailer and a payload of 26 tonnes typically consumes 25 to 30 lde/100 km when running empty, and upwards of 45 lde/100 km when running a full load. For every tonne of additional payload, the actual fuel consumption of an HFT increases by about 1 lde/100 km, on average (GFEI, 2016). Within the MFT category, a truck for regional traffic and a payload of 5.5 tonnes consumes around 20 lde/100 km empty, and 25 lde/100 km under full load. . A modern, smaller truck for distribution purposes that would classify as an LCV with a payload of 0.5 to 1 t may consume between 7.5 and 11 lde/100 km, depending on the payload carried. As with passenger vehicles, the actual fuel consumption of road freight vehicles is further affected by traffic conditions, roads and driving behaviour, among other factors.

Regional differences in vehicle attributes, payloads, policy frameworks and mission profiles, as well as the average age profiles of the truck fleet, mean that the average specific fuel consumption by road freight vehicle category can be markedly different across various countries. Table 4 summarises our best understanding of the average fuel consumption of new vehicles for the three main truck categories discussed above, taking into account regional specificities and the range of different vehicles that are included in the categories adopted here.

In the United States, on-road fuel economy data point to real-world fuel consumption of US heavy-duty trucks remaining flat for two decades prior to the implementation of the Phase I Standard (Oak Ridge National Laboratory, 2014). In the European Union, a series of studies by NGOs and researchers (see, for instance, Transport and Environment [2016] and Muncrief and Sharpe [2015]) as well as ACEA (2010) and Shell (2010), showing that tractor-trailer fuel efficiency (in lde/km) had stagnated from the mid-1990s, were among the justifications for the European Commission's decision to promulgate heavy-duty CO_2 standards (Todts, 2016).[13]

[13] Currently, there is some controversy on whether or not tractor-trailer fuel economy stagnated in Europe. Fuel economy stagnated when comparing trucks with the same engine size, and improved slightly when comparing trucks with the same engine power. This suggests that, although trucks were subject to technological improvements, part of the technology development was used for improved performances. Another fraction may have been used to reduce pollutant emissions. In addition to this, if engine power increases accompanied increased load capacity, they may have led to improved operational

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Table 4 • Typical average fuel consumption of new trucks at representative payloads, by truck category in selected countries (lde/100 km)

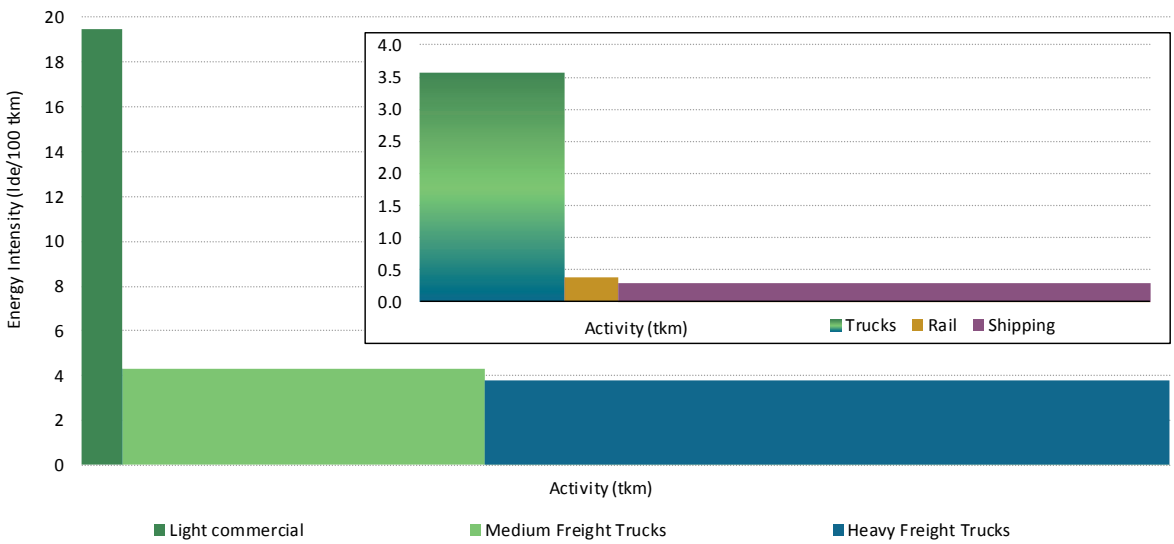
Country	LCVs			MFTs			HFTs		
	lde/ 100 km	payload (tonnes)	lde/ 100 tkm	lde/ 100 km	payload (tonnes)	lde/ 100 tkm	lde/ 100 km	payload (tonnes) tkm	lde/ 100
United States	7.9	0.55	14.4	28.2	6.4	4.4	41.2	15.4	2.7
European Union	6.8	0.62	11.0	23.3	7.0	3.3	34.6	14.5	2.4
China	9.9	0.82	12.1	23.3	8.7	2.7	39.1	13.3	2.9
India	6.4	0.96	6.7	25.0	9.7	2.6	44.9	12.9	3.5

Note: Differences in vehicle attributes, such as engine size and power, the availability of auxiliaries, and the mission profiles and vehicle size distributions in each category, complicate the comparison of average fuel economy and load across regions. Average payloads shown include estimated share of empty running.

Source: IEA (2017a), Mobility Model, June 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

While heavy-duty trucks consume much more fuel on average per kilometre driven than smaller trucks, this does not necessarily mean that they represent a less efficient mode of freight transport. In terms of useful service (i.e. per tonne-kilometre), HFTs are most efficient at transporting goods and require an average of about 3.8 lde to transport 1 tonne of good over a distance of 100 hundred kilometres. MFTs require about 4.3 lde to perform the same service, while LCVs require about 19.5 lde (Figure 18). In comparison with freight rail and maritime freight (inset), road freight is quite inefficient: both rail and ships use on average about 15% as much energy (between 0.4 lde and 0.5 lde, respectively) as HFTs per 100 tkm.

Figure 18 • Global stock average freight energy intensity and activity in 2015



Notes: The area of each box indicates the total final energy consumption by each respective mode in 2015. The values cited here are global averages. Regional variability around these averages is quite wide, to say nothing of the variability of specific operations within regions. At a national and regional level the average useful intensity ranges from about 3 lde/100 tkm to 4 lde/100 tkm for HFTs, 4 lde/100 tkm to 6 lde/100 tkm for MFTs and 16 lde/100 tkm to 30 lde/100 tkm for LCVs. Note, also, that a direct comparison between this figure and Table 4 is not straightforward: the table shows the fuel economy of new trucks sold in 2015, which were, in general, more efficient (in terms of lde/100 tkm) than the global average stock efficiency.

Source: IEA (2017a), Mobility Model, June 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

or "useful" efficiency (on a MJ/tkm basis). The latter are not accounted when comparing trucks on the basis of a MJ/vkm metric. For more details, see Muncrief and Sharpe (2015) and Transport and Environment (2016).

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Market failures in road freight and policies to improve truck efficiency

With the generally high average fuel consumption of long-haul trucks, in particular, fuel costs are a large component of the operating costs for road haulage companies. In the United Kingdom and the United States, fuel represents 20-30% of operating costs (ATRI, 2016), and in China, it can be 40-50% or more. Carriers and shippers operate in a competitive market under an imperative to maximise profits. This implies that where the economic case for more efficient trucks exists, operators are likely to make the investment in more efficient trucks. Yet, the cut-throat competition in many truck markets is also a key obstacle: for operators of heavy-duty trucks in the United States, for example, fleets of 1-20 consider only technologies with paybacks ranging from 6 to 36 months (and averaging a year), while those operating the largest fleets (of 501 or more vehicles) consider a payback period of 18-48 months (and averaging two years) (Schoettle, Sivak and Tunnell, 2016). Other surveys in the North American truck market show that large fleets consider a payback period of about two years (Roeth et al., 2013).

Such evidence suggests that there is a degree of market failure that prohibits further efficiency gains from materialising. The following interlinked factors are the key reasons for this failure to make up-front investments in vehicle efficiency technologies:

- the *payback gap*, i.e. the time it takes until the efficiency investment is fully amortised by fuel cost savings
- *imperfect information*, i.e. the lack of access to accurate information about technology performance for operators
- *split incentives*, i.e. when different agents (such as the truck driver and the fleet manager) do not share the same incentive in implementing energy efficiency measures, most often because the operator does not own the capital asset
- *liquidity and scale constraints*, i.e. a lack of available capital for investing in more efficient technology, in particular for smaller firms and firms in lower-income countries
- *trade-offs*, i.e. when operators make choices between energy efficiency investments and other priorities.

All these factors are tightly interwoven, in particular the first two, which also tend to be most often cited barriers across all market actors in road freight. Deficiencies in the credibility and certainty of payback periods, particularly for new and emerging efficiency technologies, and the lack of clear and easily accessible information on the real-world performance of these technologies leads to a reluctance among vehicle purchasers to invest in them. The lack of strong perceived demand on the part of OEMs and component makers then may result in reduced market availability, particularly in regions with low fuel taxes where fuel efficiency is valued among truck purchasers.

Various private companies have begun to successfully address these market failures through business ventures, such as in the case of truck and component suppliers that allow for payments in instalments, through services that provide driver training and further fuel-efficient driving and vehicle maintenance, or the use of energy service company business models in road freight. In addition, the above indications of market failure have prompted regulators in several markets to actively seek to overcome them. The approaches and policy responses differ by the individual barriers and the individual market context; Table 5 provides an overview of the measures that have been implemented to overcome specific market barriers to improving truck fuel efficiency. In the following section, we provide an overview of some of the specifics of individual policy approaches.

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Table 5 • Policy measures that address market barriers to truck fuel economy investments

Market barrier	Policy types	Examples
Payback gap	Regulations and fuel economy standards compel firms to prioritise spending on fuel economy measures, usually with positive net present value (NPV) Grants, tax breaks and other fiscal measures targeted at measures with longer paybacks Scrappage schemes reduce transaction costs associated with the replacement of the existing fleet	Fuel economy standards in Canada, China, Japan and the United States; Hong Kong, China's 2010 anti-idling bill; California and other US states' anti-idling bills California Clean Air Action Plan for the Ports of Los Angeles and Long Beach China's "old swap new" programme (2010) India's vehicle fleet modernisation programme (under development)
Imperfect information	Set up forums for knowledge exchange Disseminate experience with the reliability of new technologies and prioritise ensuring reliability in research programmes Independent accreditation schemes	SmartWay Transport Partnership; Green Freight Asia; Transport Limpio (Mexico); Ecostation (Australia); EcoStars (United Kingdom); Lean & Green (Netherlands and other European countries); Global Green Freight Alliance; and many others Smartway Transport Partnership provides accreditation for manufacturers of low-carbon vehicles
Split incentives	Standardise use of technologies that reduce the influence of driver behaviour Information provision about the benefits of performance feedback for drivers Provide eco-driving training or incentivise eco-driving through monetary and other rewards Fuel economy standards ensure that truck leasing companies adopt technologies that will benefit their clients	Mandatory speed limiters in the European Union Royal Dutch Shell's FuelSave Challenge Partner system; GreenRoad's real-time fuel consumption feedback system, as used, for instance, by the Dutch carrier Emons FleetSmart, Canada, and many documented examples among Finnish, German, United States and other carriers Fuel economy standards in Canada, China, Japan and the United States
Network and learning externalities	Support to the innovation ecosystem for developing and piloting new technologies	Innovate UK; California Air Resources Board's Low Carbon Transportation and Fuels Investments and Air Quality Improvement Program; Swedish Strategic Vehicle Research and Innovation Program; European Union mandates on alternative fuelling infrastructure (EC, 2016a); European Truck Platooning Challenge
Liquidity and scale constraints	Grants, tax breaks and other fiscal measures International co-operation on vehicle standards to harmonise new and used vehicle standards	Japanese HDV purchase subsidies. Texas Natural Gas Vehicle Grant Program Mexico emissions standards for used equipment and scrappage scheme.
Trade-offs	Align maximum truck weight limits and fuel economy objectives. Facilitate accreditation for efficiency retrofits	Australia's Performance-Based Standards (PBS) and Intelligent Access Program (IAP) (see the discussion of 'High-capacity vehicles' in Chapter 2). Smartway Transport Partnership provides accreditation for "Upgrade" packs for retrofitting

Sources: *Payback gap*: for sources on fuel economy standards, see the discussion in this chapter, for Hong Kong, China and various state-level anti-idling regulations in the United States, see: EPD (2013) and CARB (2016a), and US EPA (2006), respectively. For the California Clean Air Action Plan, see http://www.cleanairactionplan.org/. *Imperfect information*: for sources on the Green Freight Alliance programmes, see the section discussing those programmes in this chapter. *Split incentives*: on Shell's FuelSave Challenge program, see Garthwaite (2011); on FleetSmart, see NRCan (2012); on other eco-driving programmes, see Tacken et al. (2011) and Hedenus (2007); *Network and learning externalities*: for sources on Innovate UK, see, ; on CARB Low Carbon Transportation and Fuels Investments and Air Quality Improvement Program, see Gov.UK (2017); on EU mandates on alternative fuelling infrastructure, see EC (2016a, 2016b); for European Truck Platooning Challenge, see IEA (2017c). *Liquidity and scale constraints:* for sources on Japanese HDV purchase subsidies, see JAMA (2009); on the Texas Natural Gas Vehicle Grant Program, see TCEQ (2017); on Mexico emissions standards for used equipment and scrappage scheme, see GIZ (2014). *Trade-offs:* for sources on Australia's Performance-Based Standards (PBS) and Intelligent Access Program (IAP), see DTMR (2017) and Roads and Maritime Services (2016); on Smartway Transport Partnership, see EPA (2017).

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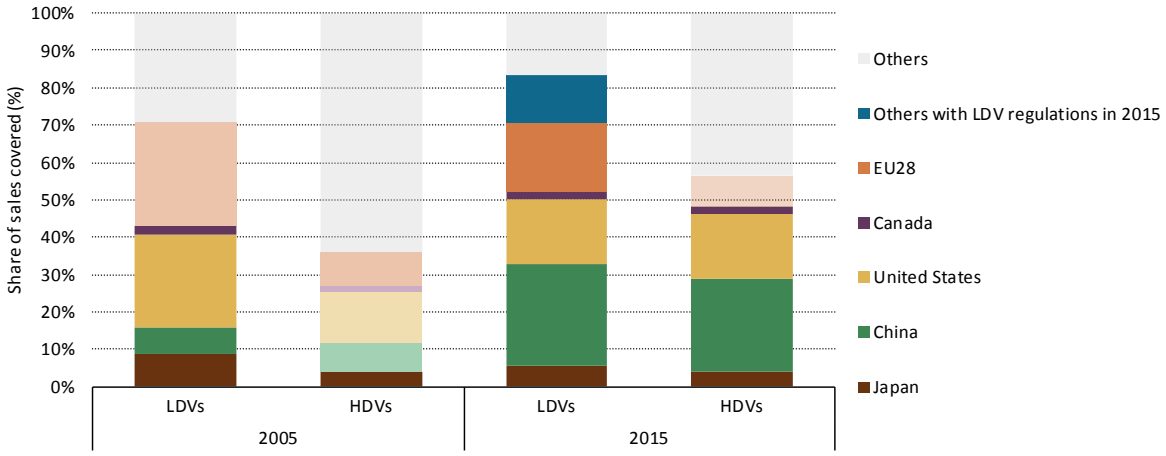
Vehicle efficiency regulations

Compared with passenger vehicles, policies and standards for improving energy efficiency and the emissions intensity of road freight vehicles have not yet been widely adopted. Standards to improve the fuel economy of passenger vehicles cover more than 80% of global passenger vehicle sales, while standards to improve the efficiency and emissions intensity of heavy-duty trucks cover only about 50% of road freight vehicle sales (Figure 19).

Figure 19 • Share of light- and heavy-duty vehicle sales subject to fuel economy regulations



Note: The HDV sales shares shown in the figure include buses. The share of all HDV sales covered by fuel economy standards (including trucks and buses) was 51%.

Sources: ICCT and DieselNet (2016); IEA (2017a), Mobility Model, June 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport .

The history of fuel economy and emissions standards for heavy-duty trucks is much shorter than for passenger cars. Unlike with passenger vehicles, where the United States was the first country to implement fuel economy standards already almost 40 years ago, the first road freight vehicle standards were enacted in Japan only in 2005. To date, four countries have enacted and implemented standards to reduce carbon emissions from and/or to improve the efficiency of road freight HDVs: Japan since 2005 and Canada, China and the United States since 2011. Together these markets make up more than half of total truck sales. Other countries and regions are in the process of evaluating standards, including the European Union, India, Mexico and Korea (Box 3).

Regulating the efficiency of road freight vehicles has proven more difficult than regulating the efficiency of passenger vehicles, which explains, in part, the lag in designing and implementing vehicle efficiency standards for these vehicles. Trucks are highly stratified by size and mission profile, which means that standards must accommodate this heterogeneity while still spurring fuel economy improvements. In contrast to light-duty vehicles, which are predominantly designed to move passengers or light loads, and so have a fairly narrow range of engine power requirements and driving conditions, medium- and heavy-duty road vehicles are designed for a wide range of different commercial and vocational purposes. In addition, the engine power of some trucks may be diverted for specific missions and vocational purposes, such as to concrete mixers in concrete transport trucks or the hydraulic mechanism in dump trucks. Consequently, HDV standards need to take into account the size and function of specific vehicles. They also need to be developed for engines on the basis of specific (and as representative as possible) output requirements while setting threshold values for emissions and fuel efficiency based on the vehicle usage profile.

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As the operational performance of a truck depends not only on engine performance, standards should refer to the vehicle's overall performance, including the brake horsepower per hour (bp-hr) engine performance. Regulating vehicle performance is more complex as it depends on the vehicle's duty cycle, which, as outlined above, can have a significantly higher variance than for passenger vehicles. For example, a vehicle's efficiency and performance will differ when hauling a payload and without a payload; a long-haul tractor chassis may be high performing when running without any payload but perform poorly (in terms of fuel consumption) when hauling a payload over a certain weight. This complexity has led regulators to build models to estimate the performance of different vehicles under different operating assumptions, vehicle configurations and equipment types.

While each national regulatory scheme is different, they share a number of basic characteristics in their design and enforcement and differ in others:

- *Regulated entities:* The regulated entities for standards are the truck chassis manufacturers, and may include the engine manufacturers. In the Phase II standards in the United States, trailers will be regulated, and trailer manufacturers will be another regulated entity.
- *Standard type measurement:* The metric for regulation is either a fuel consumption metric similar to existing passenger vehicle standards measured in units like energy (litres) per tonne kilometre (tkm), or the work delivered at the shaft (bhp-hr), or a metric based on the GHG performance (and therefore typically measured in grammes CO_2 per tkm or bhp-hr). The United States has both fuel consumption and GHG standards with which manufacturers must comply, but these standards are equivalent (i.e. compliance with one implies compliance with the other).
- *Phases and compliance period:* To date, standards have been developed in phases that allow for gradual compliance with the final regulated target. Japan's standards, while enacted in 2005, only reached full compliance in 2015. In China, the first phase of standards implemented in 2012 was used partly as a data collection and verification exercise to measure the efficiency and fuel consumption of trucks on the market. Phase II integrated the findings from Phase I to develop more effective standards. In the United States, the first phase of standards was implemented in 2014 and will run until 2018. The second phase, published in 2016, will apply to trucks between 2018 and 2027.
- *Truck types regulated:* Separate regulations are typically developed for tractors used for distance hauling, medium and heavy-duty trucks used for vocational purposes, and buses. Depending on the scope of the regulations, they may also cover light-duty pickup trucks, vans and coaches. In the United States, the Phase II standards incentivise the significant opportunities for fuel efficiency improvements on trailers.
- *Standard thresholds:* Within each truck type, standards are stratified by vehicle size and purpose. For example, in US and Canadian regulations, tractors are divided into ten separate classes based on the gross vehicle weight and physical size as measured by the roof height. Vocational trucks are divided into light, medium and heavy-duty categories and are further divided by function depending on whether they are primarily used in urban, regional or multipurpose contexts. In Japan, non-tractor trucks are regulated based on a dynamic simulation of fuel consumption reflecting the truck's operational environments. China regulates trucks not by weight class but by the total vehicle and payload weight.

Each national standard aims to achieve notable improvements in efficiency and reductions in fuel consumption and GHG emissions. A summary of the scopes, timelines and ambitions for existing regulations is provided in Table 6.

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Table 6 • Specifications of implemented national truck fuel economy and GHG emissions standards

Country/ Phase	Compliance period / Standard type (target metric)	Truck types regulated	Truck size categories	Average targeted efficiency improvement
Japan Phase I	Established in 2005; came into effect from 2015 Fuel consumption (km/litre)	Tractors, trucks, transit buses and coaches	2 weight bins for tractors > 3.5 tonnes (t), 11 bins for non-tractor trucks > 3.5 t	9.7% over model year (MY) 2002 baseline for tractors by 2015 12.2% over MY 2002 baseline by 2015 for all vehicle classes other than tractors
Canada Phase I	2014-17 GHG (g CO_2/tkm, g CO_2/bhp-hr)	Tractors, pickups, vans, and all other medium and heavy-duty vocational vehicles	2 weight bins for tractors > 3.856 tonnes (t), 2 bins for heavy-duty pickup trucks and vans, 7 bins for vocational vehicles	6-23% over MY 2010 baseline, set for MY 2014-16 and updated for MY 2017, depending on truck type and size
United States Phase I	2014-17 Joint: GHG and fuel consumption (g CO_2/ton-mile, g CO_2/bhp-hr, gal/1,000 ton-mile)	Tractors, pickups, vans, and all other medium and heavy-duty vocational vehicles	3 bins for combination tractors, 2 bins (gasoline and diesel) for heavy-duty pick-up trucks and vans, 3 bins for vocational vehicles	7-20% over MY 2010 baseline for combination tractors (no trailers) from MY 2014 to MY 2017 10-15% for heavy-duty pickup trucks and vans by MY 2018 10% for vocational vehicles from MY 2014 – MY 2017 The standards for combination tractors and vocational vehicles are also supported by engine standards for MY 2014 and MY 2017
United States Phase II	2021-27 (trucks, large pickups, vans and buses) 2018-27 (trailers) Joint: GHG & Fuel consumption (g CO_2/ton-mile, g CO_2/bhp-hr, gal/1,000 ton-mile)	Tractors, semi-trucks, large pickups, vans, buses and work trucks Includes trailers	3/4 bins for combination tractors, 4 bins for trailers, 2 bins for heavy-duty pick-up trucks and vans, 3 bins for vocational vehicles	Additional efficiency requirements for models beyond MY 2018 Reductions of 16% for pickups and vans, 24% for vocational vehicles, 25% for tractors and 9% for trailers in MY 2027 compared to MY 2017, with interim standards for MY 2021 and MY 2024 Updated modelling capacity (GEM v2); focus on promotion of advanced technologies Estimated annual fuel savings of 10.5-11.7 billion litres of gasoline equivalent, or from 4.6-5.2% of total fuel used by HDVs, by 2025
China Phase I	2012-15 Fuel consumption (litres/100 km)	Tractors, trucks (excl. dump trucks,) buses and coaches	8 bin for tractors > 3.5 t, 11 bins for non-tractor trucks > 3.5 t	First standard to benchmark energy consumption of trucks. Consumption limits based on weight between 38 - 56 l/100 km for tractors, 15.5 – 50 l/100 km for non-tractor trucks and 14 – 33 l/100 km for busses/coaches
China Phase II	2014-20 Fuel consumption (litres/100 km)	Tractors, heavy-duty vocational vehicles, buses and coaches	8 bins for tractors > 3.5 t, 11 bins for trucks (excluding dump trucks) > 3.5 t, 11 bins for dump trucks	10.5% for coach buses, 11.5% for trucks and 14% for tractors, compared to MY 2012 Phase I fuel consumption limits from July 2014 (type approvals)/July 2015 (all sales), depending on truck type and size
China Phase III	From 2019 Fuel consumption (litres/100 km)	Tractors, dump trucks, trucks (excl. dump trucks), buses and coaches	8 bins for tractors > 3.5 t, 11 bins non-tractor/non-dump trucks > 3.5 t, 11 bins of dump trucks	15.9% (for buses), 21.7% (for coach buses), 23.7% (for trucks [excl. dump trucks]), 14.1% (for dump trucks) and 27.2% (for tractors) compared to MY 2012 Phase I fuel consumption limits from July 2019 (type approvals) / July 2021 (all sales), depending on truck type & size

Sources: ICCT and DieselNet (2016); Government of Canada (2013); MIIT (2012, 2014); EPA/NHTSA (2011, 2016); ECCJ (2005); ACEEE (2016); ICCT (2014).

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Japan was the first country to implement fuel efficiency standards (measured in km/L) for heavy-duty vehicles. With binding CO_2 targets just coming into effect, and impelled also by energy security considerations, in 2006, three Japanese ministries (the Ministry of Economy, Trade and Industry, the Ministry of Environment, and the Ministry of Land, Infrastructure and Transport) set fuel efficiency regulations in the context of broader policies to promote eco-driving, logistics and other energy and GHG reduction measures in road freight (as well as in transport more broadly). Japan applied its "top runner approach" to heavy-duty vehicles, which takes the best-performing vehicle in the market as the baseline for standards. In the case of HDV standards, the best-in-class vehicles in each category from the model year 2002, plus an additional 9.7% fuel efficiency gain for tractors and 12.2% gain for trucks, were used to set the 2015 fuel efficiency targets. The long lead time from implementation to binding regulation was intended to give OEMs the chance to develop new technologies to meet the standards while moving gradually toward the targets in the intervening production cycles. Separate limits were set for 13 categories of trucks (and 12 types of buses) by GVW bin. The mandates are technology neutral. Compliance is determined by the model-derived vehicle fuel economy based on engine dynamometer testing on a cycle (JE05) specific to Japan and designed to reflect the unique characteristics of the country's (very small and light) truck fleet and unique (mountainous and population dense) geography. Each manufacturer must comply with the standards for each vehicle category it sells with no cross-bin crediting.

In 2008, China's Ministry of Industry and Information Technology (MIIT) announced its plan to design fuel consumption standards for commercial heavy-duty vehicles. In 2012 the MIIT put in place a type approval standard (Phase I), in large part to establish a benchmark against which to design a subsequent round of appropriately stringent standards. By 2015, these more stringent Phase II standards were applied on all new heavy-duty vehicle sales (Phase II). Phase II standards differ by fuel (i.e. gasoline versus diesel, where diesel standards are more stringent) and vehicle type (designations include dump trucks, city buses, coaches (intercity buses), trucks and tractors). Within each of these designations, a step function mandates maximum fuel consumption by gross vehicle weight (GVW). Testing is performed on a version of the World Harmonised Transient Vehicle Cycle modified to reflect Chinese on-road conditions (MIIT, 2012, 2014). Chinese standards were estimated to have reduced CO_2 emissions by 2 Mt CO_2 in the year 2015. A new round of regulations that further tightens fuel consumption standards (Phase III) was recently opened to public comment and is expected to be introduced between 2019 (for type approvals) and 2021 (for all new vehicle sales). China's Phase III standards target a reduction in fuel consumption of about 15% in 2020 from 2015 levels and will be accompanied by other measures to improve efficiency in the road freight sector, including driver training and measures to improve logistics (Delgado, 2016a).

In the United States, regulatory movement began in 2007 with the Energy Independence and Security Act, which required the National Highway Traffic Safety Administration (NHTSA) to conduct a study on the fuel consumption of commercial medium- and heavy-duty vehicles. In 2009, the Environmental Protection Agency (EPA) issued a report on the health and welfare impacts of these vehicles under the Clean Air Act. Data gathering, consultation and cost-benefit analysis were followed by the implementation of parallel fuel consumption and GHG standards (Phase I standards) in 2014. Phase I standards regulate both the CO_2 emissions (by the EPA) and fuel consumption (by the NHTSA) of heavy-duty engines and vehicles with a GVW exceeding 3 856 kg. The EPA standards cover not only CO_2 but also NO_x and CH_4 tailpipe emissions. The standards mandate limits for three broad, heavy-duty vehicle classes (i.e. upwards of 3 856 kg): combination tractors, vocational vehicles, and heavy-duty pick-ups and vans. Beyond this, separate limits based on distinct test cycles and predefined payloads are set for the subcategories of each category (GPO, 2011). Standards become tighter each year, although

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market mechanisms for averaging, banking and trading allow for some flexibility in how manufacturers meet the standards. The estimated savings resulting from reduced fuel consumption total USD 50 billion, together with emission reductions of more than 270 Mt CO_2. The estimated payback period for the technologies needed to meet the Phase I standards is about one year for both vocational vehicles and combination tractors. The US standards were adopted in Canada in 2011 with minor modifications (e.g. to cover heavier vehicles that operate more broadly in Canada). US Phase II standards, which will begin to take effect from 2018 and extend over the coming decade while becoming increasingly stringent, will regulate not only truck efficiency but also trailer efficiency (US EPA, 2016a). Implementing standards that target environmental performance (i.e. specific emissions of CO_2 or other pollutants) and that are maximally representative of real-world operations while still being simple and inexpensive to test is deemed preferable to mandating technologies. Finally, by giving some flexibility through corporate average targets, banking and trading, regulators aim to ensure that all OEMs are able to find their own individual profit-maximising paths to compliance.

Given the dominance of only a few OEMs in the US and EU markets, fuel economy and GHG standards implemented in one region can potentially provide spillover benefits (such as low compliance costs) to the other region. For example, the Phase I standards in the United States are likely in the short term to reduce the burden of complying with the standards soon to be phased in across Europe.

Box 3 • Progress on heavy-duty fuel economy standards in the European Union and other countries

The European Commission presented a strategy in 2014 to reduce the CO_2 emissions of HDVs, focusing on short-term actions to certify, monitor and report emissions. The Commission has also developed a computer simulation tool, VECTO, toward this end. Having developed this tool, the Commission brought forward proposals for legislation in 2017 requiring the certification, monitoring and reporting of CO_2 emissions from new HDVs registered in the European Union. This was the first step toward a more transparent and competitive market and the adoption of the most energy-efficient technologies.

In 2016, the Commission further adopted the European strategy for low-emission mobility, which sets the objective of cutting by at least 60% transport greenhouse gas emissions by mid-century compared to 1990 levels (EC, 2011), and announces that the Commission will prepare legislation on HDV CO_2 emission standards by 2018-19. Analytical work to design such emission standards is currently underway.

Other countries around the world, including India, Korea and Mexico, have begun setting the groundwork for HDV fuel economy standards. Mexico is a major producer of HDVs, many of which are exported to the United States. These vehicles will need to meet US regulations, including the US Phase II HDV fuel economy standards and emission standards for CO_2 as well as local pollutants (Current HDV air pollutant standards in Mexico meet the Euro IV emissions standards). At the 2016 North American Leaders' Summit, the intention to design an aligned North American HDV standard for fuel consumption was announced. The goal is to match fuel economy standard ambitions through 2027 for Canada, Mexico and the United States (Government of Canada, 2016).

In India, the introduction of HDV engine standards is expected in the near future. The Petroleum Conservation Research Association and the Bureau of Energy Efficiency have been given the task of assessing the feasibility of and formulating fuel consumption regulations. The standards are expected to be introduced in 2017 and fully implemented by 2020 (Sharpe, 2015). Complications, however, arise due to the regular alterations of HDVs by independent mechanics, causing a significant split between point-of-sale and real-world fuel efficiencies for vehicles (CSIR, 2014).

Korea currently has no HDV fuel economy standards, but it does have well-developed fuel economy regulations for LDVs. Extending these to HDVs has been identified as a current goal of the country's government, and work on this is ongoing. The implementation of these regulations is expected around 2020 (Sharpe, 2015).

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Brazil and Chile face a more uncertain timeline for HDV fuel economy regulations. In both countries, the main focus to date for HDVs has been on improving pollutant emission regulations, which currently meet EURO V standards, as opposed to fuel efficiency standards. The lack of a clear political framework for implementing fuel efficiency standards in Chile poses a significant barrier to progress on such standards. Despite this, energy efficiency regulations are being considered by the Chilean government, and insofar as these include transportation, they are likely to focus only on LDVs.

The International Council on Clean Transportation (Delgado, 2016b) estimates that by 2020, the European Union, India, Korea and Mexico will have adopted standards for HDVs. In 2015, these countries comprised about 20% of the world's sales of new heavy-duty vehicles (including both buses and MFTs and HFTs). Hence, if these countries were included among the countries with fuel economy standards, the coverage of global sales would total nearly 70% of global HDV sales.

Pricing policies to improve the efficiency of trucking

While standards to improve the efficiency of truck engines, chassis and trailers are an important policy tool for reducing the fuel consumption from trucks, governments have other levers that can also work to improve the efficiency by which freight is moved by trucks. Among the most widely adopted are fiscal measures, which can act directly as well as indirectly on improving the efficiency of trucking.

Direct fiscal measures to encourage energy efficiency in transport more broadly include, for example, differentiated purchasing schemes and purchasing subsidies. Although so far not widely deployed for freight vehicles,[14] their effect can in principle be immediate and straightforward for operators: by moderating the additional upfront investment needs for more efficient trucks (see Chapter 2), the payback hurdle is lowered, and the buyer has a direct incentive to invest in a more efficient truck.

Beyond such direct measures, there are pricing tools that act indirectly and less immediately (and which are the focus of the following sections). Their adoption is much more common for road freight transport, with the most broadly applied pricing policies being fuel taxes and road pricing schemes. The former consists of the widespread practice of taxing fuel purchases at the pump. The latter entails charges paid by the user according to the number of kilometres or time spent on a road. These may or may not differentiate pricing levels depending on how much carbon dioxide is emitted by the vehicle, referred to as CO_2 differentiation. Such policies are not traditionally developed with the objective of improving the fuel consumption of trucking. But they act upon all possible aspects of road freight efficiency, from improving the economic case of energy efficiency investments to incentivising the systemic improvements that minimise operation (such as through better logistics). They can additionally pave the way towards the use of alternative fuels, although their adoption typically requires additional policy support, in particular where an additional refuelling infrastructure is required.

Fuel taxes

Fuel taxes are among the simplest fiscal instruments currently used to finance infrastructure maintenance and construction and/or the environmental and social costs associated with the operation of transport vehicles. Due to the low sensitivity of transport fuel consumption to changes in fuel prices (i.e. the low fuel price elasticity of demand), fuel taxes have also been

[14] The US National Clean Diesel Campaign and the Diesel Emissions Reduction Act are examples of lending schemes to provide financial assistance for vehicle retrofits, especially for buses (US EPA, 2017b).

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levied by public authorities to collect revenue to fund other transport modes or other (non-transport) public programmes.

Table 7 summarises the taxation rates applied in major global regions, classifying them into major categories that reflect the assessment made by GIZ (2016).

Table 7 • Country clusters applying different levels of taxation on gasoline and diesel fuel

Fuel type	High subsidies	Intermediate subsidies	Low/intermediate taxes	High taxes
Gasoline	Iraq, Saudi Arabia, Venezuela	Middle East	Africa, ASEAN, Australia, Canada, Central Asia, China, India, Japan, Latin America, United States	Europe, New Zealand
Diesel	Iraq, Saudi Arabia, Venezuela	ASEAN, India, Middle East	Africa, Australia, Canada, Central Asia, China, India, Japan, Korea, Latin America, United States	Europe

Notes: High subsidies are below the price of crude oil on the world market; intermediate subsidies are between the crude oil price and the level of taxation adopted in the United States. The boundary between intermediate taxation and high taxation is the price of fuel applied in Luxembourg.

Source: IEA elaboration based on GIZ (2016), and previous annual releases of fuel price data.

Overall, European economies apply high tax rates on gasoline and diesel fuels, with few exceptions among Eastern European countries that adopt intermediate taxes. Across Africa, there is a wide variability in automotive fuel taxation; the continent includes both countries that subsidise fuels and ones that tax them heavily. Fuel taxes in North America and Central America are appreciably lower than in Europe. In many cases, fuel costs in this region tend to remain fairly close to the levels determined by the price of crude oil on the market plus refining cost mark-ups. Taxation in these regions aims mainly to finance the construction and maintenance of the road network. The variability in tax regimes is larger in South America, where, for instance, Venezuela and Ecuador heavily subsidise fuels, while Uruguay applies high taxation rates. Middle Eastern countries generally heavily subsidise fuel, with a few exceptions. North African countries, including Algeria, Egypt and Libya, heavily subsidise gasoline, while countries in Central Africa and Southern Africa tend to apply moderate-to-high fuel taxes. Australia and countries in Asia tend to have moderate taxes, but there is variation at the country level; Japan and Korea have high tax rates, while Malaysia subsidises fuel sales.

Given the direct relationship between the volume of liquid fuels used (and combusted) and CO_2 emissions, fuel taxes directly reflect the environmental costs of CO_2 emissions. Despite this, tax levels on diesel fuel, which is disproportionately used by commercial vehicles and emits more CO_2 on a volumetric basis than gasoline, tend to be lower than taxes applied to gasoline. The most notable exceptions to this are the United States and Australia. Within Europe, Switzerland and the United Kingdom are the only economies that currently apply higher taxation rates to diesel fuel than to gasoline.

Changes in fuel prices have an influence on the evolution of road freight activity. Rising fuel prices, whether due to rising oil prices or the imposition of environmental taxes, lead to higher fuel costs, which tend to affect decisions made in the logistics system, reducing vkm and increasing loads. Nevertheless, given the various market failures outlined in the previous section, and since transport costs typically only represent about 30% of total vehicle operating costs, the extent to which changes in fuel prices influence these parameters is limited (IEA, 2009).

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Road pricing schemes

Road pricing typically requires vehicles to pay for the use of the road infrastructure they use and the environmental impacts derived from the use of the road network (e.g. due to the emission of air pollutants) and may include charges aimed at managing travel demand to reduce congestion and increase road safety. Road charging can also be useful to generate sources of revenue to fund the development of new infrastructure.

The implementation of road pricing takes a variety of forms in different countries. In Europe, the "Eurovignette" Directive provides the legal framework for charging freight transport vehicles (including MFTs and HFTs) for the use of road infrastructure and for the costs due to traffic-based air pollution and noise (EC, 2011) with tolls (i.e. fees based on the distance travelled) or user charges (charges based on time).[15] On 31 May 2017, proposed legislation was released calling for a revision of the Eurovignette charges to incorporate CO_2 emission targets and better reflect the "polluter pays" principle. The revision would phase out the current toll system in favour of distance-based charging, including mandatory differentiation on the basis of CO_2 emissions (as opposed to by vehicle weight class, as is the case in most countries under the current system). It would also add passenger cars, buses and vans to the regulatory scope of these new distance-based charges, which currently apply only to heavy-goods vehicles (EC, 2017).

Examples of the use of road pricing for demand-side management, i.e. to regulate the number of cars or trucks in circulation in particular in urban areas, are congestion charges and low-emission zones, which have been applied in urban areas, including in the cities of London and Singapore.

Given their impact on operational costs, road pricing schemes can directly influence energy use and emissions from road freight trucks. Charges designed to finance infrastructure cost, for example, may also be designed to differentiate the distance travelled (or the duration of the use of infrastructure) and the type and size of a vehicle and its emissions class. This can make road pricing a decision criterion both for the purchase of new trucks as well as for their daily operation. A selection of road charging schemes is shown in Table 8. While potentially effective in improving the overall efficiency of road freight transport, the effectiveness of the schemes can be enhanced if such annual road levies are harmonised across countries, in particular in highly interconnected markets such as the European Union.

Table 8 • Road tolls levied on heavy-duty vehicles in selected countries

Country (source)	Measure (start year)	Features
Austria (ASFiNAG, 2017)	HGV road user charging ASFiNAG (2004)	Applies to vehicles of 3.5 t and above. Based on a basic per kilometre rate for infrastructure costs (i.e. the right to use the road), a surcharge for traffic-related air and noise pollution, emissions class (EURO 0 - VI), number of axles (two to four, or more) and time of circulation (i.e. day or night).
Belgium (Viapass, 2017)	Eurovignette Viapass (2016, 1995)	Applies to vehicles of 3.5 t and above. Based on distance travelled, the vehicle's weight category, emissions class (EURO 0- VI), and type of road used (motorway versus urban areas).
Germany	LKW-Maut (2005, 1995)	Since 2015, applies to vehicles of 7.5 t and above. From 2005-15, applied to vehicles of 12 t and above. Roads subject to tolls include highways (approximately 13 000 km), marked sections of "first class" roads, expressways and certain federal roads (approximately 2 300 km in total). Based on distance travelled; the rate of the toll per km, which includes infrastructure costs (differentiated by the number of axles, from three to

[15] The "Eurovignette" Directive initially only targeted heavy vehicles with a permissible laden weight exceeding 12 t. Medium trucks with a gross vehicle weight over 3.5 t were covered in later amendments. It does not oblige member states to introduce road tolls or user charges.

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		four, and above) and external costs (differentiated by emissions class EURO 0 - VI).* From 1 July 2018, all federal roads will be covered (corresponding to an additional 40 000 km).**
Poland (viaTOLL, 2017)	ViaTOLL (2011)	Applies to vehicles of 3.5 t and above. For the transport of goods on motorways only. Based on the vehicle's emissions class (EURO 0 – II, or cleaner), number of axles and validity period (one day, week, month or year).
New Zealand (RUC, 2017)	Road User Charges RUC (1977)	For vehicles over 3.5 t, or vehicles using diesel or other fuels that are not taxed at the source. Based on distance travelled, the vehicle weight category and number of axles. Funds are used for the National Land Transport Fund.

* The rates applied are within the limits that are given by EU Directive 1999/62/EC of the European Parliament and of the Council of 17 June 1999 on the charging of HGVs for the use of certain infrastructures.

** A discussion to expand the scheme to all trucks heavier than 3.5 t and coaches as well as to levy tolls at all roads is currently underway. Such expansion would also account for external costs, such as CO2 emissions. To become effective, this proposal would require changes to the EU directive, and the European Commission has initiated a consultation process on this issue.

Sources: Austrian Motorway Operator, ASFINAG (2017); Belgium charging system for heavy goods vehicles, Viapass (2017); Germany's LKW-Maut, Umwelt Bundesamt (2016); Polish tolling system, ViaTOLL (2017); New Zealand Transport Agency, Road User Charges, NZ Transport Agency (2017).

Box 4 • The Swiss Heavy Vehicle Tax

The Swiss Heavy Vehicle Tax scheme is a road-pricing scheme for heavy-duty vehicles over 3.5 t that covers all vehicles entering Swiss borders. Three key elements determine this scheme: the vehicle's weight, its emissions category and the number of kilometres driven. The charge was introduced progressively and replaced a lump-sum charge that was already in place. The weight limit also increased from 26 t to 40 t to allow bigger vehicles to transport more goods.

A study by the German Corporation for International Cooperation (GIZ, 2014) found strong economic and environmental benefits from the scheme, including net revenue for the government that outweighed the administrative cost of implementation: about EUR 500 million (euros) collected between 2001-02, with administrative costs equivalent to 8% of this amount. CO_2 emissions also fell by 30%, the number of trucks on the road was reduced slightly and the number of kilometres driven declined by 6%.

Liable companies reported strong economic benefits through this study, which led to an overall higher acceptance of the pricing mechanism. Reported benefits included reduced overall traffic in towns, fewer stops, faster travel times, greater efficiency and reliability in operations, increased utilisation of vehicles, better organisation of freight and improved fleet composition.

Green freight alliances

An array of national and regional green freight programmes has emerged over the past decade or so for bringing together companies in logistics with public policy makers, government departments and non-governmental organisations.

The flagship programme, SmartWay, has either inspired or provided direct assistance to all subsequent green freight alliances and was launched by the US EPA in 2004 (Bynum et al., 2016). As the world's first voluntary, market-based national green freight programme, SmartWay draws from both the private and public sectors, including industry associations; environmental organisations; federal, state, and local governments; and corporations. Since its inception with 15 charter members, it has expanded to include over 3 500 corporate partners and 250 affiliates. Its corporate partners include shippers, carriers, logistics companies, retailers and manufacturers of all sizes.

The SmartWay programme consists of four elements:

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- a partnership of entities that collaborates to benchmark and improve upon current operations as well as to share best practices and highlight the achievements of the best performers[16]
- a technology programme that tests and verifies emissions reductions achieved by high-efficiency fuel and vehicle technologies
- a finance initiative that offers innovative mechanisms for accessing capital for the purchase of more efficient technologies
- an outreach and education effort that disseminates information on domestic projects and aims to provide lessons and guidance to countries seeking to design their own programmes to spur the adoption of green freight technologies and operations.

SmartWay expanded in 2012 to include Canada and was credited with reducing US CO_2 emissions during the period 2004-16 by 72.8 Mt (nearly on par with the annual emissions of Mexico's entire road freight sector) and reducing total fuel costs in the US trucking sector by more than USD 20 billion. The programme has also expanded from road freight to include rail, air and inland marine freight. The US EPA is working to add ocean freight to the freight modes covered to make the programme's coverage more comprehensive.

SmartWay's reporting and publishing of the fuel consumption of the participating fleets shows an average improvement of 10% fleet efficiency since 2012 (US EPA, 2017a). Going forward, programme planners aim to monitor and reward not only truck technologies but also logistics and other systemic efficiency improvements.

In addition to addressing imperfect information problems, SmartWay has facilitated loan and finance programmes, including funding under the US Diesel Emissions Reduction Act (DERA) (US EPA, 2017b), to help small trucking companies purchase fuel saving technologies and equipment. Through regular interaction with participants across the value chain, SmartWay is well placed to understand whether the incentive systems are well designed and to potentially overcome concerns that managing public grants can have undesirable labour costs for small businesses. As an example, Bank of America has partnered with the EPA to offer government-backed Small Business Administration Express loans, which require no collateral and provide flexible terms to truck companies for the purchase of fuel-efficient technologies and upgrade kits (UNEP FI, 2007).

The experience accumulated in the United States has provided guidance to green freight initiatives in other countries for international collaboration. For instance, SmartWay, together with Clean Air Asia and the World Bank, collaborated with freight companies in Guangzhou and later across Guangdong province, China, on what began as a pilot project to install vehicle retrofits (mainly devices that improve aerodynamics and reduce tyre-rolling resistance, such as side skirts or tyre pressure monitoring systems) and to train truck drivers in eco-driving practices. Due to the low speeds of the trucks operating in this Chinese province (average speeds were about 70 km/hr, as compared with upwards of 100 km/hr in the United States), the project prioritised low-rolling resistance tyres over aerodynamics.

Inspired and guided by the SmartWay example, industry-led, multi-national green freight initiatives have expanded in global reach (Table 9). All of these programmes are voluntary, and although most were established by national and federal ministries, a few (such as Green Freight Asia) are industry founded. The initiatives are collaborations between private industry and public policy makers, and, in many cases, non-governmental and/or research advocacy groups also contribute to ensure efficacy and to promote awareness of the programmes.

[16] For reasons of corporate responsibility and/or branding, shippers have shown interest in the availability of such benchmarking assessments as a means of selecting from among carriers. The pressure to do so comes from their customers, shareholders, investors, and non-governmental organisations. In response, shippers measure and report on their progress through corporate sustainability reports and by disclosing their emissions.

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Table 9 • National, regional and global green freight programmes

Name	Year founded / Countries of operation	Description
SmartWay	2004 United States, Canada	The flagship green freight programme (see text).
Transporte Limpio	2010 Mexico	A national voluntary programme that aims to reduce the fuel consumption, emissions and transport operation costs of both passenger and freight transport through the adoption of strategies, technologies and best practices. The freight programme includes carriers, shippers, OEMs and component providers.
Brazilian Green Logistics Program (PLVB)	2016 Brazil	A strategic initiative of a group of private companies that seeks to capture, integrate, consolidate and apply knowledge with the objective of reducing the intensity of GHG emissions and improving the efficiency of domestic logistics and freight. The programme seeks to train the shippers, carriers and logistics service providers that support and/or act in these activities.
Ecostation	Pilot launched in 2009 Australia	A voluntary scheme introduced by the Victorian Transport Association and the Victorian Environmental Protection Agency, aiming to improve the diffusion of efficiency technologies and of best practice operations.
EcoStars	Based on a scheme in South Yorkshire, United Kingdom, in 2009 Municipal and regional schemes), in the United Kingdom and in other European Countries	Open to all (private and public) freight truck operators. Fleets joining the scheme benefit from help in identifying vehicle and operational measures that improve efficiency, and from recognition once they adopt such measures.
Lean & Green	2008, in the Netherlands Based in the Netherlands, but with programmes in Australia, Germany, Italy, Spain, Luxembourg and the Czech Republic	The programme covers a broad range of supply chain and logistics operators (including manufacturers, shippers, LSPs, carriers and retailers) across all modes (e.g. shipping, road and even air freight). Membership is based on a number of flexible criteria, and members work in sectoral groups to baseline, report, and improve logistics efficiency while maintaining the confidentiality and anonymity of data.
Objectivif CO_2 (and FRET 21)	2008 (2010) France	Established by the Ministry of Transport, Environment and Energy Management Agency, the programme aims to promote sustainable passenger and freight transport. In Objectivif CO_2, freight carriers are eligible to earn a green label by demonstrating efficiency performance improvements across four foci: (i) driving (ii) fuel (iii) vehicles, and (iv) the organisation of logistics and management. In FRET 21, the same structure is replicated for shippers.
Green and Smart Transport Partnership	2012 Korea	Implemented by the Korea Energy Management Corporation, the partnership aims to enhance energy security and reduce GHG emissions and fuel consumption; 24 companies have joined.
China Green Freight Initiative	2012 China	Launched as a public-private partnership by the China Road Transport Association and the Ministry of Transport, the China Green Freight Initiative is a voluntary scheme that sets standards for green trucks and carriers for members to meet. The three pillars are green management, green technologies and green driving.
Green Freight Asia (GFA)	2013 Australia, Bangladesh, Cambodia, China, Hong Kong, India, Japan, Malaysia, New Zealand, Pakistan, Singapore, South Korea, Thailand, Viet Nam	Shippers are given a GFA label of a certain grade (four levels exist) when they choose carriers that have obtained a GFA label, and have their operations evaluated. Truck and technology manufacturers share information on their products.
Global Green Freight Action Plan	2014 Global	Initiated by the Climate and Clean Air Coalition, more than 50 organisations pledged their support to the global green freight project at the UN Climate summit. The initiative's goals are to align and enhance the existing green freight programmes, develop and support new programmes, and incorporate these into a wider framework of black-carbon reduction initiatives.

Note: Subnational programmes also exist, including the Clean Trucks programme of the Port of Los Angeles and Long Beach (LA, 2017), and China's Guangdong demonstration project (World Bank, 2017).

Sources: SmartWay: EPA (2017); Transporte Limpio: SEMARNAT (2014) ; Brazilian Green Freight Program: www.ltc.coppe.ufrj.br/index.php; EcoStars: EcoStars (2016) and EC (2017b); Lean & Green: Lean & Green (2016) and Anten et al. (2014); Objectivif CO2: Ministry of Ecological and Solidarity Transition (2017); FRET 21: FRET 21 (2015); Global Green and Smart Transport Partnership : Global Green Freight (2015); Green Freight China : China Green Freight Initiative (2016); Green Freight Asia : Green Freight Asia (2016); Global Green Freight : Global Green Freight (2015); For a comprehensive update of gree freight programmes, see: Smart Freight Centre (2017).

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These regional efforts culminated in the launch of a Global Green Freight Action Plan in May 2015. Led by the Climate and Clean Air Coalition (CCAC), and supported by a broad coalition of international governmental organisations, non-governmental organisations and civil society organisations, as well as industry partners, the plan aims to strengthen and harmonise the efforts of national and regional green freight initiatives and to encourage new programmes. While the project was conceived as a component of a broader strategy to reduce black-carbon emissions by consolidating and co-ordinating efforts to improve the service efficiency of road freight, the impacts of the latest plan are likely to be far broader and benefit economic productivity while reducing fuel consumption and GHG and local pollutant emissions.

The benchmarking work that green freight alliance programmes do to track the actual fuel consumption of regional and national trucks with a range of mission profiles provides a means of understanding the fuel savings potential for vehicle efficiency technologies. This way, the real-world payback periods of a range of technical efficiency measures, including both retrofits like low-rolling resistance tyres and aerodynamics devices as well as more efficient engines and trucks, can be established at the regional and national levels and for a wide range of vehicle and mission types.

The potential for green freight alliances to incentivise companies to invest in buying technologies with a proven rapid payback, for instance through providing favourable financing terms, is an often-mentioned aspect of the potential for such alliances to drive carrier markets. But real-world examples of such financing initiatives are scarce. One possible reason is the reluctance of banks to take on the credit risk of financing many small companies (the majority of which own fewer than five trucks). To address this issue, public partners in green freight alliances could offer a collateral backstop fund as insurance against the possibility of small carriers defaulting. Demonstration of context-relevant payback periods that apply to actual vehicle and operational profiles, together with education and outreach efforts, are needed to convince carriers that the loans are worthwhile from their perspective. Finally, loan applications should be simple, their benefits should be clearly defined, and they should focus initially only on those retrofits or technology portfolios with the most robust and fastest payback.

Scrappage schemes

Scrappage schemes are becoming more common as a means of providing incentives for freight operators to retire their older and higher polluting vehicles to trade out for newer, more efficient vehicles. Table 10 presents a list of a select number of scrappage schemes that have operated in the past focusing on trucks. Some more localised programmes are also in place to incentivise newer and less-polluting trucks. These schemes need to be designed in a targeted manner to ensure that they remove only older vehicles that are still being driven among the vehicles in the rolling stock and replace these with more efficient and lower emitting vehicles, thereby leading to reduced emissions of CO_2 and local pollutants. Retiring vehicles that travel little provides minimal benefits (Fraga, 2011).

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Table 10 • Historic and current scrappage schemes for trucks

Country	Scrappage scheme	Year(s) of operation	Truck criteria	Premium offered
Chile	Cambia tu camión	2009	> 10t GVW; >25 years old	USD 9 000-22 000
China	Old-Swap-New	2009-10	Between 10 and 15 years old	USD 1 400-2 400
Colombia	Renovación Vehicular	2013-18	> 20 years old	USD 24 600
Egypt	Egypt Vehicle Scrapping and Recycling Programme	2011-21	> 19 years old	USD 700
Japan	Vehicle replacement programme	2009-10	> 13 years old	USD 3 600-16 000
Mexico	Esquema de Sustitución y Renovación Vehicular	2003-18	> 10 years old	15% toward the trade-in of a new HFT
Spain	PIVE 1-8	2012-16	> 10 years old LCVs Only	USD 1 800

Sources: Chile: Agencia Chilena de Eficiencia Energética (AChEE, 2010); China: MOC (2010); Colombia: Ministerio de Transporte (2013); Egypt: UNFCCC (2009); Japan: Japan Automobile Manufacturers Association, Inc. (2009); Mexico: Diario Oficial de la Federación (2015); Spain: Instituto para la Diversificación y Ahorro de la Energía (2012).

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Opportunities and barriers for reducing road freight energy demand and emissions growth

The history of road freight activity and energy use has been one of a continuous upward rise; as economies have grown, so have trucking activity and oil use. This does not mean that efforts to moderate road freight activity growth and dampen fuel use have been absent. However, efforts undertaken so far have not been sufficient to offset the strong rise in demand for road freight activity (see Chapter 1).

The future might hold different prospects for the development of road freight activity, energy use and emissions. Technologies are improving, their costs are being reduced, and the barriers and bottlenecks for more efficient road freight activity, as well as the means to overcome them, are increasingly being understood. The main mechanisms for reducing future energy demand and emissions growth broadly span three areas:[17]

- improving vehicle efficiency, i.e. reducing the amount of energy used by individual trucks
- systemic improvements, i.e. improvements to the way the larger road freight system operates with a focus on reducing the road activity (in ton-kilometres [t-km]) required to deliver the same amount of goods
- the use of alternative fuels, i.e. a switch away from the use of oil-based transport fuels to other fuels, such as natural gas, biofuels, electricity or hydrogen.[18]

Additional potential for reducing energy and emissions growth from road freight lies in the shift of activity from goods transport via trucks to rail or inland maritime ships. While for certain routes and commodities there exists the potential for rail and inland waterways to serve as viable substitutes for road freight, particularly in cases where ample infrastructure exists, and market conditions and regulatory structures render such modal shifts economically competitive, such analysis is beyond the scope of this report.

In the following sections, we systematically explore the various options that fall under these three broad categories, with a view to their potential to reduce future energy and emissions growth, and the costs of and key obstacles for their future adoption in road freight transport.

Systemic improvements

Road freight transport goes well beyond the individual road vehicle that delivers goods from one place to another. It is a logistical system of often complex operations that organises the flow of goods between the point of origin and the point of use and seeks to meet the requirements of the customers while minimising the use of resources. Many external drivers influence the extent to which logistics affect future oil demand and emissions growth in road freight. Among these factors, improved road quality, expansion and the improved capacity of sustainable logistics initiatives, and collaborations among companies driven by policies and market forces (including

[17] Other improvements may unfold from developments outside the road freight transport sector. For example, there is a variety of recent trends in production and logistics that may contribute to reducing the fuel intensity of goods shipment by value (McKinnon, 2014b). The main examples include product miniaturisation (e.g. from cathode-ray tube televisions to flat-screen televisions or from desktops to laptops and tablets), digitalisation (e.g. of media products such as books, magazines and newspapers), 3D printing (which could enable the transition from "just-in-time" to "print-on-demand" business models [Birtchnell et al., 2013]) and postponement (delaying product packaging and customisation until they reach their final market). In the long term, these trends may contribute to the eventual decoupling of road freight activity from economic growth.

[18] Alternative fuels can in some cases lead to increased energy use, but in such instances, their adoption is motivated by other motives and/or policy goals, including energy security, economic benefits or GHG emission reductions.

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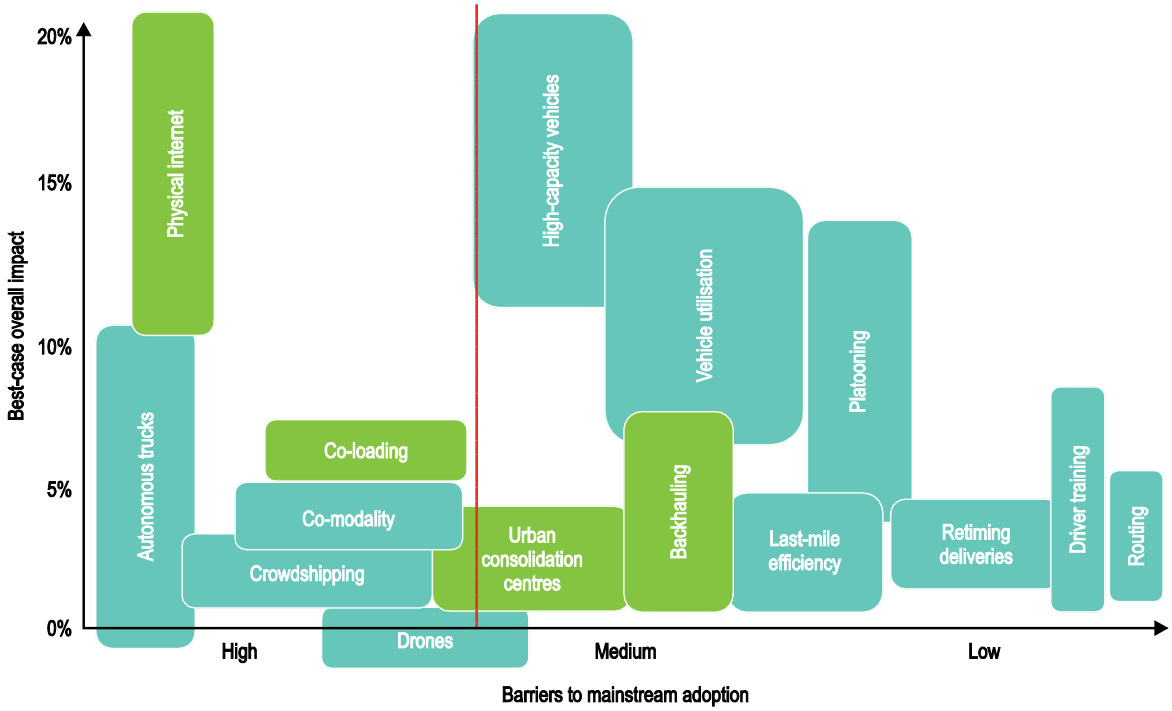
shipping industry consolidation, which tends to accompany economic development to some degree) are likely to work in favour of efforts to reduce future energy demand and emissions growth. But there are also factors that render such efforts more difficult: growing congestion, structural shifts from rail to road that tend to accompany economic development and growing demand for just-in-time delivery all may lead to increased energy demand and emissions (McKinnon, 2016b).

There are many areas of systemic improvements that can potentially help to reduce fuel use and emissions growth from road freight transport. Figure 20 summarises the key available systemic improvements and categorises them according to their first-order estimated potential[19] to reduce fuel consumption and carbon dioxide (CO_2) emissions and by the magnitude of corporate, technical, economic and/or political barriers to their adoption.

Figure 20 • Measures to reduce fuel use and CO_2 emissions



Notes: The measures shown in blue can be implemented by a single carrier, while those in green require external collaboration across companies, either horizontally or vertically across the supply chain. The red line designates the barrier between measures that are realised in the scenario assessment (Chapter 3). Measures to the right of the line are realised only in the Reference Scenario, and many only partially, while those that become feasible in the Modern Truck Scenario are shown to the left of the line.

Source: Based on a slide by Dr Phil Greening, Centre for Sustainable Road Freight, in his presentation at the IEA-JRC joint workshop, "The future role of trucks for energy and environment," November 8, 2016 (summary and presentations available online at: www.iea.org/workshops/the-future-role-of-trucks-for-energy-and-environment.html).

Nearly all of these measures rely on some form of supply chain collaboration. Most broadly, supply chain collaboration can be either vertical (including collaboration with suppliers on the one hand and consumers on the other), or horizontal (i.e. at the same level in the transport

[19] Estimates are taken from compiled literature and/or through consultations with experts. The potential energy-saving ranges quoted do not include indirect or consequential impacts (e.g. rebounds resulting from increased demand as a consequence of reduced prices for inputs by manufacturers along the supply chain and goods by consumers). Also, estimates do not account for the overlap among measures; if multiple measures were to be adopted, one would typically expect diminishing marginal returns for each additional policy (although there are instances where policies could interact synergistically). The ranges shown indicate the impact only within a given regime of operations. For instance, while platooning may reduce energy use for heavy-freight trucks (HFTs) during steady-speed highway driving, it has no impact in heavy highway traffic or in urban driving.

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supply chain). Horizontal supply chains can be consolidated internally, or they can consist of external collaboration across firms (Barratt, 2004). In the figure, measures in blue are those that can be implemented by a single company, while those in green require multi-company (i.e. external) collaboration. As co-operation across firms requires a basis of trust, data privacy and protection, and clear long-term benefits that outweigh the potential costs, external collaboration in itself poses certain barriers to be overcome.

In the following, we provide a brief description of each measure that would allow for systemic improvements, as shown in the figure, and discuss the potential opportunities, enablers and barriers that could influence the speed and degree to which each measure can be realised. Concrete examples of measures as implemented to date, as well as current debates on the actual efficiency of certain measures, serve to provide further context. The discussion is split by those measures that have mid-to-low adoption barriers (to the right in Figure 20) and those that have high barriers and, hence, would require dedicated and co-ordinated action by firms in the supply chain (and their potential disruptors) as well as policy support.

Measures with low barriers to adoption

There is a wide range of operational modifications in road freight that can translate to efficiency improvements, while increasing bottom-line profitability by driving down shipping costs (Table 11). Many such logistics measures have already been implemented in various regions at the level of the municipality, subnational region, country or international regional trade bloc. In some cases, they are being implemented directly by the operators themselves as the benefits tend to outweigh the costs. In other cases, realisation of such systemic efficiency improvements requires at minimum a co-ordinated public and private collaborative effort to collect basic data on freight operations as a means of understanding the current systemic inefficiencies as well as best practices. Steps toward making such benchmarking common practice have been taken in certain countries, and there are promising initiatives to extend technology and vehicle operation benchmarking programmes to incorporate a wider array of logistics practices.

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Table 11 • Measures to improve systems efficiency in road freight with low implementation barriers

Category	Enablers	Barriers	Potential energy saving	Examples / Notes
Use of high-capacity vehicles (HCVs)	Performance-based standards Intelligent Access Program as in Australia	Concerns about safety and road infrastructure impacts; potential for 'reverse' mode shift (away from freight rail); increased demand for just-in-time delivery	Direct savings may be upwards of 20%, but actual savings may be lower, depending on the extent of activity rebound and of modal shift from rail.	Regulations allow for the operation of HCVs at the national or regional level in Australia, Brazil, Canada, Finland, Mexico, South Africa and Sweden.
Route optimisation	Geographic information system real-time routing data Relaxing delivery time constraints	Increased demand for just-in-time delivery	From 5%-10% for intra-city trucking, but closer to only 1% for long-haul missions.	UPS ORION, which in 2017 began its global rollout.
Platooning*	Vehicle communication and automation technologies	Traffic congestion, and mixed traffic; road capacity limitations. Need to ensure safety	From 5% to 15% for a three-truck platoon traveling at 80 km/h (depending on gap distance).**	Japan's "Energy ITS" (2008); the California PATH programme (2011); the European Commission's SARTRE project (2017).
Driver training and feedback	Rewards programmes in mid- to large fleets	Lack of consolidation among carriers (many small owner-operators)	Immediate savings of between 3% and 9% (the latter in long-haul operations).	FleetSmart, Canada, as well as many examples among Finnish, German, US and other carriers.
Improved vehicle utilisation (including backhauling)	Better data collection (as enabled by ICT) Collaboration and on-line exchanges alliances among carriers and logistics service providers (LSPs)	Legal frameworks that restrict anti-competitive behaviour (and thereby impede co-ordination among carriers, shippers, and LSPs). Lack of industry consolidation among carriers.	Potentially substantial, but difficult to quantify. Savings are enabled by better tracking basic freight operational parameters and adopting industry best practices in logistics.	The European Union's CO3 Project on horizontal supply chain collaboration. Online freight exchanges co-ordinate a large fraction of road freight movements in the United States and the United Kingdom.
Last-mile efficiency measures	Prediction of dynamic demand Increased competition, including market entry of LSPs	Increased demand for just-in-time delivery Urban traffic congestion	Likely in the range of 1-5%.	Delivery service plans developed by Transport for London; Binnenstadt service in 11 towns in the Netherlands.
Re-timing urban deliveries	Incentives to shipment receivers to accept the insurance and logistical impacts of shifting to early morning and off-hour deliveries	Concerns from local citizens about noise Customer concerns with product quality and condition upon delivery Constraints imposed by just-in-time delivery	Very difficult to estimate and generalise. Across the urban truck fleet as a whole, fuel- and GHG emission reductions are estimated in the range of 10%-15%.	A complete shift to off-hour deliveries led to a reduction in local pollutants in the range of 45-67% in New York, Bogotá and São Paulo. Pilots include POLIS (European Union) and PIEK (the Netherlands).
Urban consolidation centres (UCCs)	City regulatory policies to reduce congestion and promote air quality	Design is highly city-specific, making dissemination of best practices difficult Fiscal sustainability challenges in the absence of a dedicated public funding stream or viable business model	Vehicle activity, fuel use and CO_2 emissions within urban centres can be reduced by 20-50%.	UCCs group shipments from multiple shippers and consolidate these onto a single truck for delivery to a given geographic region. Various global cities, most of which are located in Europe, and Japan.

* Platooning refers to the practice of driving heavy-duty trucks (primarily tractor-trailers or rigid trucks) in a single line with small gaps between them to reduce drag and thereby save fuel during highway operations. Vehicle-to-vehicle and vehicle-to-infrastructure (V2V and V2I) communication technologies can enable trucks to drive in very close proximity without sacrificing safety or manoeuverability.

** According to Tsugawa, Jeschke and Shladovers (2016), the average fuel saving for three trucks driving at 80 km/hr with a 10-m gap is about 8%, and 15% with a 4-m gap. High levels of vehicle autonomy would be needed to safely operate trucks with a 4-m gap.

Sources: Browne, Allen and Leonardi (2011); Wiki4City (2014); Holguín-Veras (2016); McKinnon (2016b); Wallenburg and Raue (2011).

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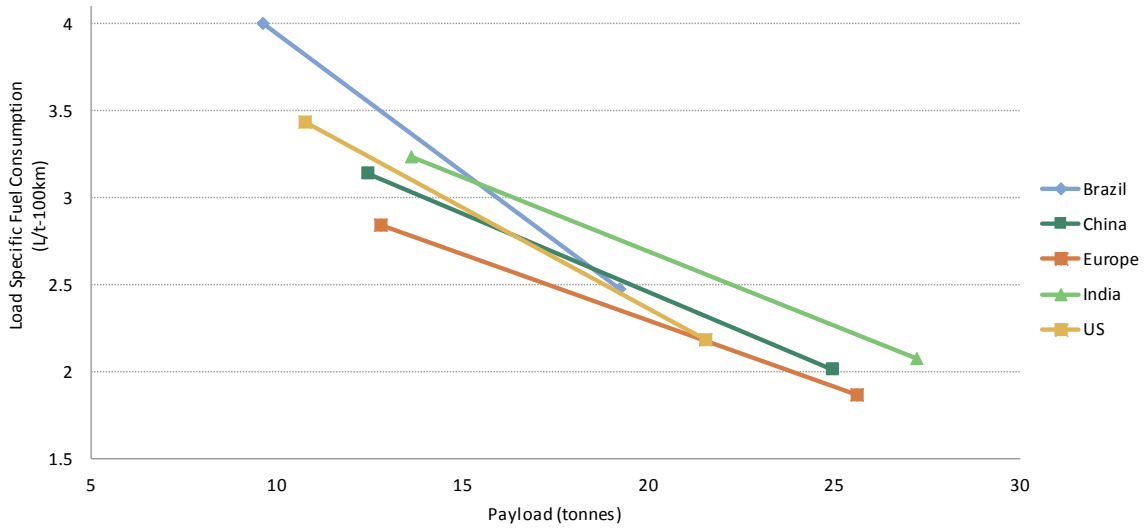
What follows is a brief description of each of the measures.

Use of high-capacity vehicles

The relationship between the gross vehicle weight (GVW) of a truck and its fuel consumption is not one-to-one. An increase in a truck's size and payload leads to a smaller proportionate increase in fuel consumption. In other words, larger trucks with heavier payloads haul each unit of freight with less fuel than smaller trucks, all else remaining equal (Figure 21).

Figure 21 • Relationship between truck laden weight and fuel consumption



Notes: The figure estimates fuel consumption using the World Harmonized Vehicle Cycle, which may not prove representative of actual on-road duty cycles in the countries modelled. Furthermore, the utilisation rate may differ systematically by vehicle payload; empty and full payloads vary substantially across markets; as summarised in Table 12, each national market has its own maximum weight limits, and kerb weights also vary.

Source: GFEI (2016).

Most countries and jurisdictions have restrictions on truck size and weight. These have been put in place mainly to limit wear and tear on roadways and bridges and to address safety concerns. On highways, in particular, usage restrictions for intercity truck transport typically set a maximum number of axles and specify a maximum axle load[20] for heavy-duty tractor-trailers. Most countries impose similar restrictions on vehicle weights, dimensions and other physical attributes (such as the height of the centre of gravity) on single-unit trucks and articulated semitrailers. For example, single-unit trucks, which make up around 40-45% of HFT sales in Europe and the United States, are restricted to less than 27 t of GVW in many countries.

Of the countries shown in Table 12, Finland, Brazil and Sweden allow for the heaviest trucks, at 76 t, 74 t and 60 t, respectively. Finland is also testing even larger vehicle combinations (34.5 m long and up to 104 t) with exemptions that permit them to drive on certain roads. In Brazil, the so-called "road train" has a gross combination vehicle weight of 74 t, up to nine axles and a length of 25 m to 30 m. In 2016, Brazil approved the use of trucks up to 91 t based on special authorisations. In the United States, federal truck size limitations are more restrictive. However, federal restrictions in the United States apply to the network of interstate highways, which comprise the dominant share of truck routing, however most states allow for larger vehicles to

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[20] The axle load is the fraction of the vehicle weight borne by a single axle.

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operate within their jurisdiction, provided the trucks are approved and have obtained the proper permits.

Table 12 • National vehicle weight and dimension limits in various countries

Country	Single unit (three axles)		Road train (four axles)		Articulated vehicle (five or more axles)	
	Weight (t)	Length (m)	Weight (t)	Length (m)	Weight (t)	Length (m)
France	26	12	38	18.5	44	16.5
Germany	26	12	36	18.5	44	18.75
Sweden	26	24	38	25.25	60	24
Finland	26	12	36	25.25	76	16.5
Brazil	--	--	--	--	74	30
Russian Federation	28	12	36	20	44	20
United States	27	--	32	--	40	--
Mexico	23	14	31.5	20.8	47.5	23
United Kingdom	26	12	38	18.75	44	16.5

Notes: The International Transport Forum collects more detailed information on permissible maximum weights and dimensions of lorries and coaches in Europe at www.itf-oecd.org/weights-and-dimensions.

Sources: ITF (2015), US DOT (2015), SEGOB (2014).

There is some momentum for revising restrictions in favour of frameworks that permit so-called high-capacity vehicles (HCVs)[21] without compromising infrastructure durability or safety. Recent ex post analyses[22] after permitting the use of HCVs has shown that HCVs can and do tend in practice to be operated more safely than typical heavy-duty vehicles as a result of investments made in driver training and safety technologies (which become affordable to operators due to higher profit margins from running the trucks).

However, there is a risk that enabling high-capacity vehicles could potentially lead to a 'reverse' mode shift from rail to road freight as a result of improved efficiencies and cheaper goods transport by HCVs. But the lack of reliable data limits the accuracy of efforts to assess this effect. HCVs are likely to improve the efficiency of road haulage, but there is not yet enough evidence regarding the extent to which the resultant reductions in energy use and CO_2 emissions are counteracted by rebounds, or on the factors influencing the extent of rebounds.

From a policy perspective, performance-based standards (PBSs), which have been tested for over a decade in Australia, are seen as a promising way to replace current limits on vehicle weights and dimensions with design criteria that ensure that vehicles operate as desired on roadways. Rather than imposing constraints based solely on the physical attributes of a vehicle, such as its weight and dimension, PBSs mandate that vehicles are able to meet specific performance criteria in common operational settings, such as on low-speed support paths, gradability, and rearward assistance. The intent of PBSs is to more rationally apply regulations that ensure the safety and durability of infrastructure while allowing for flexibility in business and technical innovation to ship goods more efficiently. Provided that the outcomes of interest are defined and measured,

[21] HCVs go by many names: in the European Union, the European Modular System is the concept of combining trailer units into longer, and in some cases heavier, trucks; in the United Kingdom, sustainability advocates promote the transition to "longer, heavier vehicles" and some Canadian provinces permit "long-capacity vehicles".

[22] For instance, in South Africa, HCVs have thus far achieved a 60% reduction in accident frequencies compared with conventional heavy-duty trucks driven under a similar pilot programme that is an opt-in, accredited certification scheme (Nordengen, 2016). Studies in Canada show long-capacity vehicles to be vehicles three to seven times safer (on a vkm basis), due to the fact that a portion of the energy efficiency savings can be reinvested in better driver training, more sophisticated routing and other safety-enhancing measures.

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pilots of PBSs and HCVs could help to prove or disprove the utility of enabling HCVs. But PBSs do not come without concerns. As PBSs enable vehicles to operate on certain routes given a particular freight task, companies might inappropriately exploit the flexibility enabled by the standards, such as by driving on non-PBS designated roads. For these reasons, Australia coupled its PBSs with the Intelligent Access Program (IAP) in 2008 to address concerns by monitoring vehicle operations using satellites and wireless tracking technologies. The IAP can be used to verify strict compliance and to monitor HCVs' potential impacts on safety and infrastructure durability. If applied judiciously to restrict HCV operations on long-haul corridors where viable and/or competitive rail or waterway networks exist, it could reduce the risk of a reverse modal shift (McKinnon, 2017).

Route optimisation

Among the most obvious ways of saving fuel is optimising delivery routes. Global Positioning System (GPS) units can assist drivers in finding the shortest route, avoiding traffic congestion, and with the tracking and dispatching of vehicles. The penetration of GPS units is already high, particularly in industrialised countries. For example, in the United States, between 76% and 95% of vehicle activity across all long-haul operations by carriers uses GPS and other routing technologies (NACFE, 2016), while in the United Kingdom, it was 35% in 2010, up from 13% in 2004. GPS units have already become inexpensive, particularly relative to the costs of fuel on a per km basis, and thus have a very short payback period.

Geographic information systems (GIS) plus real-time routing data have been estimated to enable time and fuel savings ranging from 5% to 10% for intra-city trucking, but more typically closer to only 1% for long-haul missions in road freight (Carbon War Room, 2012). Various large logistics companies are increasingly relying on routing systems to reduce fuel costs – one example is UPS ORION, which in 2017 began its global rollout. Further savings may be possible, particularly if policies effectively relax delivery time constraints (e.g. by allowing for night-time deliveries in cities).

Platooning

Platooning refers to trucks that closely follow each other and are equipped with state-of-the-art driving support systems, forming a platoon of trucks driven by smart vehicle communication and automation (CAV) technologies. The trucks communicate, meaning, for example, that if the first truck brakes, the following one will brake immediately without any reaction time, improving road safety. This allows trucks to drive closer together at near-constant speeds, which reduces air resistance (and thereby fuel consumption) and increases the capacity of roads.

The fuel savings of truck platooning are estimated to range from 5% to 15% for a three-truck platoon travelling at 80 km/h. The lower bound of this estimate represents an average across all three trucks driving with a 20 m gap (Tsugawa, Jeschke and Shladovers, 2016). The upper bound applies to a 4 m gap; such fuel savings potential is possible only with automation (Wadud et al., 2016). The actual efficiency improvements, CO_2 savings and costs are likely to vary significantly across regions with differing fleet structures and baseline technology penetrations. They depend not only on the composition of the truck fleet but also on the mission types and other variable conditions of the actual operations (such as the road quality, road grades, speed limits and congestion profiles).

Platooning demonstrations facilitated by CAV technologies began as early as 2008 in Japan with the country's "Energy ITS" project (Tsugawa, Jeschke and Shladovers, 2016). The demonstration employed sensors and systems for lateral and longitudinal control and V2V communication, features that have continued to be exploited to the present day in more recent demonstrations. The potential for platooning is limited by highway capacity and road quality. Autonomous and

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assisted driving technologies will promote the technical feasibility and effectiveness of platooning.

Driver training and feedback devices

Investments in driver training and the installation of feedback devices that monitor and reward more fuel-efficient driving, as well as predictive cruise control, tend to be among the most consistently cost-effective operational measures with the fastest payback periods, which tend to be reliably less than two years across a wide range of vehicles and missions (Greening et al., 2015). The greater potential for such programmes to cut fuel use and CO_2 emissions is in the long-haul segment (both by 9%), but fuel use can be cut by around 5% even in urban operations. Fleets that offer bonus pay or other rewards for fuel-efficient driving have also found such programmes to reduce costs.

Technologies like (predictive) cruise control and real-time fuel economy monitors can enhance the efficacy of conventional courses. Such instruments also enable monitoring of driver performance, which can be used to measure and verify fuel savings.

Improved vehicle utilisation

The wider logistics system within which trucks operate imposes limits on the extent to which they are able to haul cargo versus what is known in trucking parlance as "shipping air". It is a question of vehicle utilisation, which has a number of different perspectives to it. First and foremost, it is a matter of trucks that are operated below full cargo weight: when laden, trucks may carry only about 40-60% of their maximum rated payload.[23] There are a variety of deficiencies in logistical processes that explain why this may occur. But this does not mean that additional tonnage is necessarily available. For example, on many deliveries, trucks fill their cargo volume (or "cube-out"), and so their operations are often volume and not weight constrained.

Maximisation of the loads carried by trucks can generally be achieved both via internal logistics improvements and through external (i.e. across-firm) collaboration. In terms of operations within a single firm, the principal way of realising improved loads is through more systematic monitoring, collection and analysis of shipment operations (also across road, rail and shipping), for which purposes ICT (including GPS and other on-board devices, and fleet management software) can be harnessed to great effect.

Collaboration with other firms (i.e. external collaboration) requires standardised data on weight and volumes on a common platform.[24] Online freight exchanges or procurement platforms can enable "load matching" across various shippers, thereby increasing laden trip utilisation as well as reducing the share of empty running. In some countries, such as the United States and the United Kingdom, online markets for logistics services have been in place for nearly 20 years and have come to operate over a large fraction of road freight movements (McKinnon, 2016b). Alliances among carriers to group shipments are also already

[23] The 40% figure is for Japan; Srinvasan and Leveque (2016) report average utilisation rates on loaded trips of 56% for the United States and 54% for Europe.

[24] Collaboration among companies is most effective in regional markets in which many shippers or logistics service providers (LSPs) of roughly similar size (and where none dominate the market) fulfill shipments that are smaller than their trucks' capacity under tight deadlines, to customers that are distanced from one another (Cruijssen et al., 2007a). The main barriers to external horizontal alliances are the challenges of establishing and maintaining trust among companies, and of defining a fair mechanism for allocating benefits. However, provided these challenges can be successfully overcome, most LSPs expect for such collaboration to be an effective cost-saving measure. Setting up formal mechanisms for information sharing, contracts for aligning and apportioning benefits and costs, and maintaining flexible relationships can all facilitate co-distribution, and ICT provides a secure and transparent medium for doing all three (Cruijssen et al., 2007b).

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quite common in Germany and Italy (Wallenburg and Raue, 2011). Start-ups have begun to emerge on digital platforms, seeking to disrupt established LSPs and 3PLs. These firms have developed apps aiming to streamline fleet management, match shippers and LSPs with carriers, improve cargo matching and plan backhauls. For instance, 27 technology start-ups have emerged in the past five years in the United States (Buxbaum, 2016).

Projects to demonstrate and promote external collaboration have shown their effectiveness and begun to delineate the barriers it still faces. In the United Kingdom, the Starfish project used data collected from the fast-moving consumer goods sector to model the opportunities from backhauling, the reconfiguring of logistics networks, and other changes to logistics operations requiring external collaboration. The European Union's CO3 Project aims to promote external collaboration by applying knowledge acquired on enablers and barriers on a case-by-case basis (Greening et al., 2015).

In developing and emerging economies, public and commercial platforms are at a much earlier stage of commercialisation, though they are being promoted in countries such as Viet Nam by green freight alliances.

National and regional initiatives to collect such data would be the first step toward facilitating external collaborations and could take the form of incentives and/or mandates. Ultimately, however, co-operating firms will need to share more detailed data, including delivery deadlines, origins and the destinations of loads. Third-party platforms, as well as legal and technical frameworks that ensure proprietary data are protected, are needed to provide confidence that the risks of collaboration are outweighed by the benefits. Collaboration platforms, such as E2OPEN, GTNEXUS and Nallian, are in their infancy but may benefit from blockchain technology (an open-source, anonymous record-keeping system used, for instance, by bitcoin).

Shifting to bigger vehicles, using (urban) consolidation centres, and relaxing time constraints (including just-in-time [JIT] delivery) are also among the most effective available means for improving vehicle loads. In certain regions, regulations intended to prohibit anti-competitive market practices may hinder external collaboration. In such instances, regulations could be revised to clarify the types of logistics collaboration they permit. Substantive liberalisation allowing collaboration across logistics operations could be complemented by requiring companies to share data – which could be anonymised or aggregated as necessary – on their operations that allow regulators to measure crucial metrics, including energy and carbon intensity trends.

Backhauling

Backhauling is a specific case of improving vehicle utilisation and refers to the practice of delivering cargo on return trips, thereby offsetting other trips. Realising most of the efficiency potential from backhauling requires collaboration across shippers, which typically has higher barriers than most other measures listed in this section. Surveys, nevertheless, suggest that efforts to reduce empty running are widespread – for instance, 90% of regional and long-haul carriers in the United States cite it as a common practice (NACFE, 2016).

Running vehicles empty cannot entirely be avoided, as mismatches between vehicle and cargo, together with delivery constraints, logically dictate some degree of empty running. Available data from the United States and the European Union suggest that about 25-30% of vehicle-kilometres are run empty.[25]

[25] De Angelis (2011) estimates that 27% of vkm in the European Union are run empty. Frost and Sullivan (2016) corroborate this figure for more recent years and estimate that in the United States, 25% of truck vkm are run empty. In the United Kingdom, the share of vkm without any cargo was estimated at around 29% in 2013 (DfT, 2015a).

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Time constraints are the major barrier to carriers taking advantage of backhauling (Cherrett et al., 2012). Relaxing scheduling constraints would hence be an effective way to promote the practice. Empirical studies find that the potential for backhauling to reduce vehicle-kilometres is somewhere between 2% (Greening et al., 2015), with the latter estimate being possible by lifting time constraints to give more time between delivery and pickup to enable cargo matching. In fact, the potential for backhauling is likely much greater in regions where logistics and supply chain operations are less optimised. Backhauling may also be promoted by better fleet and logistics management practices (internally to a carrier) or by data sharing and (external) collaboration.

Co-loading

Co-loading is another specific case of increasing vehicle utilisation and refers to bundling shipments across product categories with similar shipment characteristics (e.g. destination and time constraints). It takes the form of improved economies of scale (e.g. through joint route planning) and of scope (e.g. through the sharing of warehouse resources) (Van Lier et al., 2010).[26]

Co-loading can be realised through two kinds of supply chain collaboration: internal collaboration across warehousing functions, and external collaboration with a non-competing firm. Internal (horizontal) collaboration requires cross-dock operations at seaports and better integration within and across nearby distribution centre or warehouse operations. Internal cross-product co-loading at ports and distribution centres has an impact on operations, such as the trailer throughput time and standing time, and the capacity utilisation of gates (Van Lier et al., 2010).[27] In the case of external collaboration, co-loading with a complementary shipper can result in increased outbound and inbound shipment loads.

The barriers to implementation of co-loading are higher than for the other means of improving vehicle utilisation discussed previously. For this reason, co-loading is listed among the systemic measures with high barriers to implementation (Table 13).

Box 5 • Limiting speeds – Delaying delivery or improving overall cost-effectiveness?

Among the most obvious ways to reduce fuel consumption from road freight trucks is the reduction of truck speed. The literature evidence is very clear: the fuel economy benefits that could be gleaned from reducing the speed of freight trucks range from about 7% (US EPA, 2009) up to 27% (Garthwaite, 2011) for a reduction of 10 miles per hour (mph). Franzese and Davidson (2011) found that fuel economy of medium- to heavy-duty trucks carrying heavy loads (with a total vehicle weight of greater than 65 000 lbs or about 29.5 t) on highway operations reaches its maximum from about 80 km/hr to 105 km/hr, and that the optimal speed within this range is, in fact, 59 mph (around 95 km/hr). The US Environmental Protection Agency further estimates that a typical combination truck spends at least 65% of its operating time driving at highway speeds (US EPA, 2009). Cooper et al. (2009) estimate that reducing speeds by 1 mph would result in an average 0.7% reduction in fuel consumption (or a 0.43% reduction per 1 km decrease in cruising speed). Most European countries mandate the use of speed governors on trucks, i.e. devices that limit truck speed. In the United States, although such devices are not mandatory, large fleets typically use them, and the majority (85-90%) of operators take measures to limit highway speeds (NACFE, 2016). Indeed, reducing the speed of highly energy-intensive modes, like road freight (and

[26] Hageback and Segerstedt (2004) found that "co-distribution" – horizontal collaboration across companies, which results in better filling of incoming and outgoing trucks between distribution centres and demand hubs – across 20 companies in Sweden reduced costs by more than one-third and indeed became an essential component of competitive practices.

[27] A case study of the potential to exploit internal co-loading potential at the European Distribution Centre in Flanders found that average vehicle fill rates could be increased by 5%, the share of trailers carrying less than have a full load could be decreased from 34% to 23%, and the greater utilisation of trailers could result in an 8% decrease in the number of trailers needed to fulfill orders (Van Lier et al., 2010), all without any changes in warehouse planning processes.

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including international shipping as well), is one of the few measures that is unlikely to incur any rebound effect (McKinnon, 2016c). However, the potential to save fuel by reducing speeds is limited in developing countries, where speeds are restricted in any case on many routes by suboptimal highway infrastructure.

An effective programme of reducing the carbon intensity of the logistics supply chain would require incorporating carbon emissions data into value chain mapping and, in particular, understanding the relationship between carbon intensity and time over all the stages of a given supply chain. This would include the production, storage and consolidation stages at each node (including the final point of sale) as well as during transport, loading and unloading (McKinnon, 2016c).

Finally, while road and shipping speeds can be reduced, increasing the speed of rail may improve its competitiveness and complementarity (in co-modal operations) with roads, thereby further minimising logistics emissions. Improvements in logistics management, including all of the systemic improvement measures outlined here, could enable deceleration in road and shipping operations without incurring any resultant lag between order and delivery. That is, the increase in movement and transit time could be (potentially more than) offset by reduced order lead time and storage at (production, distribution and final retail) facilities. While relaxing "just-in-time" delivery constraints may well contribute to reduced life cycle emissions, only by mapping the emissions across a specific supply chain can its efficacy (or counter-effectiveness) be determined.

Urban logistics: Last-mile efficiency measures, re-timing urban logistics, and urban consolidation centres

Improving urban logistics is another key element of systemic improvements with potentially limited barriers to adoption. The exposition of the potential measures in this realm is split into three parts, which are briefly outlined below: last-mile efficiency measures, the re-timing of urban deliveries, and urban consolidation centres.[28]

Last-mile efficiency measures

As household and small business demand grows for the rapid delivery of a growing basket of goods, a growing share of energy use and emissions is incurred in the "last mile" of delivery. The allocation and prediction of dynamic demand can help to prepare for and smoothen seasonal and daily peaks. In theory, increased competition among urban carriers should lead to greater last-mile efficiency. Particularly in congested urban regions, there may be potential for logistics service companies to capitalise on ICT and the sharing economy to more cheaply and efficiently ship goods over the last mile (see the sections below on crowdshipping and digital freight matching), though the viability and potential for emission reductions of such business models remain to be proved. Innovations in the realm of last-mile deliveries include "click-and-collect" options, such as DHL's Packstation, local store collection and return options for online purchases, and the use of unattended drop-boxes at apartments and private residences.

With the growth of online retail and demand for "just-in-time" delivery, the relevance of last-mile deliveries is set to grow. Relaxed delivery times can stimulate flexibility and increase the potential for bundling of cargo in last-mile deliveries.

[28] In addition to the measures outlined here, the shift of freight activity to human pedal-powered, pedelec or electric cargo bikes (for instance, UPS, FedEx and DHL began using e-trikes for deliveries in Europe as early as 2013 [electricbike.com, 2013]; more recently, DHL has scaled up its City Hub concept [RedRobot, 2017]; electric and conventional internal combustion engine (ICE) motorbikes are often commonly used for delivery in Asian cities) or to drones (see Box 6) (Goodchild and Toy, 2017) are options that may offer limited potential to reduce energy use and emissions of urban "last-mile" deliveries, particularly of high-value and lightweight products.

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Re-timing urban deliveries

A complete shift to off-hour (or night-time) deliveries has been shown to lead to a reduction in local pollutants in the range of 45-67% in cities such as New York, Bogotá and São Paulo (Holguín-Veras, 2016). The fuel and CO_2 emissions savings are also likely to be considerable, but across the urban LCV and MFT fleet, as a whole, they are estimated more conservatively to be in the range of 10-15%. A crucial prerequisite for successfully shifting to off-hour deliveries is to provide incentives to shipment receivers (such as grocery stores and retail outlets) to accept the insurance and logistical impacts of shifting to early morning deliveries. Proof that night-time operations can be performed without excessive noise will also be needed to convince sometimes sceptical nimbyism.

Urban consolidation centres

Various cities, most of which are located in Europe (and a few in Japan), have effectively reduced local traffic and emissions by setting up urban consolidation centres (UCCs). By grouping shipments from multiple shippers and retailers and consolidating them onto a single truck for delivery to a particular geographic region, vehicle activity and CO_2 emissions within urban centres can be reduced by an estimated 30-80% (Allen et al., 2012).

As many cities in the developed and developing world alike struggle to reduce air pollution, UCCs may prove an effective and attractive measure for reducing congestion and emissions. However, the design of UCCs is highly specific to individual cities, making dissemination of best practices difficult. To promote their incorporation into the urban delivery network, municipalities may consider easing land use restrictions in appropriate locations. Moreover, by adding a link to the supply chain, UCCs may increase delivery costs (Cherrett et al., 2012). Indeed, many existing UCCs in European cities have required additional public funding (e.g. from local councils, municipal governments or the European Union). In some cases, UCCs have been able to improve their fiscal viability by incorporating value-adding activities, such as store preparation and waste packaging collection.

Measures with high barriers to adoption

The above measures can improve the overall efficiency of freight logistics at relatively low costs and with generally low-to-modest barriers to implementation. Yet, there are further measures that can improve the overall system efficiency. They require even closer collaboration, including the sharing of assets and services between and among companies (i.e. “horizontal collaboration”) and a more radical re-envisioning of how logistics systems operate. Such measures would require considerable political and institutional commitment to overcoming barriers and, in some cases, to ensuring that such changes actually do bring about overall systemic benefits from an energy efficiency and environmental point of view. Policies that reward efficiency and collaboration, as well as regulations and/or pricing to discourage “just-in-time” and same- or next-day deliveries and other similar practices, can drive radical changes and lead to further improvements in the efficiency of the overall road freight system.

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Table 13 • Measures to improve systems efficiency in road freight with high implementation barriers

Category	Enablers	Barriers	Potential energy savings	Examples/Notes
Physical Internet	Legal and regulatory frameworks; ICT to collect, process and protect proprietary data	Anti-trust or other non-harmonised national legislative frameworks	Work to date on this concept suggests a potential 20% systems-wide efficiency improvement.	An open, shared system of all physical resources (e.g. ports and warehouses) used in goods delivery. The realisation of complete collaboration across shippers and carriers to maximise vehicle utilisation (Wible, Mervis and Wigginton, 2014).
Co-loading*	Legal and regulatory frameworks to promote energy savings while protecting companies' intellectual property	Just-in-time delivery; lack of industry consolidation among shippers and carriers	Estimated at 5-10%.	Co-loading uses supply chain collaboration within a company and/or across firms to increase vehicle utilisation (load) on outbound operations (Van Lier et al., 2010).
Crowdshipping/ Co-modality/Digital freight matching**	Deregulation of urban delivery markets as well as the protection of citizen-carriers' labour and liability	Legal and regulatory hurdles surrounding liability and insurance Requires a certain scale to realise savings	Difficult to assess; highly dependent on the degree of spatial and temporal matching. Likely 5-10% in urban areas, with the possibility of counterproductive impacts.	**Crowdshipping**: a recent proliferation of platforms and apps in Australia, the People's Republic of China (hereafter, "China"), the United States and throughout the European Union. **Co-modality**: examples of using public transport infrastructure to ship goods exist in a few European and East Asian cities. **Digital freight matching (DFM)**: a proliferation of start-ups, concentrated in the United States, have entered the DFM market in the past five years.
Autonomous trucks	Clear and standardised regulations on technology certification, liability, security and privacy	Truckers' unions; hasty rollout could result in a single accident leading to public backlash	Limited and estimated to be 5% from smoother driving in other conditions. Potential rebound effects might be very substantial.	Rio Tinto's autonomous mining trucks in Australia (Rio Tinto, 2014). Otto's autonomous highway beer delivery (Isaac, 2016).

* Co-loading is discussed in the previous section as it is among the measures that can be taken to improve vehicle utilisation.

** Crowdshipping is when citizens perform the services of couriers. Co-modality refers to the usage of (often public) passenger transport modes for freight delivery. Digital freight matching is the use of online platforms and apps to match vehicles and cargo in real time. All three are described in more detail below.

The physical Internet

The "physical Internet" describes an open, shared global logistics system inspired by the movement of data on the Internet, in contrast to the proprietary logistics systems that are common today. Currently, nearly all logistics service providers and carriers maintain proprietary assets, both physical (e.g. warehouses and trucks) and operational (e.g. information on routes, customers and markets). Many LSPs and carriers compete on the basis of these assets and see their exclusivity as both a source of competitive advantage and a barrier to clients' switching to another shipper (Wible, Merivs and Wigginton, 2014).

The physical Internet is intended to eliminate competition on the basis of supply chain secrets – companies would compete on the basis of their products, not how well they are

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delivered – and enable complete external collaboration.[29] Achieving this would require developing standardised containers, a common protocol and tools, and shared transport and technological assets (Wible, Merivs and Wigginton, 2014). Delivery of standardised, modular packages between the nodes (shared ports, warehouses, and distribution and consolidation centres) that make up a network would allow for fast stacking and combining. Shared and real-time information on the origin, destination and delivery date of each package would be based on the open and connected data collection and software systems (Trebilcock, 2012). Certain data would be open not only to logistics service providers but, in certain cases, also to manufacturers and customers. Such data would include the times and locations of product orders, location and delivery (Wible, Merivs and Wigginton, 2014).

While work to date on this concept suggests a potential 20% systems-wide efficiency improvement, the benefits of realising such a shared network of physical resources and data may extend beyond greater efficiency:

- By rationalising the supply chain, companies' profits could increase even while prices faced by consumers decline.
- Reduced road freight delivery distances would translate to less road congestion (Sarraj et al., 2014).

However, taking advantage of the physical Internet for the overall improvement of road freight efficiency faces significant barriers. The technology is generally ready to deliver: digital information, communication and GIS technologies will help streamline the collection, processing and effective exploitation of data. The challenge lies in making use of and sharing such information: platforms for sharing data among actors in the manufacturing and supply chain (including manufacturers, LSPs, carriers and consumers) will need to ensure that proprietary data are protected. In certain regions, anti-trust or other non-harmonised national legislative frameworks may pose barriers to the deep levels of collaboration required to realise the vision of the physical Internet. Streamlining and revising regulations would permit, and even incentivise, logistics and supply chain collaborations, as well as facilitate anonymised and aggregated data collection by public authorities. Regulations may be required to monitor collaborations and to ensure that the reduced costs of shipping are passed down to consumers.

Crowdshipping, co-modality and digital freight matching

The distinctions between crowdshipping, co-modality and digital freight matching are blurry as the three concepts are somewhat intertwined. Crowdshipping refers to the phenomenon of recruiting citizens to serve as couriers, which has to date been primarily an urban phenomenon. Citizen-couriers may be enticed to serve in the delivery chain by not only offering reimbursement for their services but by appealing to their sense of civic pride or duty. As such, crowdshipping can be seen as a kind of "co-modality", a term that was coined by the European Commission in 2006 and refers to the use of one or multiple transport modes to optimise resource use for economic, societal and environmental benefits (CEC, 2006). More narrowly within the field of urban logistics, co-modality has been used to denote the use of primarily public (but also private) modes that are traditionally for passengers (such a buses, taxis and light rail) for the movement of urban goods.

[29] For instance, in the European Union, the publically funded Modulushca (Modular Logistics Units in Shared Co-modal Networks) research initiative aims to use ICT technologies to develop a standardised, modular "smart" container capable of being loaded and unloaded efficiently on both trucks and trains. Firms such as P&G have backed the vision. The EU CO3 project seeks to promote external horizontal collaboration across logistics companies and bundle shipments across carriers. The project's high-level industry board is made up of 35 European companies, representing a range of industries (EU CO3, 2017). In France, the retailers Carrefour and Casino shared their data with researchers, who demonstrated that shifting to shared operations could lead to multiple and substantial benefits.

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Digital freight matching uses online platforms and mobile apps to match cargo and vehicles. As such, it aims to revolutionise the conventional function of LSPs, 3PLs and brokers, thereby reducing shipment costs and increasing shipment efficiency. While the use of such apps is by no means limited to urban regions, they may prove to be most disruptive in this context. To the extent that private vehicle owners or public transit operators are allowed to and in fact do use digital freight matching platforms to deliver goods (particularly in cities), this latter innovation may overlap with the previous two.

Crowdshipping

Crowdshipping is effectively a means of translating the concept of crowdsourcing to freight and is intended to accommodate last-mile delivery through deploying a wide number of individual citizens as couriers. Overall systemic efficiency improvements occur if the people who act as couriers take routes that they would have made anyway (i.e. if they were not being enlisted to deliver goods). Under such conditions, crowdshipping offers an enticing solution to the environmental inefficiencies and the low margins of the last mile of freight delivery.

Over the past six to seven years, online crowdshipping platforms have proliferated, particularly in the United States but also in Australia (MeeMeep), China, Finland, Germany, the Netherlands and Norway (McKinnon, 2016d). The businesses that have entered this new market, including Roadie (United States), Zipments (New York City) and numerous others, are all marketing this aspect heavily. Bigger companies, including Walmart, DHL and Uber, have also joined the market with city-level pilot projects, such as DHL's short-lived experiment, the MyWays service, in Stockholm; or spin-off services like Uber's UberRUSH parcel delivery service (Uber, 2017). The online retailer Amazon has scaled up its own pilot crowdshipping platform, which was started in Seattle in 2015, to include 29 US cities and one UK city as of 2016 (McKinnon, 2016a).

Depending on how crowdsourcing develops, there may be potential societal drawbacks. Insurance issues may arise when couriers deliver goods that are fragile, dangerous or illegal. Until services reach a sufficient scale, they are also likely to have difficulties in ensuring adequate service coverage and quick deliveries. Couriers may be exploited – if they undervalue their own time and neglect vehicle depreciation costs (and instead only anchor their costs to fuel). There is also the potential for a rebound (through lower costs) in urban freight delivery activity and hence greater congestion and emissions and reduced system-wide efficiency.

Ultimately, the degree to which the latent efficiency potential can be exploited via crowdsourcing depends on the degree of spatial and temporal matching, that is, the overlap between trips that would be taken anyway and the delivery routes of citizen couriers. In light of the fact that the strongest growth has been in the business-to-customer market, and given the strong financial incentive for large logistics companies to reduce last-mile costs, it is more likely that urban deliveries will not become more efficient through crowdshipping but rather that conventional parcel deliveries will be substituted by a private car-based workforce. If this turns out to be the case, the benefits in terms of congestion and emissions are likely to be marginal, if not detrimental.

Co-modality

Various modelling studies have shown the efficiency potential of extending the operations of not only private citizens' trips but also public transit and taxi operations to deliver goods in urban settings (Ronald, Yang and Thompson, 2016). This would require the co-operation and integration of operations that are typically segmented: urban delivery by shippers, retailers and carriers would need to co-ordinate with public transit operators and/or private or public taxi fleets. This co-ordination of multiple actors fits nicely into the broader rubric of "city logistics" (Taniguchi,

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2015), which seeks to organise public and private actors (including companies involved in urban logistics, public administrators and transit operators, and residents) around common goals of passenger and freight mobility, economic efficiency and competitiveness, environmental sustainability, livability, and resilience. While technologies such as GIS, ITS, ICT, online apps and vehicle automation could, in theory, aid in achieving far greater efficiency in urban goods movement than is currently realised, governance at the municipal level is seen as the key catalyst for moving towards practical implementation of this vision.

Digital freight matching

In addition to the growth of the business models that outsource the last-mile delivery market, there has been a proliferation of digital freight matching platforms and apps in the past five years. New market entrants and established LSPs alike have scrambled to develop their own software and services. There may be potential for online platforms to disrupt the traditional business model of LSPs by matching shipments with trucks also in regional and long-haul operations: LSPs (or 3PLs or brokers) may add as much as 15% to total delivery costs.

Many carriers' operations, even in industrialised countries, are still decidedly not high-tech. Shippers and carriers maintain close relationships, and shipment matching is often done by phone, while data processing often involves lots of redundant paperwork. To the extent that algorithms and digital technologies can enable better utilisation of scarce, expensive and rapidly depreciating assets (trucks), the opportunities for such platforms seem promising. The analogy to Uber is easily made, implying that if shippers and carriers do not themselves embrace new technologies to streamline their operations, they may be leaving themselves vulnerable to such technology changes.

However, the conditions that made urban passenger transport services rife for disruption are not as opportune in the case of road freight (Smith, Lewis and Menzies, 2017). In contrast to the anonymous and relatively short contractual relationships in passenger ride services, shipper-carrier relationships are well established and based on trust and reputation, and shippers and LSPs gradually accumulate knowledge of product-specific supply chains. Whereas rides are a fairly homogenous and simple service, there is great heterogeneity in cargo types and requirements (e.g. refrigeration and the necessity of maintaining the cold chain, and the shipment of fragile or perishable products). Finally, in contrast to the growing and centralised network of registered drivers willing to contract their services for passenger ride-share services, in trucking, there is often a lack of spare capacity that can be quickly mobilised during demand spikes. Road freight requires trained, certified drivers, who in many countries are prohibited from driving more than a certain designated number of hours per day.

For such reasons, it is likely that "Uberisation" of road freight will occur primarily in urban settings, where carriers and shippers eager to outsource low-margin last-mile deliveries are able to utilise the dense and flexible networks of the citizen-courier supply. In the case of regional and long-haul operations, the first among the established shippers and LSPs have already begun to realise the cost savings and competitive advantages of switching to real-time, digital technologies for tracking, analysing and optimising logistics flows. In these operations, such developments are likely to offer a competitive advantage but are less likely to transform freight operations or established companies.

Autonomous trucks

There are multiple ways to think of the automatisation of road freight services, ranging from the use of GPS to the use of vehicle communication and automation and web applications. All these can serve to improve the overall logistical system (as described above). Autonomous trucks are a step beyond such efforts and imply a fully digitalised "driverless" truck, which is

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fully automatised and operated remotely. While autonomous vehicles are attracting particular interest for passenger cars, they may penetrate the road freight sector in advance of many passenger transport applications for two reasons. First, driver training, benefits and salary constitute a key operational cost for most fleets in developed countries. At 39% of total operational costs in 2015, driver-based costs were the only costs to exceed fuel costs in the United States (ATRI, 2016),[30] and, in high-wage contexts like European Union member countries, driver salaries constitute 30-60% of carrier costs (Sternberg and Harispuru, 2017). Second, since highways constitute a relatively predictable and stable driving environment compared with urban areas, introducing vehicle autonomy is relatively simple and has already been demonstrated to be technically viable in the near term.[31]

The potential benefits of automated trucks are many. Reduced frequency of crashes not only means fewer fatalities but also less risk and uncertainty and increased longevity of expensive capital investments. Autonomous trucks are able to drive at night, thereby making better use of highway infrastructure and reducing congestion in daytime and peak hours. Less congestion plus smoother driving enabled through connections among vehicles and infrastructure (V2V and V2I) implies improvements in on-road vehicle efficiency. Existing driving assistance technologies have to date largely contributed to making driving safer and more fuel efficient when it comes to applications of digital technologies on public roads,[32] but fully autonomous trucks are actually already in operation, for example in mining.

From an energy and emissions point of view, the likely benefit of autonomous trucks can be significant (potentially in the 15-25% range), given that autonomous driving can enable some of the solutions discussed earlier and bring them together under a single umbrella. Key examples of fuel-saving solutions enabled by autonomous driving are platooning, predictive cruise control and overnight driving (which comes with significant advantages in terms of reduced congestion). Increased capital utilisation and higher mileages for first owners of autonomous trucks would likely lead to greater interest in fuel-saving technologies. However, from a broader systemic point of view, energy-saving benefits may potentially be fully offset (or more) by increases in trucking activity due to the major cuts in operational expenses that driverless or remotely driven vehicles could enable. Overall, these considerations of a likely rebound in activity growth, combined with the challenges and high costs of ultra-low or zero-emission technologies in long-distance road freight, suggest that full autonomy in trucks is more likely to result in an increase of aggregate energy use than are self-driving passenger cars.

Other societal impacts of automation are also not positive. Particularly in the short term, autonomous trucks will pose difficult dilemmas. A few high-profile crashes in the early adoption phase could set back vehicle automation technologies by decades (see Stewart, 2017) and all the more so for trucks. The issues of vehicle and software certification, liability, security and privacy must be addressed. Perhaps the most severe impacts could be borne by truckers – in the United States, for example, around 3.5 million jobs are held by truck drivers (Solon, 2016), and the

[30] Over the past five years, either fuel costs or driver wages and benefits have constituted the majority of operational costs for trucking in the United States, depending on the fluctuating price of diesel (ATRI, 2015).

[31] Uber's acquisition of the technology start-up Otto, a company pioneering self-driving truck technologies, in August 2016 was followed by the high-profile 120-mile delivery of Budweiser beer on Interstate 25 of Colorado, United States. But various levels of autonomy were demonstrated on highways as early as 2012, when the European Union's Safe Road Trains for the Environment project successfully demoed a four-truck platoon in which the following trucks were connected by V2V technologies to the lead truck to mimic acceleration, braking and turning at close proximity (as little as 6 m). Real-world applications have already started: Rio Tinto used 53 autonomous trucks for mining operations in 2014.

[32] For instance, nearly 45% of regional and long-haul fleets in North America have trucks that use predictive cruise control (NACFE, 2016). In the European Union, adaptive and predictive cruise control was installed on 50% and 40%, respectively, of tractor-trailers sold in 2015 (Rodriguez et al., 2017).

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career is one of the few remaining jobs that pays well above the median wage but does not require a university education.

Box 6 • Delivery by drones: An urban niche delivery market takes off?

Delivery by unmanned aerial vehicles, or drones, has already begun in some Chinese, Indian, and Californian cities, and Amazon's first drone delivery in the United Kingdom garnered a fair amount of popular and media attention (The Guardian, 2016).

The economic feasibility of delivery by drone can be extrapolated straightforwardly based on simple physical and technical calculations. The first takeaway of these calculations is that the operational costs per km of delivering a 2-kg package could be brought down to a rather low level: only about USD 0.01 per km (this includes capital costs for a tolerably efficient lithium-ion battery and assumes an average electricity price of USD 0.1 per kWh (D'Andrea, 2014). However, safe and reliable delivery drones are still quite expensive, and even if mass production lowered costs, distribution by drone would require a broad restructuring of distribution networks. Warehouses and consolidation centres are typically located far enough from urban centres to take advantage of low property values while still being close enough to encompass operations in an urban catchment area, typically far outside the 20-km range over which drone operations would be viable. In densely populated metropolitan areas with multiple offices, apartments and/or residences per building, drone delivery would only be possible if shared take-off and landing pads ("drone dispatch hubs") were built. Established retailers in cities with sufficient rooftop real estate to operate their own drone operations could incorporate these facilities at lower costs, and homeowners could have deliveries made to their driveways and yards, though reliable and safe delivery may require that specialised facilities be built.

Since drones would be only able to deliver one package at a time, under reasonable assumptions for loading, unloading and flight times, it would take about 15 drones operating around the clock to deliver the same product volume as a single light commercial vehicle does in a typical 8-hour shift (McKinnon, 2014b). This differential in service volume, plus the capital costs of the drone and distribution network, implies that the per km costs of drone delivery will most likely be far higher than the already relatively high costs of conventional truck-based urban delivery. This further implies that the growth in the drone delivery market is likely to remain restricted to affluent customers in the near-to-midterm. Safety, security, liability and noise considerations are further barriers that would need to be overcome.

Even if the market for drone delivery were to grow rapidly enough to become a new fixture of the urban landscape, the energy and environmental impacts would likely remain limited. Their performance on an energy or environmental metric would depend on the alternative delivery mode for which they substitute. While a drone delivery unambiguously emits less and uses less energy than a dedicated car trip for a single product, if the mode of comparison is a well-loaded van, then technical details of each vehicle's power source, efficiency, and operations would be needed to compare their relative emissions.*

As shown by the simple example above wherein 15 drones operating night and day would be needed to offset a single van operating for 8 hours, the massive volume of commodities circulating throughout a city restricts the feasibility of drones as substitutes – even if the costs of the full drone delivery chain were brought down precipitously. To make a dent in urban logistics activity, the urban airspace would need to be teeming with drones. Fortunately, this is an unlikely scenario. At most, drones are likely to develop gradually into a niche market for high-value goods for the urban elite, not a staple to replace urban logistics, let alone a solution to the last-mile problem.

* Since drones operate on batteries, their emissions are tied to the carbon and local pollutant emissions intensity of the regional grid – as grids shift from fossil resources to renewables, drone delivery will become less emitting. However, light commercial vehicles are well placed to transition to electric drive as well and, hence, are likely to win in terms of efficiency improvements and emission reductions vis-à-vis drones over the long term, simply due to their operational efficiency.

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Improving vehicle efficiency

Several investments in vehicle efficiency both reduce energy consumption and pay for themselves either over the short term (i.e. within three years, corresponding to the upper boundary of the typical time horizon for the investment decisions of truck fleet operators)[33] or else only over a longer time span. As outlined in Chapter 1, a number of barriers and market failures restrict the market uptake of technology investments that do not end up paying for themselves within a very short time period, from less than a single year in the case of many owner-operators to within three years for most of even the largest fleets.

Investment in longer-term efficiency technologies will hence require deliberate interventions into the market. Technologies that have a payback period of longer than three years can be usefully classified into those that are nevertheless cost-effective only over the entire lifetime of the vehicle – typically between 8 and 15 years (sometimes more), where large fleets tend to replace their trucks more often. In a separate class are technologies that have been proven to be technically viable but are too expensive to pay for themselves even in the long term; these may become viable with economies of scale in mass deployment or else through further research, development and deployment (RD&D).

The following section outlines first those measures with a short payback period (less than three years). While many of the market failures identified in Chapter 1 may still need to be addressed to encourage their more rapid adoption, these are measures that are likely to gradually diffuse throughout the operating fleets where they are most viable, first in developed regions and then through fleets in the emerging and developing world. Thereafter, this section describes the efficiency potential of technically viable demonstrations. Then follows a brief treatment of the current status and future potential of alternative fuels (including natural gas, biofuels, electricity and hydrogen) and of alternative vehicle technologies. The section concludes with a cost comparison across alternative vehicle powertrain technologies.

Vehicle components with short payback periods (less than three years)

Ranges of the potential for technical and operational efficiency investments that pay for themselves from the perspective of the truck operator within three years over the 2015-30 timeframe average about 23% (Schroten, Warringa and Bles, 2012), albeit with wide variations among vehicle missions and types, with generally greater potential for savings in heavy-freight than in medium-freight trucks.[34] The study examines a range of commercially available technology options across six truck vehicle-mission categories: service and delivery vehicles (with less than 7.5 t GVW), urban delivery and collection vehicles, municipal utility trucks, regional delivery vehicles, long-haul heavy-duty trucks and construction vehicles.

A study released by the ICCT (Meszler et al., 2015) examines the costs and fuel-saving potential of efficiency technologies that could be adopted to meet the United States' final Phase II

[33] Typical payback periods range from as short as six months in the case of owners or operators of individual trucks to as long as three years in the case of large fleets. Most carriers will only invest in efficiency technologies that have a clear and proven payback period of less than one-and-a-half years.

[34] The cost assessment figure cited here is for a representative truck and is based on the total cost of ownership over three years or over the full vehicle lifetime (which ranges from 8 to 19 years by vehicle type) using reference fuel prices from the *International Energy Outlook 2011* of the US Energy Information Administration with a 4% discount rate. According to these assumptions, the potential for fuel savings, by vehicle-mission category, is 6% for service vehicles, 10% for urban delivery vehicles, 15% for municipal utility trucks, 28% for regional delivery trucks, 33% for long-haul vehicles and 21% for construction vehicles. A study by The International Council on Clean Transportation (ICCT) (Meszler, Lutsey and Delgado, 2015) finds an even greater potential for efficiency technologies in the tractor-trailer segment to pay for themselves over a very short timespan: it estimates that by 2025, fuel consumption can be reduced by 38% with payback periods in the base case of less than a single year, relative to a 2010 baseline vehicle.

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fuel-efficiency and GHG emissions standards for heavy-duty vehicles. Both of the above studies draw heavily on Law, Jackson and Michael (2011) and AEA/Ricardo (2011), and the ICCT study draws further from Argonne National Laboratory's Autonomie model (ANL, 2014), as well as data from the EPA/NHTSA rulemaking (EPA/NHTSA, 2016). The discussion of the near-term technology potential below draws heavily on all four of these reports in addition to other reports and IEA analysis.

Vehicle design improvements that reduce energy needs include improvements in aerodynamics, reduced-rolling resistance for tyres and truck weight reduction. Enhanced powertrain efficiency can be realised via improvements to the engine, transmission and drivetrain – powertrain controllers that integrate transmission and engine controls can bring additional fuel savings. Battery-powered electric auxiliary power units can provide on-demand power for climate control and other cabin devices while saving fuel.

Table 14 summarises the vehicle efficiency measures with the greatest potential for near-term cost and fuel savings. Actual real-world potential for efficiency improvements and cost and CO_2 savings vary significantly across regions with differing fleet structures and baseline technology penetrations, and depend not only on the composition of the truck fleet but also mission types and other variable conditions of actual operations (such as road quality, road grades, speed limits and congestion profiles). The presence or absence of fuel economy regulations also influences the remaining near-term cost-effective potential.

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Table 14 • Near-term vehicle efficiency measures with a net savings over the vehicle lifetime

Measure	Description	Potential energy savings
Aerodynamics	A wide range of aerodynamic fittings (such as aft box tapers, aerodynamic tractor bodies, mud flaps, trailer tails, box skirts and cab/box gap fairings) can reduce the drag coefficient, thereby reducing road load.	Individual vehicle components reduce fuel use by 0.5-3%, depending on the truck type and aerodynamic retrofit.
Low rolling resistance (LRR) tyres; **Tyre pressure systems (TPS)**	LRR tyres can be designed with various specifications, including dual tyres or wide-base single tyres with aluminium wheels, and next-generation variants of these designs.	The potential ranges from about 0.5% to 12% in the tractor-trailer market. TPS alone could reduce fuel use by 0.5-2%.
Light-weighting	Broadly, all HDV vehicle types except utility trucks could cost-effectively reduce weight by upwards of 7% within the next ten years.	The CO_2 savings potential is about 1% by 2020, 2-3% by 2030 and 2.7-5% by 2050.
Transmission and drivetrain	Moving from manual to automatic/automated manual transmission can greatly improve efficiency. Adding gears, reducing transmission friction and using shift optimisation in manual automated or fully automated transmissions can also improve drivetrain efficiency.	Automatic/automated transmissions reduce fuel consumption by 1-8%, depending on truck type; other improvements lead to fuel savings of about 0.5-2.5%.
Engine efficiency	Engine improvements include increasing injection and cylinder pressures, both of which typically improve incrementally on a yearly basis.	Improvements in the coming decade could lead to fuel savings of approximately 4% (in service/delivery vehicles) to 18% (in long-haul trucks).
Idling reducing technologies	These include auxiliary power units and generator sets, battery air conditioning systems, plug-in parking spots at truck stops and thermal storage systems.	As much as 2.5% of the fuel consumed by road trucks may be due to idling operations. As such, this is an upper threshold on the potential fuel savings (energy savings are less).
Hybridisation	Parallel hydraulic hybridisation may be the most cost-effective near-term technology option for municipal utility vehicles, while electric hybridisation tends to be the best hybridisation option for most other mission profiles.	Dual-mode hybrid: 8-30% Parallel hydraulic hybrid: 15-25% Parallel hybrid: 6-35% – all ranges depend on vehicle type; gains are lowest (around 6%) on long-haul vehicles operating at constant highway speeds.

Note: The potential energy savings cited are for near-term (i.e. over the coming decade) technologies and measures that reduce the total cost of ownership over the vehicle or measure lifetime.

Sources: Aerodynamics: Schroten, Warringa and Bles (2012); US EPA/NHTSA (2016). Low-rolling resistance tyres and tyre pressure management systems: Schroten, Warringa and Bles (2012); Meszler, Lutsey and Delgado (2015); US EPA/NHTSA (2016). Light-weighting: Ricardo-AEA (2015). Transmission and drivetrain: Schroten, Warringa and Bles (2012). Engine efficiency: Schroten, Warringa and Bles (2012). Hybridisation: Law, Jackson and Michael (2011); Schroten, Warringa and Bles (2012). Idling reducing technologies: Vernon and Meier (2012); ANL (2013).

Aerodynamics: A wide range of aerodynamic fittings (including everything from hoods and fenders, and bumpers and mirrors to larger fittings, such as aft box tapers, roof air fairing, aerodynamic tractor bodies, mud flaps, trailer tails, box skirts, cab/box gap fairings and box skirts) can reduce the drag coefficient, thereby reducing road load. Drag is the key source of energy losses in long-haul, heavy-duty applications. The drag force increases at the square of the speed; at typical highway speeds (90 km/hr to 120 km/hr), it accounts for most of the tractive energy requirements. In addition to the long-haul mission profile, aerodynamic retrofits can deliver the most fuel savings in the regional delivery mission segment, but aerodynamic vehicle design and retrofits are also cost-effective in service (drag reduction) and urban delivery (e.g. aft box tapers, roof deflectors and box skirts) vehicle missions.

Uptake of aerodynamic retrofits has been quite rapid in the North American tractor and trailer fleet – 83% of trailers across 17 fleets surveyed in an annual survey now use trailer skirts, and the adoption of aerodynamic packages on tractors and trailers has penetrated the US truck fleet faster than any other efficiency technology over the past five years (NACFE, 2016). These

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technologies are far less widespread in the European Union, for instance, where only about 10% of new trailers were sold with side skirts in 2015 (Rodriguez et al., 2017).

Low rolling resistance (LRR) tyres: LRR tyres can be designed with various specifications, including dual tyres or wide-base single tyres with aluminium wheels, and next-generation variants of these designs. In general, the rolling resistance of single-wide tyres is lower than dual tyres, with ranges of improvement from about 10% to upwards of 36% in the tractor-trailer market (Meszler, Lutsey and Delgado, 2015). Automatic tyre pressure adjustment systems maintain proper tyre pressure for safety and fuel economy. Long-haul, service, urban delivery and construction trucks can all benefit from LRR tyres, and indeed in many of these mission segments, they consistently rank among the most cost-effective, fuel-saving measures available. About 11% of tractors sold in the United States in 2015 were equipped with single-wide tyres, while only about 2% of tractors sold in the European Union and China had them in the same year (Rodriguez et al., 2017).

Awareness of the importance and good practices of tyre pressure inflation has become somewhat commonplace in North American regional and long-haul operations, with penetration rates increasing from less than 10% a decade ago to nearly 80% in 2015. Tyre pressure monitoring systems have also become more prevalent but are still used by selected trucks in only about 15% of North American carriers, and automatic inflation systems are still very rare (NACFE, 2016). The sales penetration of tyre pressure monitoring systems was less than 5% in the United States, European Union and China in 2015 (Rodriguez et al., 2017).

Like eco-driving and vehicle aftermarket technologies (including aerodynamic devices on tractors and trailers as well as other truck types), LRR tyres have multiple immediate advantages, including very short payback periods and the capacity for use across operating fleets without the need for new vehicle purchases (Greening et al., 2015).

Lightweighting: For an articulated truck, Ricardo-AEA (2015) estimates that the vehicle kerb weight can be reduced by about 2% in the very near term (to 2020), 16% in the medium term (2030) and 30% in the long term (2050). Broadly, all HDV vehicle types except utility trucks could cost-effectively achieve a 7% reduction in weight within the next ten years. Construction trucks have the greatest cost-effective lightweighting potential, with a potential vehicle kerb weight reduction of more than 13%. Even in utility trucks, the cost-effective mass reductions are around 4-5% (Ricardo-AEA, 2015). The carbon reduction potential from such measures is in the order of about 1% by 2020, 2-3% by 2030 and 2.7-5% by 2050 (Ricardo-AEA, 2015). Most of the weight reductions can be realised by materials substitution for the following vehicle components, from greater to least potential: the chassis, mounting system, vehicle body, suspension, wheels and tyres, and cabin. Vehicles operating under frequent stop-and-go driving, such as municipal utility and urban delivery trucks, can achieve the greatest near-term cost-effective fuel and CO_2 savings from lightweighting, in the order of 1-1.5% by 2020. The long-term potential for lightweighting through materials substitution to reduce fuel consumption in regional and long-haul truck segments is also considerable, in the range of 2.25% by 2050. These estimates are robust even at lower mileage and fuel price assumptions and would be higher under assumptions of longer average mileage and higher fuel prices (Ricardo-AEA, 2015).

Transmission and drivetrain: Shift optimisation in manual automated or fully automated transmissions tend to be most cost-effective on trucks with urban and regional operations, such as municipal utility trucks and urban and regional delivery and collection vehicles. In the European Union, truck sales with automated manual transmission (AMT) have grown from a low base (0-5% over the past two decades) to penetrations in new sales in 2015 of over 70% and 50%, for tractor-trailers and rigid trucks, respectively (Rodriguez et al., 2017). AMT has been adopted by nearly half of regional and long-haul tractor-trailer fleets in North America, while fully

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automatic transmissions are far less common (and have been adopted by less than 5% of surveyed operators) (NACFE, 2016). The opposite is true for rigid trucks: over half of rigid trucks sold in 2015 had automatic transmissions in the United States, while less than 10% were equipped with automated manual transmissions (Rodriguez et al., 2017). In China, AMT has only begun to penetrate the truck market since 2012, and sales shares of AMT and fully automated transmission are around 3% (Rodriguez et al., 2017).

Vehicle auxiliaries that are typically gear- or belt-driven (such as the water, oil, fuel injection, and power steering pumps; the cooling fan; air conditioner; HVAC system and alternator) lead to "parasitic" losses that increase with engine speed. These auxiliaries can use up to 9% of the energy of a truck. This can be avoided or mitigated by decoupling them when they are not in use using clutches, operating them only at optimal speeds with variable speed motors or variable flow pumps, switching to vehicle inertia as a supplementary energy source or running them with variable speed electric motors (Meszler, Lutsey and Delgado, 2015). Friction within the transmission, shaft, differentials and axles can be reduced via improved in-gear efficiency, lubricants and bearings (Meszler, Lutsey and Delgado, 2015).

Engine efficiency: Reductions of frictional losses in bearings, valves and at the interfaces between engine parts result in direct increases in brake work. Each annual vehicle model cycle sees improvements to designs for piston rings, low-viscosity lubricants, and low friction coatings and finishes.

Engine improvements include increasing injection and cylinder pressures, both of which typically improve incrementally on a yearly basis. These higher pressures optimise combustion, reducing exhaust and heat transfer losses and increasing the amount of useful work performed. Improved fuel automatization and in-cylinder distribution, higher compression ratios, and improved thermal insulation and management can all serve to optimise the combustion system. More broadly, advanced engine controls manage fuel injection and air intake. These can be complemented by systems that more efficiently manage other vehicle systems, including exhaust gas recirculation, auxiliaries and after-treatment.

Approximately 45% of the energy converted by a conventional large diesel engine is lost as hot exhaust gases and through the engine cooling circuit (Thiruvengadam et al., 2014). Waste heat recovery (WHR) systems recover this lost energy either by making use of the Seeback effect (with thermo-electric generators that generate electricity from a temperature differential) or via the Rankine cycle.[35] While no trucks using WHR are currently on the market, component suppliers and OEMs are researching and developing WHR concept technologies that could be integrated into new trucks within the next five years (Rodriguez et al., 2017). Waste heat recovery is estimated to have the potential to reduce fuel consumption in tractors by 3-6% (Reinhart, 2015).

Engine downsizing can be enabled by a range of engine and transmission efficiency packages, including many of those discussed above (as well as through hybridisation, discussed below), without compromising vehicle performance in terms of operational speed and road load power output.

Idling reducing technologies: Argonne National Laboratory (ANL) has created an open-access online calculator to estimate the fuel consumption associated with vehicle idling (ANL, 2013). Based on industry surveys conducted in the United States in 2008, Vernon and Meier (2012) estimate that engine idling to supply heating, electricity and other in-cab services during rest

[35] Diesel engine efficiency is typically measured in terms of peak brake thermal efficiency; for engines that incorporate WHR technologies, such as turbo-compounding and Organic Rankine Cycle WHR, the peak brake thermal efficiency is measured as the efficiency of an engine that would result in the same performance. The peak brake thermal efficiency for long-haul tractor-trailers in the US market may range from about 42% to 46%. WHR can improve efficiencies as measured by this metric to 49% (through turbo-compounding) in the near term and up to 55% in the long term (Meszler, Lutsey and Delgado, 2015).

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time consumed more than 3.8 billion litres or at least 2.5% of the fuel consumed by the road trucks. They note that the penetration of off-the-shelf products that supply electrical power and heating or cooling was somewhere between 26-36% in 2006. California has banned idling for more than five minutes per event, and there is a growing network of truck stop electrification sites across the United States (there were 116 in 2013). Plug-in ports on heavy-duty trucks allow drivers to use electricity for air conditioning, heating and electric power rather than idling their engines, and they are a particularly effective option for sleeper cabs. In the European Union, the penetration of start-stop systems to avoid idling in rigid truck sales peaked in 2012 at 15% (Rodriguez et al., 2017).

A 2015 survey of major regional and long-haul carriers in the United States found wide a variation in the technologies that fleets have adopted to reduce fuel consumption from idling: a minority of fleets still used diesel auxiliary power units. This solution was less common than start-and-stop technologies, which followed electric heating, ventilation and air conditioning (HVAC) systems and anti-idle electronic engine controls as common technologies to reduce idling. Some carriers also adopted driver training and incentives to reduce idling (NACFE, 2016).

Efficiency technologies with longer payback periods (more than three years)

The preceding discussion focused on technology measures that have fast payback periods. But greater improvements than those outlined above have been proved to be technically possible using best-in-class technologies. From the end-user's perspective, and adopting the full vehicle or technical measure lifetime as the time horizon for the comparison of the TCO, the net negative cost potential for near-term (2015-20) technology options to reduce fuel consumption (and thereby cut CO_2 emissions) across an "average truck" are in the order of 30% (Schroten, Warringa and Bles, 2012).

In the US tractor-trailer market, technology packages that pay for themselves over the period of ownership of the first owner and which can achieve a reduction in fuel use of 54% (on a vkm basis) will be possible by 2025, based on a 2010 baseline vehicle (Meszler, Lutsey and Delgado, 2015). The technologies that can deliver this magnitude of reduction include advanced engine and powertrain efficiency technologies and waste energy recovery. This potential is resilient to a wide range of discount rates and fuel price assumptions.

Emblematic of such improvements are those demonstrated by the United States Department of Energy's (US DOE) SuperTruck programme. The programme targeted separate energy efficiency improvements for the improvement of both engines (in which the target was brake thermal efficiency of 50%) and in prototype Class 8 trucks (in which the target was a 50% improvement in terms of gallons of diesel fuel consumed per tonne-mile transported) (US DOE, 2015a). The programme led to four separate contracts with four different truck OEMs, all of which met and exceeded the targeted efficiency gains, each resorting to independent technical solutions. Among these were engine downsizing, common rail fuel injections, turbo-compounding, mild hybridisation and waste heat recovery (see for instance Daimler [2012] and Volvo [2016]). The US DOE has also announced the goal of building upon the first SuperTruck programme with a SuperTruck II programme, which aims to be both more ambitious and more easily applicable to the real-world conditions. SuperTruck II targets a brake thermal efficiency of 55% and a 100% improvement in vehicle energy efficiency on a gallon per tonne-mile basis. Furthermore,

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SuperTruck II will measure and assess solutions based on their cost-effectiveness as well as efficiency gains.[36]

Hybridisation: Hybridisation can improve fuel economy through regenerative braking (which recovers braking energy losses as electricity for accessories or torque assist); start-stop and coasting (which turn off the engine when the vehicle is stopped or going downhill); and torque assist, which can enable engine downsizing while maintaining the same power output (Meszler, Lutsey and Delgado, 2015).

There is considerable potential for hybridisation to deliver fuel savings; however, in most cases, the payback period exceeds three years. Indeed, across nearly every vehicle and mission type, hybridisation reduces costs over the total measured lifetime (and hence is associated with a negative marginal abatement cost) but ranks close to last among the technical options available.

Parallel hydraulic hybridisation may be the most cost-effective near-term technology option for municipal utility vehicles, while electric hybridisation tends to be the best option for vehicle and mission profiles with longer mileages (Schroten, Warringa and Bles, 2012).

Parallel electric hybrids couple an ICE and a motor so that both provide power to the shaft. This reduces the size and power requirements of the electrical system, but in parallel hybrids, engine operations are unable to optimise engine operation in the same way as series hybrids because the engine and motor speeds are coupled to the vehicle speed and load. Of all electric hybridisation options,[37] the parallel configuration is the best suited to heavy-duty vehicle applications (Rodriguez et al., 2017).

Fuel-economy benefits of hybridisation vary widely by truck type and mission profile. Long-haul tractor-trailers operating at near-constant highway speeds can benefit from up to 6% better fuel economy (Lajunen, 2014), although the fuel economy benefit is higher (around 10%) in stop-and-start driving (Delorme et al., 2009). The benefits of hybridisation are greater in rigid trucks operating in urban and regional deliveries – fuel savings estimates range from 7% to 36%. The actual fuel economy benefits depend heavily on the share of transient versus highway operations. For MFTs driving a large share of their operations in start-and-stop conditions, fuel savings are likely to range from 15% to 35%.

Alternative fuels and powertrains

Alternative fuels complement energy efficiency as a means of addressing the many near- and long-term economic, societal and environmental dilemmas posed by the continued reliance on oil. This includes diversifying the energy supply to road freight to capitalise on the economic benefits of multiple alternative fuel sources, cutting local pollutant emissions to mitigate their severe health and environmental impacts, and decarbonising the transport sector to avoid the

[36] The current budget proposed by the new United States administration cuts funding to the US DOE's Solar and Vehicle Technologies Offices by nearly 70%. The latter is the office responsible for the SuperTruck II initiative. As such, the future of this programme, and potentially also of Phase II fuel economy and CO_2 standards in the United States, are called into question.

[37] In series hybrids, the ICE provides energy to an electric generator, which then powers a battery and/or electric motor. In this manner, the ICE can be partially decoupled from the load and vehicle speed, thereby enabling more efficient use of the engine by operating it within a narrower range. On the other hand, the vehicle's power must be wholly supplied by the motor and the electrical power system, which requires larger and greater capacity electrical components.

Power-split (or "dual-mode") hybrids combine the functionality of series and parallel hybrids. The electrical system includes both a motor and a generator, and the ICE and motor are mechanically coupled with an epicyclic gear. This allows the engine to be operated within a narrow and efficient range that is independent of vehicle power and load, or, if needed, to directly power the shaft. The added complexity of the additional electrical components, the epicyclic gear and vehicle control software make this configuration less suitable for most heavy-duty applications.

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worst impacts of climate change. Additionally, in the long term, alternative fuels will provide the only means for deep decarbonisation of the road freight sector.

Notwithstanding the opportunities provided by alternative fuels and powertrains to diversify away from oil as the dominant fuel for road freight and to decarbonise the sector, there are many challenges:

- The literature points to the high abatement costs of alternative fuels (Malins, 2011; Holland et al., 2015).
- There is considerable debate regarding the extent to which alternative fuels can lead to real-world reductions in greenhouse gas emissions – an issue that is exemplified by the controversy surrounding indirect land use change (see Box 7) but that is also relevant for natural gas and to a lesser extent the cases of electricity and hydrogen.

In the cases of all of these alternative energy carriers, delivering reliable GHG emissions reductions will require that production and supply pathways are themselves decarbonised. Hence, this requires an analysis not only of vehicle technologies but also of the economic, technological and environmental characteristics of fuel production, transformation and refining, storage, transport and fuelling infrastructure – these are the well-to-tank emissions that are accounted for in well-to-wheel accounting frameworks (Box 7).

This section considers the potential benefits, enablers and barriers of four alternative fuels that could be used in road freight. It explores the costs and challenges in building the required supply, transmission, distribution and fuelling infrastructure for each of these fuels. It further discusses the changes to vehicle technologies, and their implications for vehicle costs and performance, that would need to accompany a switch to each of the fuels. Finally, it outlines the potential economic, societal and environmental benefits of promoting each fuel and discusses the policy framework that would foster their adoption.

Box 7 • Well-to-wheel accounting of greenhouse gas emissions

This report has thus far discussed CO_2 emissions attributable to road freight. But a complete picture of the impacts of fuel-switching requires a more comprehensive, well-to-wheel framework for evaluating GHG emissions across the complete path of fuel production, transmission and distribution, and final use.

To decompose the contributions to reducing GHG emissions by switching to alternative fuel pathways, it is necessary to introduce the distinction between upstream and tailpipe emissions. Upstream (or well-to-tank) emissions come from the production and distribution of transport fuels – from the extraction of primary feedstocks to final delivery to the end user. These may include many GHG species other than CO_2. Tailpipe (or tank-to-wheel) CO_2 emissions occur during the combustion of the fuels by vehicles. The sum of these two makes up well-to-wheel (WTW) GHG emissions. This does not include emissions from vehicle or battery manufacturing or those offset by material recycling, among others that would be included in full life cycle accounting.

Natural gas

Medium heavy-duty compression ignition engines can be designed to run on a blend of diesel fuel and methane, where methane is typically mixed with small volumes of diesel to provoke ignition.[38] Vehicles using such engines are called dual-fuel vehicles. Alternatively, engines can be

[38] Natural gas autoignites at much higher temperatures (methane at 580 degrees Celsius [°C]) than gasoline (250°C) or diesel (210°C).

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manufactured to run solely on methane, using positive ignition systems. Dedicated engines are less flexible as they are reliant solely on methane.

Natural gas is the main source of methane currently available and used in dual fuel and dedicated engines. Biomethane is also suitable for this purpose. Methane needs to be in the form of compressed natural gas (CNG) or liquefied natural gas (LNG) to make it a suitable transport fuel. Compressing it to a pressure of 200 bars to 300 bars (CNG, including compressed biomethane) or liquefying it by cooling it to -162°C (liquefied natural gas [LNG], including liquefied biomethane)[39] increases the volumetric energy density to a threshold that makes it viable for use in trucks. CNG and LNG trucks both store their fuels in on-board cylinders. LNG trucks require cryogenic cylinders to maintain low temperatures and avoid boil-off, which typically begins within about five days if the tank is left unvented.

Refuelling of CNG can be done at one of two station types:

- Time-fill stations, where fuel lines from a utility deliver CNG at low pressure to an onsite compressor, which then generally directly fills the vehicle's on-board storage cylinders. As fuelling generally takes longer but utilises the compressor more efficiently (constant operating conditions increase efficiency and reduce wear), these stations are typically used by fleets that refuel at a central location each night.
- Fast-fill stations are best suited as retail sites serving vehicles that operate on heavily trafficked corridors and need to fuel quickly. These stations compress natural gas from a local utility line to high pressure and then store it for quick and easy fuelling. CNG is delivered at high pressure (around 300 bar), which, due to temperature increases in the fuel tank, results in the partial loss of usable storage volume (about 20%). The need for more powerful compressors and storage vessels means that fast-fill CNG stations have higher investment and operating expenditures than time-fill stations.

Refuelling a truck with LNG can be achieved at similar speeds as gasoline or diesel, but LNG refuelling stations require complex and specialised equipment (e.g. cryogenic storage tanks, cooling systems and security devices to ensure that critical increases of the LNG storage pressure are avoided). Methane can be transported to stations via truck directly from LNG production and distribution terminals. Drivers must be trained to refuel with CNG or LNG, which comes at a cost.

The lower energy density of CNG fuels compared to diesel means required in-vehicle fuel storage volumes are up to six times higher. In contrast, around double the volume of LNG fuel is required to deliver a comparable travel distance to diesel (although this varies widely depending on engine efficiency); liquefied natural gas thus enables trucks to travel over extended ranges as required in long-haul operations.

The choice of CNG or LNG is primarily a function of vehicle size and mission.

- LNG is best suited for larger vehicles with a high annual mileage (typically 100 000 km or more), such as in regional and long-haul operations. Due to the boil-off risk, LNG also needs to be used in trucks that drive regularly.
- Smaller trucks (i.e. LCVs and MFTs) with lower annual mileage and/or less regular operations tend to use CNG.

Some OEMs produce either dual-fuel or dedicated trucks or both, but dual-fuel vehicles are primarily a retrofitting solution in most European Union countries as it is difficult for them to meet tailpipe emissions standards. Cummins Westport offered both spark-ignited dual-fuel engines and dedicated natural gas engines designed for use in medium-duty applications like delivery trucks and shuttles as well as heavy-duty ones like refuse and cement trucks, long-haul

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[39] The volume of LNG is about 600 times less than natural gas at standard temperature and pressure.

tractors and transit buses in the North American truck market (NGVAmerica, 2017). The truck manufacturers MAN and Iveco also offered engines with 340 kW, on par with the power rating of diesel models (DENA 2014). Retrofit and repower options are also widely available in many of the world's largest truck markets.

Dual fuel vehicles using methane as a fuel face the issue of the incomplete combustion of the methane, termed "methane slip". Given the high global warming potential of methane, this issue limits significantly the CO_2 emission benefits that are attributable to the lower carbon content of methane in comparison with diesel, especially for natural gas (biomethane delivers much higher well-to-wheel GHG emissions reductions and is, therefore, less affected by this drawback). Reducing incomplete combustion is a key area of engine development.[40]

Deployment status

The penetration of natural gas trucks varies across regions based on a number of factors that determine the viability of natural gas in the road freight sector. Key among these are the availability and cost (in particular, the cost differential with diesel) of: *i*) the resource itself; *ii*) natural gas transmission and distribution networks; and *iii*) CNG and LNG fuelling stations. Policies play an essential role in influencing all three of these determinants. Different incentives, subsidies, and taxation regimes for different fuels influence the attractiveness of switching to natural gas. Public goals to provide natural gas infrastructure for commercial and residential use, and to build up a network of refuelling stations for transport, also influence the balance of costs and benefits that fleet owners make when deciding to purchase or retrofit trucks to run on CNG or LNG. Natural gas infrastructure is also bolstered by public policies seeking to address environmental concerns (including local pollutant emissions in densely populated areas) as well as corporate social responsibility guidelines. These are currently the main reasons for logistics companies to invest in trucks using natural gas or biomethane as a fuel, if the investment in the truck has an acceptable payback profile.

Globally, in excess of 23 million methane-driven vehicles are in use with established markets in countries such as Brazil, China, Italy and Pakistan (NGV Global, 2017). However, freight vehicles represent only a small fraction of these. Trucks fuelled by CNG or LNG accounted for about 1% of the total stock in 2015, with about half a million HFTs on the road, mostly in India and China, and about a quarter of a million MFTs. Most of these trucks are operated in developing regions and economies, including Eastern Europe, Latin America, the Russian Federation (hereafter, "Russia") and Southeast Asia.

The three regions where recent developments have favoured (or have been seen as influencing) the penetration of methane in trucking are the United States, China and the European Union. The following section reviews these developments, focusing primarily on natural gas as a supply option. Further discussion of the prospects for biomethane is included in the following section, which looks at biofuels.

In the United States, the prospect of a rapid shift to natural gas trucks arose because of booming domestic shale and tight gas production, which from 2009 led to a dramatic drop in wellhead natural gas prices. The price advantage for natural gas over products of petroleum was strengthened by rising oil prices over the following couple of years but was then undercut by the rapid drop in Brent oil prices from 2015.

From about the beginning of this decade, natural gas fuelling infrastructure in the United States has expanded at central hubs for private fleets and along main road freight highways. The build-out of natural gas stations has been promoted since 2015 by the Fixing America's Surface

[40] For instance, see the development of the Westport HPDI 2.0 engine, to be released on Volvo Trucks in Europe this year: www.westport.com/is/core-technologies/hpdi-2.

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Transportation Act, which requires that the United States Department of Transportation sets national targets for the deployment of alternative fuels infrastructure. For natural gas, the act sets the target of maximum distances of 150 miles (241 km) between CNG stations and of 200 miles (322 km) between LNG stations along major corridors. By the end of 2016, there were 1 741 CNG stations and 143 LNG stations operating (up by 50% and 230%, respectively, from 2012), of which only just more than half were public (NGVAmerica, 2017). The capacity for public CNG stations to service trucks is further limited by size restrictions at many CNG fuelling stations.

In the early 2010s, around half of waste collection trucks and a high share of buses were dual-fuel CNG vehicles (IEA, 2013). Major firms, including UPS, FedEx, Ryder Systems and Dillion Transport, have recently begun to purchase a growing share of natural gas trucks as they renew their fleets, including purchases of LNG long-haul tractor-trailers. In the North American market, the offer of heavy-duty truck models with natural gas engines (the latter built primarily by Cummins Westport) is quite large and includes the major OEMs, such as Freightliner, Kennworth, Peterbilt and Mack.

Legislative action, like the Alternative Fuel Excise Tax Credit, which transitions to tax rates based on energy content, has in recent years begun to address the tax rate disadvantages of alternative fuels, including natural gas, relative to gasoline and diesel.[41] Inconsistencies also exist, and vehicle-based taxation disadvantages CNG and LNG trucks, but there are indications that these taxes (such as the Federal Highway Excise Tax) may be reformed in the near future.[42]

The market growth for natural gas trucks in China has been driven by the favourable price differential with respect to diesel, the low costs of retrofitting existing vehicles to run on CNG and by government policies. The use of natural gas in transport saw an annual growth rate of around 11% between 2010 and 2016, reaching a share of 10% or 20 billion cubic metres (bcm) (0.78 EJ). A significant share of this growth came from the use of natural gas for trucks. Despite the fact that the sales of natural gas vehicles in general and trucks, in particular, dropped dramatically in 2015 (due to the drop in global oil prices), a strong push from the central government to improve air quality is raising the potential in this sector over the medium term.

The number of stations supplying natural gas in China has grown from around 1 000 in 2008 to 7 950 in 2016. The stock of natural gas road vehicles operating in China grew from 6 000 in the year 2000 to 5 million in 2016 (Wang, 2016). In the early years, the majority of vehicles sold or retrofitted in China to use natural gas were light-duty vehicles, such as taxis and private passenger cars. However, the share of heavy-duty vehicle (HDV) sales fuelled by natural gas in total gas vehicle sales grew in the early 2010s as the spread between natural gas and diesel prices grew. Indeed, by 2014, 28 500 trucks were produced in China, accounting for 34% of natural gas vehicle production in that year, with the majority (56%) of these trucks being dedicated natural gas vehicles (Wang, 2016).

The price gap between LNG and diesel has been fairly consistent and robust even following the 2015 drop in oil prices: on an energy equivalent basis, the price of LNG has fluctuated over the past decade at around an average of 55% of diesel. This price differential has been exploited also in trucking: the stock of LNG heavy-duty vehicles grew from 7 000 in 2010 to 132 000 in 2015.

[41] Historically, federal and state taxes gave preference to CNG and severely penalised LNG relative to diesel. This was revised by the Alternative Fuel Excise Tax Credit, which expired at the end of 2016. As a result of this act, federal taxes on diesel in 2016 were USD 0.0645 per litre of diesel equivalent. For the same energy content, the federal tax on CNG was USD 0.0546 and on LNG was USD 0.0642.

[42] The Federal Highway Excise Tax on heavy-duty trucks currently poses a burden for LNG trucks as it is levied based on the overall cost of LNG trucks, leading ultimately to a higher tax and thereby extending the payback period for CNG and LNG trucks. The Natural Gas Truck Tax Parity Act of 2016 was introduced in 2016 and aims to address this issue by creating a partial exclusion for alternative fuel trucks from this excise tax (NGVAmerica, 2016).

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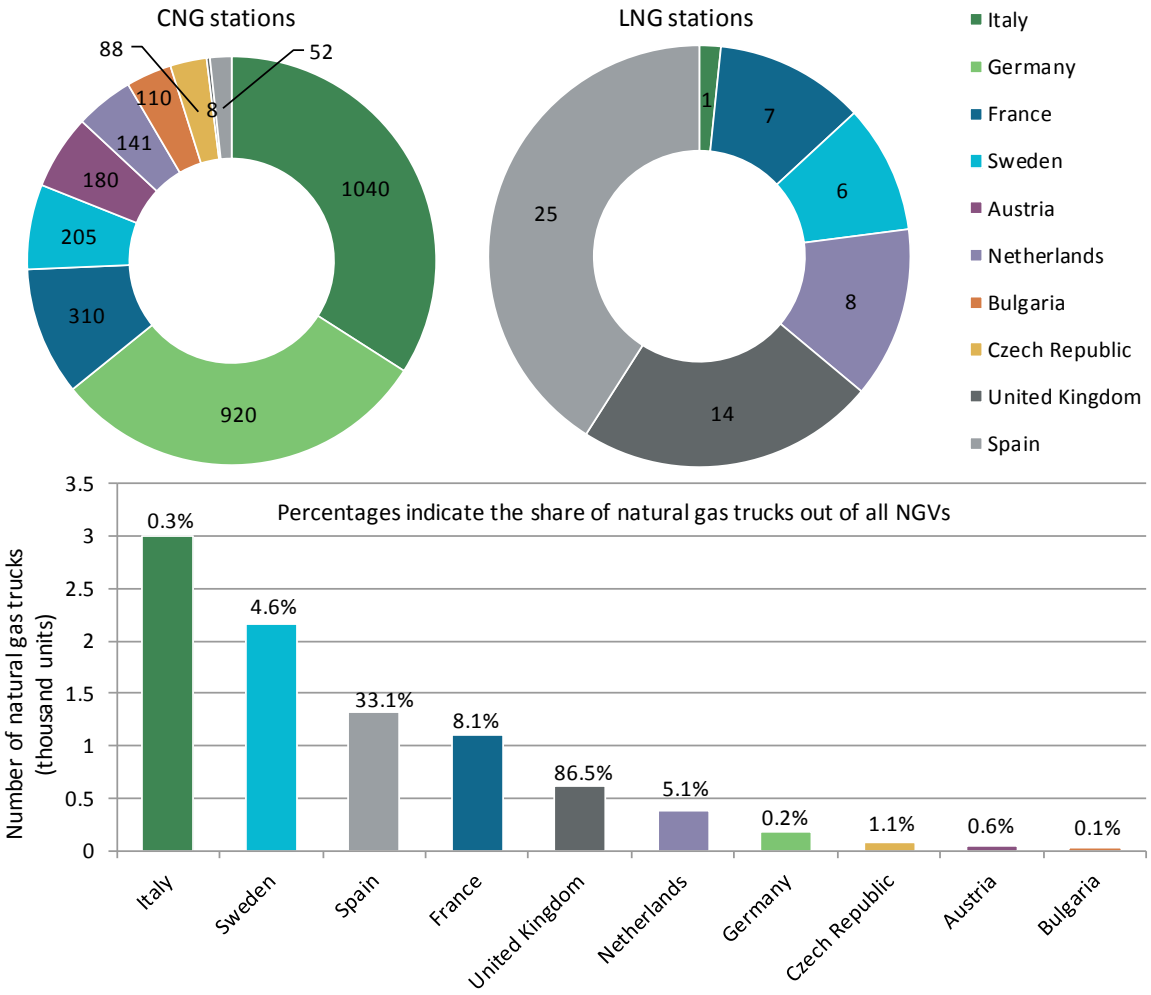
Traditionally, natural gas trucks were more common in the inland provinces (e.g. Xinjiang and Sichuan) as domestically produced gas (also being liquefied in small onshore liquefaction plants) was competitive versus oil. Better LNG accessibility in coastal regions combined with environmental policy measures to reduce emissions in Chinese cities later also promoted the use of CNG and LNG in those areas.

In order to improve local air quality, municipal and provincial governments continue to promote the use of CNG and LNG in the heavy-duty sector, including trucks. The central government continues to push natural gas as an alternative to oil primarily for energy security reasons.

The European Union is currently an example of a lesser developed market for natural gas vehicles. As of 2015, about 9 350 medium- and heavy-duty natural gas trucks were operating across the European Union's member states (EC, 2016a). The majority (over 80%) of these trucks operate in Italy, Sweden, Spain and France. Compared with China and the United States, countries in Europe lack a clear competitive fuel price advantage, and until recently had also lacked government incentives for promoting natural gas in transport. The CNG and LNG fuelling station networks would need to be further expanded to make CNG and LNG trucks competitive versus their gasoline/diesel counterparts. Figure 22 provides a country-level breakdown of the European countries with the highest penetrations of natural gas fuelling stations and trucks.

Figure 22 • Number of CNG and LNG service stations in selected European countries



Note: The percentages in the bar graph show the share of natural gas trucks among all natural gas road vehicles. Note that not all CNG refuelling stations are usable by trucks.
Source: Natural Gas Vehicle Europe (2017).

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The Alternative Fuels Infrastructure Directive (AFID) requires that European Union member states develop national policy frameworks to facilitate (amongst other fuels) CNG and LNG for road transport by providing publicly accessible refuelling points on the main corridors of the Trans-European Network for Transport by 2025 (EC, 2014). The directive suggests that refuelling points along this network should be located approximately every 400 km for LNG and every 150 km for CNG and includes a provision that aims to facilitate the supply and use of biomethane.

Cost comparisons

The incremental costs of CNG and LNG trucks are primarily due to the storage tanks.

The unit costs of compressed gas storage are lower than they are for liquefied gas storage. These costs have been estimated here at USD 1.4 per MJ of storage capacity for CNG (based on indications available from JEC (2008) for car storage tanks) and USD 2.4 per MJ of storage capacity for LNG (based on recent claims from manufacturers – see Clevenger [2014]). When applied to an MFT with a range of 700 km, these claims translate into a cost increment of USD 10 000 per vehicle and USD 17 000 per vehicle, respectively. The cost increment increases to USD 22 000 per vehicle and USD 40 000 per vehicle, respectively, in the case of an HFT. These gaps are roughly reflected in the vehicles available on the market.

For dual-fuel vehicles, injection systems needed for methane add roughly USD 1 000 per vehicle (EUR 700 per vehicle in the case of cars, according to JEC [2008]).

The payback periods depend on the technology choice and the annual mileage. The fuel costs for a new truck used for regional deliveries and travelling about 40 000 km per year amount to USD 10 000 to USD 16 000 per year, depending on the fuel price in the region where the truck operates (the range given here is for the United States to Europe and excludes countries that subsidise fuels). Considering an HFT with an annual mileage of 100 000 km, the annual fuel expenditure grows to USD 60 000 to USD 95 000.

The payback costs for CNG and LNG depend on the price differential between diesel and either CNG or LNG and are heavily influenced by the cost of refuelling infrastructure. In cases where natural gas prices are lower than diesel prices, and in circumstances under which the high infrastructure costs associated with low frequency of usage in the initial stages of adoption are not passed on to end users, both CNG and LNG offer short payback periods, sometimes as low as two to four years. Examples of such cases include refuelling points that target specific fleets or public policies designed to address this issue. In conditions where the fuel price gap is narrow, and there are no instruments to avoid passing the costs of early fuel distribution infrastructure developments to the truck operators, the economic case for the use of CNG and LNG is less compelling.

GHG emissions implications

Despite the lower carbon content of natural gas compared to diesel, switching to natural gas trucks results in only minor reductions in well-to-wheel (WTW) GHG emissions once issues related to methane are considered. These include methane's high global warming potential (particularly in the near term) and leakage issues in production, processing, transmission and distribution. On the vehicle side, the lower efficiency of most heavy-duty engines running on natural gas relative to diesel, as well as issues with methane slip, counterbalance the potential benefits of the lower carbon intensity of natural gas.

Various sources quote conflicting ranges of WTW GHG emissions reduction potential for natural gas relative to diesel. These range from a reduction of as much as 20% when looking purely at fuel properties (JEC, 2014a; DBI, 2016; Dominguez-Faus, 2016), to no net benefits whatsoever when accounting also for engine performance (JEC, 2014b; IEA-AMF, 2016), to near-term climate

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damages as a result of the higher short-term radiative forcing of natural gas (Camuzeaux et al., 2015). Ultimately, the range of results reflects variability in natural gas production and upstream leakage as well as in engine technologies. Even if the factors that minimise the life cycle emissions of natural gas are rolled out rapidly, the limited GHG emission savings achievable from switching to natural gas rule it out as a contributor to decarbonisation as explored in scenarios such as the IEA two-degree scenario (2DS).[43]

The local air quality benefits from switching to natural gas are far clearer – switching from diesel to CNG in urban fleets directly reduces emissions of hydrocarbons, carbon monoxide, nitrogen oxides and particulate matter emissions.

Enabling conditions

Fuel cost differentials offer arbitrage opportunities, most immediately in regions where natural gas supply infrastructure is already well developed. In many world regions (including transition economies in Europe and Asia, Canada and the Russian Federation, as well as many Latin American and African countries), the cost of natural gas, expressed in energy equivalent units (by lower heating value), is less than one-third that of diesel. Some, but not all of these countries and regions have built mature transmission and distribution pipeline networks. Countries in which both conditions are fulfilled are primed to exploit the cost difference in trucking as a means of realising near-term economic and energy security gains, even while reducing local pollutant emissions.

Even in regions where natural gas infrastructure is not well developed, in urban and industrial regions where captive fleets operate proximate to natural gas production sites and transmission networks, there is an opportunity to switch to CNG and LNG operations and thereby to capitalise on the economic, energy security and local pollution benefits discussed above. Moreover, biomethane can fuel vehicles that run on CNG and LNG. As such, it is one of the few promising options for relatively cheap low-GHG energy carriers with the potential to fuel road freight.

Countries willing to prioritise energy security and local pollutant emission mitigation will need to ensure that price differentials between natural gas and diesel are resilient to oil price fluctuations, and set up mechanisms that give retailers the confidence to make investments to build out fuelling infrastructure. Large fleets can spur fuel station rollout by negotiating deals with fuel retailers, thereby helping to overcome the chicken-and-egg dilemma that faces all alternative fuels. GHG emissions reductions could then be promoted by the increased uptake of biomethane, but the limited availability of sustainable biomass production constrains this potential.

Stricter standards on specific emissions of local pollutants, and in particular particulate matter, are likely to become increasingly difficult to meet for diesel engines. Increasingly stringent emissions standards being put in place for instance in China and India are likely to erode the cost disadvantage of CNG and LNG engines vis-à-vis gasoline and diesel engines.

Natural gas trucks may also provide other environmental and societal benefits beyond reduced local pollutant emissions. Natural gas fuels are far less toxic than gasoline and diesel, and, unlike these fuels, natural gas is non-carcinogenic. Engines running on natural gas emit less noise than those running on diesel, a benefit for trucks operating in urban environments that especially facilitates night-time deliveries.

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[43] See www.iea.org/etp/ for more details on IEA's modeling of the energy system's transition under low-carbon scenarios.

Biofuels

A range of biofuel options has the potential to replace petroleum product consumption in heavy-duty road transport and decarbonise the sector. The case for biofuels is strengthened due to their high energy densities and, for several fuels, their compatibility with existing vehicle fleets and fuel distribution infrastructure. Production processes for the following fuels are technically mature, with heavy-duty vehicles suitable for their use available from major OEMs and growing consumption in a variety of countries:

Biodiesel can be produced from a number of different feedstocks; including oil crop feedstocks, used cooking oil (UCO) and animal fat wastes. Consumption in road freight is most commonly in blended forms from B5 to B20,[44] providing a high degree of compatibility with existing vehicle fleets and fuelling infrastructure. Higher blends, such as B50 or pure biodiesel (B100), can also be used but require modifications to freight vehicles.

Hydro-treated vegetable oil (HVO), also known as renewable diesel, can be produced from a similar range of feedstocks to biodiesel, and research is ongoing to widen the range of applicable waste and residue resources suitable for production. HVO is technically a "drop-in" fuel. This means that it can be used unblended (HVO100) without modifications to heavy-duty diesel engines or changes to fuelling infrastructure. However, blends with fossil diesel (e.g. 30-50% HVO by volume), are currently more commonly used.

Biomethane is a fuel similar in its physical and chemical quantities to natural gas, and it can be used in natural gas fuelled vehicles. Biomethane is produced by upgrading raw biogas produced from the anaerobic digestion of high moisture content organic wastes.

Depending on future technological progress and the achievement of higher production levels, a further set of transport biofuels that are not widely commercially available at the current time could supply heavy-duty road freight moving forward. These include:

- *ED95 ethanol*, from either conventional crop-based and cellulosic feedstocks, consists of 95% fuel ethanol alongside lubricants and additives to improve ignition and protect against corrosion. ED95 can be used in heavy-duty transport within suitably adapted diesel (compression ignition) engines. However, availability of these vehicles is still relatively limited.
- *Biofuels from thermochemical production processes*, such as gasification and pyrolysis, can produce fuels suitable for use in heavy-duty transport from a range of biomass feedstocks, including forestry and agricultural residues, and municipal solid waste (MSW). Syngas produced from gasification can be subsequently be upgraded to biomethane (BioSNG) for use in the same manner as biomethane produced via anaerobic digestion. Alternatively, syngas can be subjected to conversion processes to produce biomethanol, dimethyl ether (bioDME) and Fischer-Tropsch (FT) diesel. Pyrolysis oils can also be upgraded to diesel-substitute fuels. Collectively, these are referred to as biomass-to-liquid (BtL) fuels.
- Power-to-X (PtX) synthetic fuels combine hydrogen (e.g. produced via electrolysis) with carbon or nitrogen to produce gaseous or liquid fuels. PtX fuels may or may not use renewable electricity and carbon streams. Nevertheless, interest in PtX technologies has emerged primarily from polices that mandate the decline of the carbon intensity of fuels, and, therefore, opportunities are strengthened for production pathways based on renewable energy and carbon sources. PtX technologies can also produce ammonia (from hydrogen and nitrogen) as an energy carrier.

[44] The number relates to the percentage volume share of biodiesel blended with fossil diesel. This also applies to B30, B50 and B100. Blends need to adhere to the relevant technical standards to ensure vehicle warranties are not compromised.

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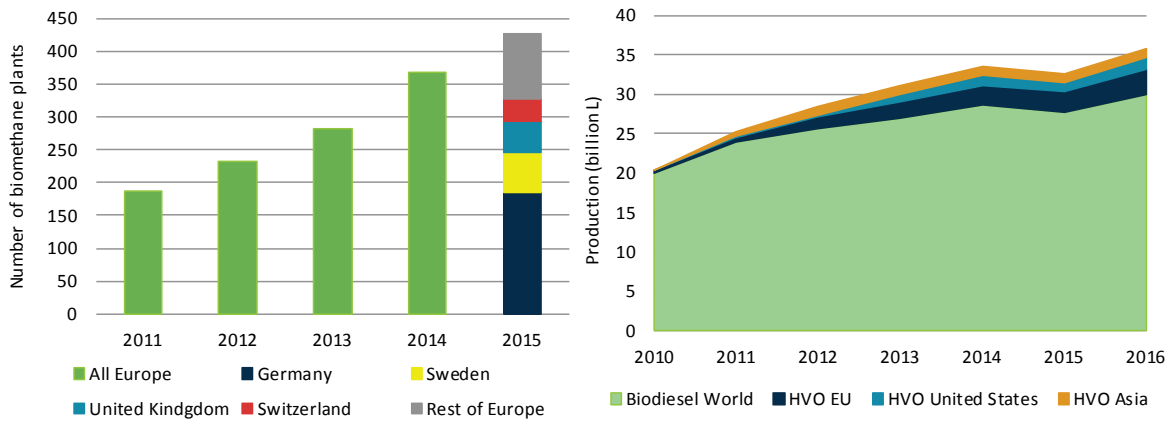
Deployment status

Biofuel consumption in heavy-duty transport is determined by the volume of fuel production and, for non-drop-in biofuels, the availability of suitable freight vehicles and fuelling infrastructure. Globally, over 31 billion litres (L) of biodiesel were produced in 2015, making it the most commercialised biofuel option for heavy-duty transport. HVO production is on an upward trend, with global production capacity now exceeding 5 billion L. Global biogas production has also been on a steady upward trend and reached around 1.3 EJ in 2014. Biomethane production is most prominent in Europe, and by the end of 2015, there were in excess of 450 biomethane plants in operation (European Biogas Association, 2016a). However, in most cases, production from these is fed into natural gas distribution networks and is not ring-fenced for transportation use.

Figure 23 • European biomethane plants 2011-15 (left) and biodiesel and HVO production 2010-16 (right)



Sources: EBA (2016b); IEA (2017d); F.O. Lichts (2017).

With global production of around 100 billion L in 2016, fuel ethanol is the most established biofuel, but ED95 only accounts for a very small share of total output. Currently ethanol consumption in freight transport is primarily limited to LCVs. Production volumes of thermochemically produced biofuels in heavy-duty road transport are also currently limited, with technical challenges in ensuring consistent output at scale and the current high investment costs for facilities as contributing factors. The production of BtL transportation fuels is predominantly at the demonstration stage. Currently, most dimethyl ether (DME) is produced from fossil fuels, and BioDME production is minimal with no widespread commercial use. However, one operational BioSNG facility in Sweden represents a scale-up in capacity on preceding plants.

With regard to biodiesel, Brazil has authorised the voluntary use of 20-30% blends in captive fleets as well as agricultural and industrial users, and in the European Union, the EN 16709 standard allows for the use of blends up to B30 in fleets. HVO100 consumption in various engine families has approval from several European HDV manufacturers, and the European standard EN 15940 covers fuels from hydro treatment. HVO also meets the American Society of Testing and Materials B975 diesel standard in the United States. For other fuels, a number of road freight vehicle manufacturers offer CNG- and LNG-fuelled engine models compatible with natural gas and biomethane, and a limited number of HDV OEMs have developed suitable vehicles for DME and ED95 fuels.

In Europe, HVO consumption is on an increasing trend and reached around one-fifth of combined HVO and biodiesel demand in 2016 (F.O. Lichts, 2016a). Consumption is particularly strong in Nordic countries such as Sweden and Finland where HVO is available at service stations in blends

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with fossil diesel and as HVO100. In the United States the Renewable Fuel Standard (RFS2) scheme and California's Low Carbon Standard (LCFS), have both stimulated demand. Within the RFS2 scheme, biomethane is scaling up from a low base with consumption growing fivefold in 2016 compared to 2014 levels (US EPA, 2017c); and in Sweden, biomethane is used in municipal bus fleets. In Europe, the use of ED95 and bioDME is less widely commercialised, although consumption of these fuels has been commercially demonstrated. Fuels produced via PtX are not currently in commercial use within the transport sector and are still subject to ongoing research and development. Pilot- and demonstration-scale plants have been constructed and are being operated to display power-to-gas technology concepts, with countries such as Denmark, Germany and Switzerland leading development. Power-to-liquids plants converting electricity to synthetic liquid fuels have also been developed at the laboratory scale.

GHG emissions reductions and wider benefits

GHG emissions from biofuels vary according to the characteristics of each production pathway. This incorporates the whole supply chain, from cultivation of the feedstock (where crop based) to processing, transport and distribution. Some indicative values of GHG emissions for various biofuels from the EU Fuel Quality Directive (FQD) and California's LCFS are shown in Table 15 below, expressed in grammes of CO_2 equivalent per MJ of fuel (g CO_2-eq/MJ). By comparison, tailpipe emissions from diesel amount to 74.1 g CO_2/MJ with an additional 12 g CO_2/MJ to 17 g CO_2/MJ from well-to-tank emissions.

Feedstock choice is a key factor in the level of decarbonisation offered from biofuels compared to fossil diesel. Crop-based feedstocks are widely available. However, lifecycle GHG emissions from these also need to take into account crop cultivation and land use change, which need to be considered within a complete lifecycle analysis of crop-based biofuel GHG emissions (see Box 8).

Table 15 • Reference regulatory GHG emissions for selected biofuels

Fuel (feedstock)	GHG emissions range (g CO_2-eq/MJ)		Comment
	EU FQD	California LCFSB	
Biodiesel (crops)	32-54	49-55	EU FQD range dependent on feedstock and process fuel. LCFS values for rapeseed- and soybean-based fuels certified in 2016.
Biodiesel (wastes/residues)	10	< 30	EU FQD value for waste vegetable or animal oil feedstocks. LCFS values for UCO, corn oil and animal fat feedstocks.
HVO (crops)	27-50	No data	Rapeseed, sunflower and palm oil feedstocks considered. There is limited use of crop-based HVO within California's LCFS.
HVO (wastes/residues)	No data	10-50	UCO and tallow feedstocks. No EU FQD value is available.
Biomethane (anaerobic digestion)	12-17	< 30	EU FQD values for MSW and manure feedstocks. LCFS values for wastewater sludge and dairy biogas.
Fuel ethanol (crops)	23-57	20 to > 100	EU FQD values for wheat, corn, sugar beet and sugar cane feedstocks. LCFS values include credits for the production of co-products.

Notes: Values from the EU FQD exclude net carbon emissions from land use change. Typical GHG emissions values from the EU FQD are shown as opposed to the default values. EU FQD values are calculated based on zero tank-to-wheel emissions. Values are shown for the LCFS as per the time of data analysis as such ranges may have been subject to change as new biofuel production pathways are certified. Values for biofuels from thermochemical production processes from both sources are not included due to low levels of commercial production.

Sources: EC (2015); CARB (2016b).

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For biodiesel and HVO, the lowest life cycle emissions are linked to the use of waste and residue feedstocks. Technological development of pre-treatment processes is ongoing to expand the range of waste oil and animal fat feedstocks suitable for HVO production. While available volumes of such feedstocks are ultimately finite, should supply chains be mobilised, there is sufficient availability to allow for a considerable scale-up of current production levels. For biomethane, additional factors, such as whether the digestate storage is closed or open and whether the fuel is used in compressed or liquefied form, also determine the associated GHG emissions. In addition, if not utilised, the decomposition of waste and residue organic feedstocks used to produce biogas will emit methane directly to the atmosphere, resulting in a greater climate impact.

GHG emissions from PtX fuels are mainly determined by the carbon intensity of input electricity and the source of carbon. If renewable electricity and CO_2 are used for fuel production, the GHG emissions benefits for PtX pathways are significant (Schmidt and Weindorf, 2016).

Box 8 • Land-use change considerations for crop-based feedstock biofuels

Emissions from land-use change (LUC), both direct and indirect, also need to be considered within a complete life cycle analysis of crop-based biofuel GHG emissions. It is evident that the emissions attributed to LUC differ according to the feedstock and the region of production. However, there is scope for additional research to reach consensus on suitable values for LUC emissions applicable for crop-based biofuel feedstocks. Although each individual fuel pathway must be considered on its own merits, in studies such as Valin et al. (2015), palm oil feedstocks have been considered to result in the highest LUC emissions, with peatland drainage in certain producer countries identified as a key causal factor.

Estimations of indirect land use change (ILUC) emissions represent an area of considerable and ongoing debate, with various methodologies suggesting a range of associated GHG emissions. In the EU FQD estimates of average ILUC emissions for cereal/starch, sugar and oil crop feedstocks are included. Of these, oil crops are estimated to result in the highest ILUC emissions. California's LCFS has applied ILUC emissions factors to fuels while also encouraging ongoing reassessment of these alongside key stakeholders and according to new scientific findings. As a result, initial ILUC values in the LCFS for crop-based biofuels have subsequently been revised down in some cases.

The long-term role for crop-based biofuels in decarbonising heavy-duty transport in certain markets will depend on the extent to which the land-use change debate can be clarified. In this respect, the development of objectively determined life cycle emissions for biofuel production pathways from different feedstocks, e.g. via third-party certification or standardised benchmarking methodologies, would provide confidence to policy makers currently proceeding with caution in some regions towards policy support for crop-based biofuels.

Aside from decarbonisation, biofuels can also deliver wider benefits. Security-of-supply considerations are a key driver for biofuel policy support in many countries. Where produced from domestically produced crop feedstocks or wastes and residues, biofuels can support the diversification of the transport fuel supply and offset imports of petroleum products. For crop-based biofuels, the wider benefits also include supporting demand for agricultural crops and therefore economic development in rural areas, and the production of animal feed co-products. In addition, biofuels produced from waste and residue sources can support the implementation of enhanced waste management practices. Biofuel policy development should balance these wider benefits alongside giving due consideration to wider sustainability considerations.

Certain biofuel options can deliver reduced local air pollution impacts compared to diesel. Air quality benefits from biomethane use can include reduced hydrocarbons, carbon monoxide,

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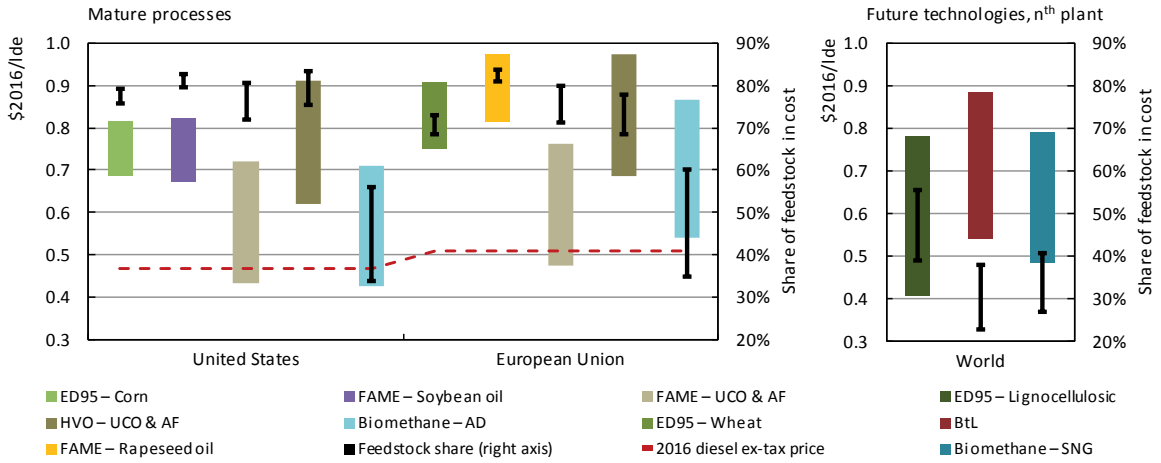
nitrogen oxides and particulate matter emissions compared to diesel fuels. Biomethane can also provide reduced vehicle noise. In addition, there are indications that HVO and biodiesel hold the potential to reduce carbon monoxide, hydrocarbon and particulate emissions. However, this is most relevant for less-sophisticated engines. Where advanced exhaust gas after-treatment is in place, the effects of fuel specification on emissions are reduced.

Production costs

Even though the majority of global biofuel consumption is currently driven by blending mandates, the assessment of production costs is needed to quantify market competitiveness versus alternative fuels, and the level of subsidisation that may be required to meet mandated volumes. Production costs are variable for both the current and future technological pathways to produce biofuels for the heavy-duty freight sector, with feedstocks anticipated to account for a lower share of total production costs for waste- and residue-based processes (Figure 24).

Feedstock prices, which vary according to demand and production levels, are a core determinant of crop-based biofuel production costs. Virgin vegetable oils, such as soybean oil in the United States or rapeseed oil in Europe, account for more than three-quarters of crop-based biodiesel and HVO production costs. This is due to competing demand from food markets; in 2016, the average soybean, rapeseed and palm oil prices were USD 720/t, USD 820/t and USD 640/t, respectively, in key markets.[45] For these technically mature technologies, capital costs account for a relatively small part of overall production costs. The same rationale applies to crop-based ethanol production, which is principally produced from corn in the United States, a range of feedstocks in Europe and sugar cane in Brazil. Given the current low oil prices, it is challenging for crop-based biodiesel, HVO and ED95 to compete with diesel without policy support.

Figure 24 • Levelised costs and feedstock price shares in the cost of selected mature (left) and future (right) biofuel production processes for the heavy-duty freight sector



Notes: AD = anaerobic digestion; ED95 = ethanol diesel 95; FAME = fatty acid methyl esters; SNG = synthetic natural gas (production by gasification of lignocellulosic biomass and methanation reaction); UCO and AF = used cooking oil and animal fats. Ethanol costs are used as a proxy for ED95 costs.

Waste and residue feedstocks are typically available at lower costs than virgin vegetable oils, but they can present additional challenges in processing due to their variable composition and the presence of impurities. Where waste and residue feedstocks are used for biodiesel and HVO

[45] Chicago futures for soybean oil, Rotterdam Freight On Board (FOB) quotation for rapeseed oil and Malaysian futures for palm oil.

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production, these are estimated to account for around 70-80% of overall production costs, a slightly lower share than for crop-based feedstocks. This can be advantageous as lower shares of feedstock to overall production costs support reduced biomass price volatility risk. Waste and residue feedstocks can typically be sourced within the range of USD 450/t to USD 750/t for waste oils and animal fats at the current time. However, increasing interest in these resources could tighten demand, therefore increasing feedstock prices and, subsequently, production costs.

The cost structure of the anaerobic digestion of wastes and residues and upgrading to biomethane is more balanced due to lower feedstock prices and investment costs associated with the upgrading process from biogas to biomethane. The large variety of lower price feedstocks, e.g. organic municipal waste, straw or animal manure, is expected to account for a lower share of such feedstocks in production costs. In addition, certain wastes can be obtained for zero or negative fuel costs where a "gate fee" can be charged for their receipt.

Several technologies that process abundant and lower value lignocellulosic and solid biomass waste feedstocks are still undergoing technological development but could potentially compete with currently mature fuel production processes in the future. However, this would only be possible if the currently high capital costs are reduced through further research and development, process optimisation, economies of scale and large-scale deployment associated with market expansion.

With increasing shares of variable wind and solar photovoltaic electricity within the power generation portfolios of many countries, growing interest has emerged regarding the potential to make use of excess electricity from these variable renewable sources to produce PtX fuels. Currently, a key weakness of the PtX fuel production concept is the high cost of fuel production, which is directly linked to the capital cost and the energy conversion losses along a complicated and multistep fuel production pathway (Schmidt and Weindorf, 2016). In addition, where demand-side management opportunities are maximised to reduce the electricity generation capacity needed to integrate variable renewable energy sources, the scope for large-scale fuel production from PtX using excess electricity production from variable renewables could be limited. Low-cost electricity from abundant and steady wind and solar resources could improve PtX production economics in the future. However, the geographical scope of where these resources are available needs to be considered.

Enabling conditions for further growth

Increasing the consumption of biofuels in heavy-duty road freight has three key pillars: reducing cost premiums compared to fossil diesel, creating demand and increasing fuel availability. With regard to eradicating cost premiums over fossil diesel, encouraging more widespread uptake of biofuels in road freight is still, at least initially, likely to require fiscal incentives in the form of reduced taxation for low-carbon vehicles and fuels. In this respect, carbon taxation applied on a well-to-wheel basis can increase the competitiveness of biofuel options and lead to deliverable GHG emissions reductions.

Implementing ambitious national frameworks for transport sector decarbonisation with a clear path towards GHG emissions reductions, increasing the contribution of renewable energy or phasing out of fossil fuels provide strong demand signals for alternative low-carbon fuels in heavy-duty freight transport. These are required to facilitate private sector investment in biofuel production facilities and the rollout of fuelling infrastructure, as well as to demonstrate to road freight OEMs that markets will exist to justify the development of compatible vehicles. Examples include Sweden's ambition to realise a fossil fuel-free vehicle fleet by 2030 and Brazil's commitment to increase the share of sustainable biofuels in its energy mix to approximately 18%.

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Where policy considerations such as the security of supply (e.g. for petroleum product importing countries) or supporting rural development are of importance, countries may wish to employ biofuels mandates covering the heavy-duty road freight sector. In addition, for less technically mature advanced biofuels with strong, long-term decarbonisation potential, a quota to assure demand while investment and production costs remain high may be beneficial in supporting early market growth. Technology-neutral carbon intensity reduction frameworks can be employed where decarbonisation is the principal policy objective. These offer a level playing field to all fuels and decarbonisation solutions relative to their current costs. These are already in place in Germany and the states of California and Oregon in the United States.

Compatibility with current fuelling infrastructure is offered by biofuels that are "drop in" or that can be blended with existing fossil fuels. In order to remove barriers to market expansion for other biofuels, growth in production needs to be complemented by measures to increase the size of associated vehicle fleets and fuel distribution infrastructure deployment. Captive fleets[46] are envisaged to play a key role in supporting initial market growth, and they represent an area where public sector leadership can positively influence private sector commitments to low-carbon fuels. As the consumption of biofuels in heavy-duty transport grows, consideration will need to be given to the strategic rollout of refuelling infrastructure along key road freight corridors. A key example in this area is the European Union's Alternative Fuels Infrastructure Directive (AFID), which obligates European Union member states to expand alternative fuel markets by ensuring refuelling infrastructure availability and clear price comparisons for consumers. The AFID is only applicable to methane and hydrogen fuels and electric vehicle charging infrastructure; however, it serves as a model that could be adapted to liquid biofuels by countries and regions.

Within low-carbon scenarios in the long term, all biofuels, as well as renewable fuels from PtX technologies, will be constrained by limits on the sustainable supply of primary biomass (IEA, 2017c). In these circumstances, the optimal use of biomass resources in transport is in long-distance transport modes (including aviation, shipping and trucks), where alternative decarbonisation pathways (such as electricity and hydrogen) have the highest cost or else are unlikely to be viable (e.g. for electricity and hydrogen in the case of aviation).

Electric trucks

Vehicle and infrastructure technologies

Electric truck technologies

While the technical principles for the electrification of trucks are similar to those available for cars, the greater size and weight of trucks, and their more rugged operations, substantially increase the barriers to batteries serving as a substitute for diesel. As with electric cars, the key performance considerations for batteries designed for use in electric trucks are the gravimetric and volumetric energy densities, the specific power (in watts per kg), the durability and number of discharge cycles a battery can undergo before losing too much capacity, the temperature management requirements and safety.

The hurdles to electrification are lower for trucks with lower GVW and shorter annual mileages. Plug-in and battery-electric LCVs and MFTs in urban contexts in municipal service and delivery operations are beginning to move out of the demonstration phase and into the early deployment

[46] Such as municipal refuse collection vehicles and city buses, which operate on established routes and are refuelled at specific locations e.g. depots.

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phase. But as HFTs serving long-haul operations constitute the majority of oil consumption and as their share of total road freight activity and hence energy use is set to grow in emerging and developing countries (e.g. in East and South Asia), demonstration projects for these operations have recently begun (as outlined in the following section on deployment).

When driving on an uncongested highway, a modern truck can achieve efficiencies from the engine to the wheel of no higher than 30%, while electric trucks can reach powertrain-to-wheel efficiencies of as high as 85% or more. Generally, an ICE converts about 44-46% of fuel energy into work at the crankshaft (peak brake thermal efficiency). Relative to a typical ICE, electric motors (which are about 95% efficient) convert to mechanical work a much higher fraction of the chemical energy coming from the battery, i.e. between 85% and 95% electrical-to-mechanical efficiency of the powertrain to the wheel at full load – or, most of the energy available through dynamic loading from the grid. This is after conversion from direct current to alternating current via the inverter. Furthermore, electric motors can be mounted either in the drivetrain before the transmission to provide energy to the driveshaft and then to the axles, or they can be installed directly in the wheelers of a truck or trailer.[47] This can further improve the efficiency of translating energy to work at the wheels, although trucks operating at highway speeds generally need a transmission.

As with light-duty electric vehicles, most batteries for electric trucks use one of a number of commercially available lithium-ion chemistries. These and other chemistries for batteries viable for use on transport vehicles are currently at the centre of many research efforts and are leading to sizeable changes in battery performance. According to the United States Department of Energy, the energy density of plug-in hybrid elective vehicle batteries for cars was about 60 watt-hours per litre (Wh/L) in 2009 (Howell, 2017 and IEA, 2017e). By 2015, it reached nearly 300 Wh/L, increasing more than a factor of four. The average energy density of battery-electric vehicle batteries being researched under US DOE programmes averaged more than 330 Wh/L in 2016 (IEA, 2017e). Batteries currently used in demonstration trucks are progressively adopting the technologies that only recently were at the research stage. For example, the company Transpower BEV uses a 270 kWh lithium iron phosphate battery in their heavy-duty electric drayage demonstration trucks with a 120 km range (CARB, 2015). Lithium iron phosphate batteries are very durable and thermally stable, and their energy density falls in the upper half of the ranges discussed above.

Infrastructure options

Due to the cost implications for large battery requirements, the challenge for the electrification of trucks, particularly in the HFT segment, is one of how to reduce battery needs through the supply of electricity to vehicles while in motion.

Electric road systems (ERS) rely on vehicles that can receive electricity from power transfer installations along the road upon which the vehicles are driving. Furthermore, the vehicles using ERS can be hybrid, battery-electric, or hydrogen fuel cell vehicles and have the ability to conduct normal driving operations, such as overtaking and driving autonomously outside of the electrical roads. The main infrastructure concepts for ERS are:

Overhead catenary lines, also requiring the installation of an overhead retractable pantograph on trucks.

[47] One example of an innovative business venture that leases regenerative braking systems that are installed in trailer wheel hubs. These systems capture and store power when the trailer is decelerating or going downhill then use the energy to power in-wheel electric motors during operations that require high power (such as climbing a hill). The system installs in under an hour, is leased for USD 500 per month, and saves an estimated USD 1 300 per month on fuel costs (Hyliion, 2017; Create the Future, 2017).

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Inductive transfer of power, requiring the installation of coils that generate an electromagnetic field in the road as well as receiving coils for electricity generation on the vehicle.

Pilot applications in Germany, Sweden and the United States have begun installation of catenary lines along roadways (Siemens, 2016).

Inductive charging has a number of advantages over conductive charging,[48] but also several disadvantages, including lower efficiency,[49] higher material requirements per lane-km, more invasive changes to the existing infrastructure, and more complex components.

Deployment status

Currently, battery- and plug-in/catenary electric trucks are in the pilot stage (for heavy-duty rigid trucks and tractor-trailers) or the early deployment stage (for medium-duty trucks in urban operations).

California remains a leader in advancing the deployment phase of these medium- and heavy-duty trucks. Costs for these vehicles and for the required infrastructure are projected to come down as sales for electric buses and trucks increase. The California Air Resources Board (CARB) has developed a sustainable freight strategy that aims to spur the deployment of zero-emissions truck technologies. CARB has incentivised the adoption of electric HDVs through pilot programmes and their Hybrid and Zero Emission Truck and Bus Voucher Incentive Project (HVIP), which provides monetary incentives for truck manufacturers to develop zero-emissions and hybrid trucks (CARB, 2017b). In various pilot programmes, CARB has worked together with various electric truck OEMs and municipal governments to pilot heavy-duty electric trucks in BNSF Railway yards in the US counties of San Bernardino and Los Angeles (Field 2017; Lambert 2017), as well as a pilot of 11 BYD electric trucks in San Francisco (Field, 2017). USD 50 million has been issued to the HVIP programme, and over 1 600 hybrid and electric trucks and buses have been purchased using vouchers from this programme as of 2013 (Kantor, 2013). Large fleets, such as UPS, have taken advantage of the HVIP to purchase hybrid and electric trucks. These demonstrations and pilot programmes help fleet owners to better understand the feasibility of these electric fleets and the related economic requirements needed for such a transition (CARB, 2015).

A handful of demonstrations of battery-electric drayage and refuse trucks are underway in California (e.g. at the ports of Los Angeles and Long Beach and in the Southern California Air Quality Management District), and the state aims to extend these to include demonstrations of short- and regional-haul heavy-duty trucks in the coming five years.

In Europe, Green Freight Europe (GFE), which is partially funded by the European Union's Seventh Framework Programme, is in charge of setting up demonstration programmes around Europe (e.g. in Amsterdam and London). In this framework, over 127 electric freight vehicles give their logistics data to the GFE (GFE 2017). FREVUE is another European Commission programme that helps cities and companies set up demonstrations for relevant stakeholders and publically disseminates information. Currently, FREVUE tracks the operations of over 70 electric freight vehicles operated by various companies (FREVUE, 2017).

[48] The main advantages include convenience due to the wireless charging, the lower risk of electrical shock, no limitations on the number of devices that can be charged (including cars, eventually), and low maintenance costs due to the lack of wear and tear of components.

[49] The efficiency of inductive power transmission is competitive with wired solutions only when the induction coils have a comparable size (less than a 50% difference) and are in close proximity (less than 10% of the size of the largest induction coil). The proximity requirement is very difficult to comply with in the case of dynamic charging and therefore very likely to pose structural limits to actual efficiency potential.

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Siemens has recently embarked on various demonstration projects of overhead catenary lines to enable trucking operations, called electric road systems (ERS). Such demonstrations are being conducted both in the United States and in Europe:

- on a 2-km test track north of Berlin
- on a 2-km stretch of highway north of Stockholm
- on a 1-mile stretch of highway from the Los Angeles-Long Beach ports.

In addition, two field trails on sections of Germany's Autobahn network (one near Frankfurt and the other near Lübeck) have been announced for 2018.

Costs

Vehicles

The main incremental cost for plug-in hybrid and battery-electric trucks is the cost of battery packs. Given the differences in battery size and all-electric range, plug-in hybrid trucks can be marketed at much lower costs than battery-electric ones. In the case of plug-in hybrid trucks suitable for use on electric road systems, additional costs for the dynamic charging system connecting the vehicle to the electricity supply also need to be factored in.

Given the growing attention and interest around electric vehicles and the significant investments mobilised for battery research, first for consumer electronics and now for automotive applications, battery cost assessments are changing rapidly. The US DOE estimates costs reflecting the production cost of technologies that are currently being researched, once they achieve commercial-scale, high-volume production. According to this assessment, current battery pack costs are close to USD 250/kWh (Howell, 2017 and IEA, 2017e). This estimate is higher than the USD 180/kWh to USD 200/kWh range of battery pack costs announced recently by GM and LGChem (Ayre, 2015) or Tesla and Panasonic (Field, 2016; Lambert, 2016a, 2016b) for batteries that are being or will be used in electric car models currently entering the market. On the other hand, the US DOE estimate is lower than the cost estimates for commercially available technologies reported in other assessments, which range between USD 300/kWh (Slowik, Pavlenko and Lutsey, 2016) and USD 500/kWh (US DOE, 2017). Technical assessments also suggest that there is significant potential for bringing down the costs of batteries: high volume manufacturing for the main categories of battery technologies being researched today confirms the encouraging signs emerging from the past decade, suggesting that battery pack costs could eventually fall within the range of USD 80/kWh to USD 150/kWh .

Using an average of USD 350/kWh to represent the current battery costs available for commercial heavy-duty applications would translate to about USD 9 000 for a battery pack equipping a plug-in hybrid MFT with a 25-km all-electric range. Once hybridisation costs (estimated at USD 35 000 per vehicle) are factored in, the cost differential with a diesel-powered truck of similar performance reaches USD 44 000, or almost double the cost of the ICE benchmark vehicle (USD 50 000). If battery costs were to fall to USD 100/kWh and hybridisation costs were limited to a lower estimate of USD 28 000, cost increments could be reduced to less than USD 30 000. Battery cost increments would be much higher in all cases for BEV MFTs, given longer-range requirements. With a 200-km range and using the USD 350/kWh estimate, battery costs would exceed USD 70 000, and USD 17 000 in the long term (this estimate assumes a battery floor cost of USD 100/kWh and also factors in energy savings from other improvements, which reduce energy demand at the shaft by an additional 15%).

Similar calculations for plug-in HFTs lead to incremental costs of USD 50 000 for plug-in hybrids (assuming USD 350/kWh for batteries and a 25-km all-electric range) against a benchmark of USD 120 000 for a diesel truck and an incremental cost of USD 26 000 in the long term (using

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USD 100/kWh for batteries and factoring in both improvements in efficiency and cost increases for the ICE benchmark due to pollution emission control). Cost increments for battery-electric trucks (in the 400-km range) are estimated to exceed USD 250 000 today and USD 40 000 in the long term. In the case of plug-in trucks with overhead pantographs for connecting the vehicle to catenary systems, the cost increment needs to account for an additional increase of USD 40 000 for the pantograph system in the near term and prospects for cost reductions going to USD 10 000 with large-scale production. Inductive charging is likely to require higher investment per vehicle than overhead catenary systems.

The payback periods depend on the technology choice and the annual mileage. Reasonable benchmarks for payback calculations, as already discussed for the natural gas trucks, are USD 10 000 to USD 16 000 per year of fuel costs for an MFT (powered by diesel fuel and using an ICE) used for regional deliveries and travelling about 40 000 km per year, and USD 60 000 to USD 95 000 for a conventional HFT with an annual mileage of 100 000 km.

Electric road systems

Electric road systems (ERS) require high investment costs. Installation costs are in the order of USD 1 million or more per lane-km (Den Boer et al., 2013; Mottschall, 2016) when dimensioned for traffic flows on the core part of the road network (around 250 trucks/hr), and may fall to half that in the long term, approaching the magnitudes of rail electrification infrastructure upgrades (Network Rail, 2009). The ERS technology builds upon a mainstream, commercialised technology that has been adopted in many cities for buses. The cost per km of infrastructure for inductive charging is on the same order of magnitude than ERS on new roads (USD 0.8 million/km) and up to four times this amount on existing roads (exceeding USD 3.1 million/km) (CODOT, 2016). Targeting infrastructure development on motorways and major trunk roads could help limit investment requirements while also covering most of the heavy-duty traffic.[50]

Emissions reduction potential

The well-to-wheels GHG emissions of plug-in and catenary-enabled electric trucks are a function of the share of electric driving versus the use of fuel from the ICE, and the carbon intensity of the electricity that is used to charge the battery or is from the catenary cable from which it draws power.[51] Plug-in electric trucks operating today are typically used for urban operations and so have a lower share of electric driving than catenary-enabled electric trucks, which would be designed to operate primarily on electric roads and be equipped with smaller diesel engines that enable a limited range on other roads.

Plug-in and catenary hybrids emit far lower levels of local pollutants than conventional trucks, and less even than conventional hybrid trucks. Battery-electric vehicles by definition emit no local pollutants at the tailpipe. However, for both cases, the upstream pollutant emissions incurred in generating and delivering electricity must be considered.

Hence, as with biofuels and hydrogen, the contribution of electricity as an energy carrier to the decarbonisation of the road freight sector is dependent on the decarbonisation of the fuel supply chain.

[50] In England, for example, the Strategic Road Network, made up of motorways and major trunk roads, accounted for 2.4% of the total road network and about two-thirds of the heavy-duty goods vehicle traffic in 2014 (DfT, 2015b). A GIS-based cost minimisation model found that between 2.9% and 4.3% of the existing global road network would need to be equipped with catenary lines to cover 78% of HDV operations (Singh, 2016). In Germany, 60% of all tonne-kilometres shipped by trucks occurs on the most heavily trafficked 3 966 km of the Bundesautobahnen (Verkehr in Zahlen, 2012; TREMOD, 2012), or roughly 2% of the total road network and 32% of the main highway network.

[51] A full life cycle perspective also requires that emissions embedded in the construction of roads are accounted for. For electric roads, this includes the materials and manufacturing emissions due to the electric road system and those imputable to the energy storage devices necessary to operate them.

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Enabling the deployment of electric trucks

Transformation cost reductions and performance improvements in batteries could be driven by researchers in industry, academia, and public research laboratories. These would hinge on the success of demonstrating improvements across key metrics (e.g. metrics of cost, performance, durability and energy density) with novel battery chemistries for which commercial viability remains to be proved, such as lithium-air or flow batteries. In the meantime, considerable improvements can be realised using lithium-ion chemistries (US DOE, 2015), and the costs of batteries and other components will be driven by technology improvements as well as scale economies accompanying the diffusion of electric vehicles in the light-duty market (for more details, see IEA [2017e]).

The importance of the availability of charging infrastructure on the prospects for electric vehicle market growth also calls for continued support for the deployment of chargers, especially for LCVs and MFTs used for short-distance applications and in urban environments. The deployment of chargers could start from captive fleets, such as municipal fleets, vehicles with predefined routes and vehicles used for urban deliveries, as this could enable greater usage rates for electric vehicle supply equipment and maximise the benefits, especially in the presence of policies placing barriers on conventional vehicle use in cities. More broadly, the need to minimise deployment costs suggests that the deployment of charging infrastructure should be tailored to the evolution of the electric vehicle stock growth and co-ordinated with the deployment of electric vehicles.

ERS could penetrate first in short-distance, local freight applications as a means of radically reducing local pollutant emissions, for instance at ports (as in the Los Angeles-Long Beach demo site) and mines. With sufficient regulatory and potentially also fiscal support from local, regional or national policy makers, ERS infrastructure could then branch out to medium- and long-distance highways with the highest freight activity. Trucks operating along ERS routes could be equipped with hybrid-electric powertrains, fully electric batteries, or hydrogen storage tanks and fuel cells to ensure flexibility of operations for a short range without catenary power conduction (i.e. when not on ERS lanes).

Public policy can play a number of roles. Options include providing standardising charging protocols and a reliable funding stream for R&D for batteries and other components; supporting the deployment of electric vehicle supply equipment; funding demonstration projects to test the economic and operational viability of various kinds of electric trucks across a range of mission profiles and duty cycles; and through introducing financial incentives and regulatory activity.

Incentives and regulations not only build market certainty, they may also provide substantial opportunities to fund the other two possibilities for public policy intervention (R&D and demonstrations). Low-emissions zones that toll or prohibit the operations of conventional trucks in densely populated areas (such as cities or ports) can incentivise companies to build upon successful demonstrations, and in the case of tolls, the revenues can be used to subsidise the costs of electric truck purchases. A long-term transition to ERS would likely require a dedicated funding stream – the Eurovignettes discussed in Chapter 1 of this report offer an existing template by which governments could generate revenue from truck operations to fund ERS deployment. This dedicated funding would provide the needed certainty on the rates of return for installers of catenary power systems and thereby promote much more rapid deployment than would otherwise be possible. Some portion of the increased up-front costs could be paid back over the following years of vehicle operations.

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Hydrogen

Vehicle and infrastructure technologies

Hydrogen fuel cell vehicles

Trucks using fuel cells and hydrogen are essentially electric vehicles using hydrogen stored in a pressurised tank and equipped with a fuel cell for on-board power generation. Fuel cell vehicle (FCV) powertrains are also hybrids, as braking energy is recuperated and stored in a battery. The battery also reduces peak demand from the fuel cell during acceleration and enables optimisation of operational efficiency. FCV powertrains benefit from technological advancement in both fuel cell and battery storage technologies. Compared with batteries, hydrogen at 70 megapascals (MPa) has much higher energy density: about six times higher per unit of volume and about 300 times higher by unit of weight. Hydrogen-powered trucks can benefit from the higher energy density of hydrogen storage tanks, making their cost somewhat insensitive to weight and range.

Hydrogen is stored on vehicles in dedicated tanks at pressures of 35 MPa to 70 MPa. As 70 MPa tanks allow for much higher ranges per unit volume, trucks need to rely on high-pressure tanks. Despite this, hydrogen storage still needs four times more space to achieve the same range as conventional diesel technology (IEA, 2015).

Hydrogen as an energy carrier

Today, hydrogen is produced and used primarily in the chemical and industrial gas industries (Suresh et al., 2013). Currently, around half is produced from natural gas through steam methane reforming, and one-third arises as a fraction of petroleum during the refining process. The rest is produced from either coal or electrolysis (Decourt et al., 2014).

Despite the few options currently used for its production, hydrogen is a flexible energy carrier. Key features demonstrating this flexibility include the following:

- Hydrogen can be generated from several primary energy sources, primarily via steam reforming of methane or electrolysis. Electrolysis is the most promising pathway for the production of low-carbon hydrogen, as it does not require the use of fuel containing carbon. Alternatively, biomethane and the use of carbon capture and storage also provide alternative ways to generate hydrogen with low life cycle GHG emissions.
- Thanks to electrolysis, which converts electricity into hydrogen, and fuel cells, which revert hydrogen back to electricity (even if these processes generate thermodynamic losses), hydrogen is one of the means currently available to store energy from electricity (where it competes with pumped hydro, compressed air, rotating masses and battery storage). As such, it could be used to integrate surplus electricity from variable renewable energy generation across different energy sectors and as a lever to integrate more renewable energy in other end-use sectors (IEA-RETD, 2016).
- If combined with carbon or nitrogen streams, hydrogen can also be effectively transformed into diverse forms of PtX fuels (see the discussion on PtX fuels in the biofuels section for more details).

The thermodynamic efficiency of hydrogen production ranges between 50% and 85% for steam reforming (with higher values achievable in large-scale production facilities) and 65-80% for most electrolysers, with lab-scale applications reaching 85-90% (IEA, 2015).

Today's energy system is heavily dependent on fossil fuels and, apart from co-generation, few connections exist between the different transmission and distribution systems. In the future, the

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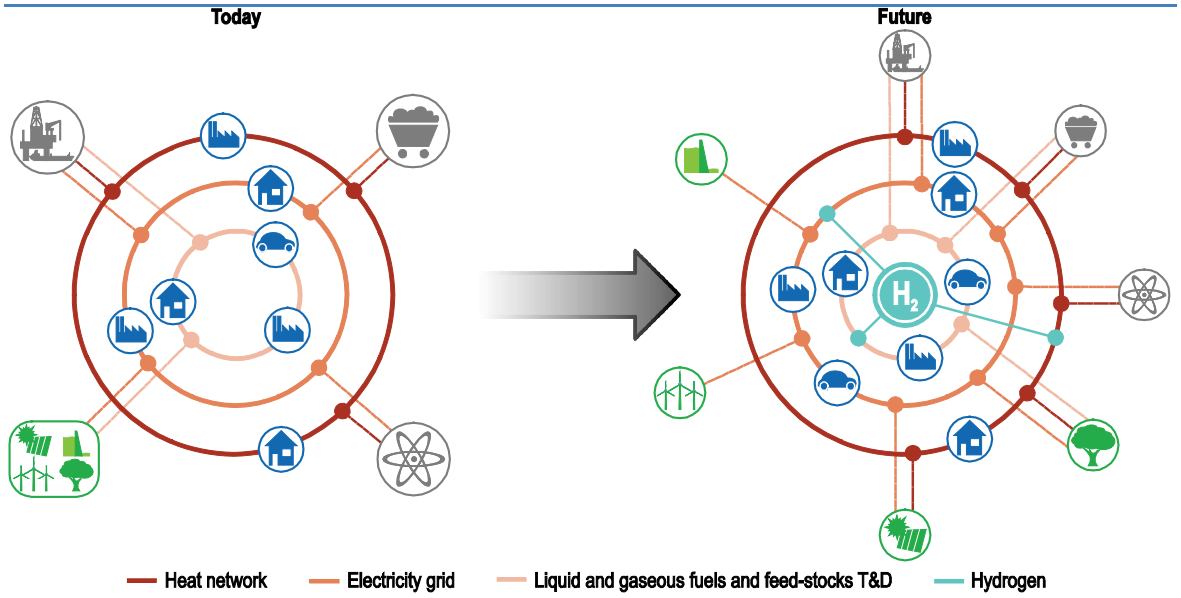
versatility of hydrogen could enable it to play a pivotal role in connecting the different layers of infrastructure, especially in a low-carbon energy system (Figure 25).[52] Thanks to electrolysis, which converts electricity into hydrogen, and fuel cells, which revert hydrogen back to electricity, hydrogen is a flexible energy carrier. As one of the currently available means of storing energy from electricity, hydrogen could be used to integrate surplus electricity from variable renewable energy generation across different energy sectors.

Figure 25 • Hydrogen's role in the energy system today and in the future



Note: T&D = transmission and distribution
Source: IEA (2015).

Refuelling

Hydrogen vehicle refuelling is a complex process that is affected by several parameters. During refuelling, the compression of hydrogen leads to a temperature increase in the storage tank. As in the case of CNG, this reduces the amount of energy that can be stored in the tank and may increase refilling times. Standards for hydrogen fuelling protocol have been established to deal with these issues and to ensure safety. Thanks to these protocols and technological development, hydrogen refuelling can take place in short timeframes, almost comparable with liquid fuels.[53]

The setup of a hydrogen station is influenced by the pressure of hydrogen in the vehicles and the daily hydrogen delivery capacity of a station. High-pressure, on-board storage (70 MPa) requires more compression capacity at the station than is required by 35-MPa vehicle storage. Station size is critical in determining the best way to deliver hydrogen to the station: gaseous trucking or on-site hydrogen production are best for small stations; liquefied trucking or the use of pipelines are the only options for hydrogen delivery to stations larger than 500 kg per day. Both on-board pressure and station size also have implications for the form of hydrogen storage at the station, i.e. whether hydrogen is stored in a gaseous (viable in smaller stations and low-pressure tanks) or liquid form (best in large stations and high-pressure tanks) (IEA, 2015).

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[52] Also, liquefied hydrogen or other forms of hydrogen-based chemicals, could play a central role in replacing fossil fuels as the main energy carriers in international energy trade and thus may be a key-enabler for deep decarbonisation.
[53] In the case of cars, refuelling times are in the range of 3-5 minutes (Hydrogen Council, 2017).

Installation of hydrogen refuelling infrastructure has been limited to date. Further, the time needed to bring hydrogen-refuelling stations online is also significant: California estimates it at two years (CARB, 2017b). However, encouraging signs in the deployment of refuelling infrastructure and vehicles have emerged in different markets worldwide, including in California, China, Germany, Japan and Korea, as discussed in the following section.

Deployment status

With 500 vehicles (mostly cars and buses) running across several demonstration projects globally, the current market is still small. Despite this, interest in FCEVs (and hydrogen as an energy carrier) remains relevant. Hyundai, Honda and Toyota commercialise fuel cell cars, mainly targeting California, a market that has deployed zero-emissions vehicle mandates and has ambitious policy goals for hydrogen deployment. Additional demonstration projects target the deployment of hydrogen and fuel cell light-duty vehicles (including light commercial models) in Europe – primarily France, Germany and the United Kingdom (Green Car Congress, 2017).

Recent pilot and demonstration projects have also targeted medium- and heavy-duty vehicles:

- Demonstration projects have begun to test the use of hydrogen in trucks in California (Fuel Cells Bulletin, 2015).
- Scania publicised its intention to start testing trucks with electric powertrains powered by fuel cells and hydrogen (Scania, 2016).
- UPS launched the world's first fuel cell electric delivery truck (Trucks.com, 2017).
- Nikola announced in 2016 the intention to manufacture a semi-trailer using hydrogen fuel cells to supply lithium ion batteries driving electric motors (Nikola, 2016).
- Toyota revealed recently that it is developing a proof-of-concept for a heavy-duty truck based on a hydrogen fuel cell system for use at the Port of Los Angeles (Toyota, 2017).

In parallel, leading economies are beginning to act on the rollout of hydrogen refuelling infrastructure: California has set the goal of having 100 stations by 2020 and has developed funding programmes for achieving this (State of California, 2013). In Europe, the Directive on the Deployment of Alternative Fuels Infrastructure gives European Union member states the option to choose to include hydrogen-refuelling points in their national policy frameworks (EC, 2014). Up to 400 stations are planned to be operating in Germany by 2023; Japan already has more than 80 stations operating; Korea and China are planning to create a hydrogen network, together aiming for 830 stations by 2025. Recent investments also show increasing momentum to shift mass transit to fuel cells (Hydrogen Council, 2017).

Costs

Fuel cell vehicles

Despite considerable reductions in the cost of fuel cells and hydrogen storage tanks over the past decade, high costs remain one of the main hurdles faced by hydrogen fuel cell vehicles, including trucks. The range of the current cost estimates is very wide: from USD 280/kWh (for current technology at 20 000 units per year, the expected cost for initial FCEV commercialisation from Papageorgopoulos [2016]) to USD 2 500/kW for 2015 fuel cell systems in transit bus applications (CARB, 2015). Using an average of USD 1 100/kW (as in Den Boer et al. [2013]) for a truck with a power rating of 260 kW, the cost of the fuel cell system would reach USD 286 000.[54]

[54] This assessment does not fully consider that the declining efficiencies of fuel cells with increasing power output put upward pressure on fuel cell costs, requiring larger cells for the achievement of higher efficiency.

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Technical assessments suggest that there is significant potential to bring down the costs of fuel cells: high-volume manufacturing with next-generation laboratory technology could bring down fuel cell production costs to values within the range of USD 40/kW to USD 60/kW (Papageorgopoulos, 2016). Den Boer et al. (2013) cites potential reductions to USD 100/kW, while CARB (2015) refers to a USD 200/kW target. At USD 50/kW, the fuel cell system for the same 260-kW truck considered above would fall to USD 13 000. At USD 200/kW, it would reach USD 52 000.

A second, significant cost component for hydrogen fuel cell vehicles is the storage tank. Tank costs are determined by expensive composite materials, which are expected to fall at a much slower pace (ANL, 2010). Available estimates from Den Boer et al. (2013) and CARB (2015) point to current costs ranging from USD 30/kWh to USD 60/kWh for 70-MPa storage tanks, and reduction prospects in the range of USD 12/kWh to USD33/kWh. For a storage tank of 1 400 kWh (estimated here to enable a 700-km range), these ranges represent costs of between USD 45 000 and USD 85 000 today and a potential reduction in the range of USD 16 000 to USD 45 000.

Using the midpoint estimates of the current fuel cell and hydrogen tank cost ranges, the total cost for a 260-kW fuel cell truck resulting from the assessment above equals USD 490 000, and USD 150 000 to USD 230 000 for cases where hydrogen fuel cell technologies achieve a very wide market deployment.

These values need to be benchmarked against the cost of a truck with a similar power rating that is currently on the market, in the range of USD 120 000, and current annual fuel expenditures (USD 60 000 to USD 95 000 for 100 000 km/year in the United States and Europe, respectively).

There are promising prospects for cost reductions for both fuel cells and hydrogen storage systems. However, asymptotic costs and learning rates[55] for heavy-duty transport applications are subject to significant uncertainties. Achieving these cost cuts will depend on the extent to which these technologies will be adopted. This, in turn, depends on the likelihood of seeing hydrogen used as an energy carrier across the energy system, including in passenger cars and other end uses. These current barriers also affect the possibility of deploying a network of publicly accessible refuelling points, although they could in the future be leveraged as synergies enabling a more rapid scale-up.

Hydrogen

The cost of hydrogen production via large-scale steam methane reforming was estimated in 2015 to be between USD 30/MWh and USD 70/MWh (USD 0.03/kWh to USD 0.07/kWh) in Europe, Japan and the United States (most of the variability stems from natural gas prices: prices in the United States are lower than in Europe and Japan). Steam methane reforming is currently the lowest-cost option available for hydrogen production. This, together with anticipated transport and distribution costs, sets the benchmark against which alternative, low-carbon hydrogen production pathways need to be measured.

The cost of producing hydrogen from electrolysis depends primarily on the price of electricity as well as the cost and capacity utilisation rate of the electrolysers.

Capital costs for electrolysers can decrease with increasing application and technology learning. Current cost estimates are at USD 2 600/kW of hydrogen (IEA, 2015); prospected cost reductions range between USD 450/kW of hydrogen and USD 640/kW of hydrogen (IEA, 2015, Hydrogen Council, 2017).

[55] Learning curves are often defined on the basis of a learning rate, a unitless parameter indicating the cost reduction per doubling of the production volume.

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For hydrogen production from renewable electricity, the capital utilisation rates are closely linked with electricity prices: relying exclusively on generation surpluses and low-cost electricity is insufficient to reach sufficient capacity factors, and high capacity factors are unlikely to be reached without having to rely on electricity production at higher price rates. Overall, estimates of hydrogen production from low-carbon energy sources may fall close to USD 100/MWh (USD 0.1/kWh). This is the minimum price that consumers of low-carbon hydrogen would pay at the pump.

Refuelling

The investment risk associated with the development of refuelling stations is mainly attributable to high capital and operational costs and to the underutilisation of facilities during FCEV market development.

In California, the total cost of the engineering, construction and general overhead costs for hydrogen refuelling stations with the capacity to deliver 130 kg to 350 kg per day of hydrogen fall in the range of USD 2.4 million to USD 3.2 million (Baronas and Achtelik, 2017). Investment costs estimated by the IEA (2005) fall in a similar range. The IEA (2005) also suggests that investments are appreciably lower for stations with lower daily hydrogen delivery capacities.

In the case of trucks, the high pressure of hydrogen stored on board (70 MPa) puts upward pressure on costs for the compressors needed at the station. On the other hand, some cost savings can be delivered from the possibility of hydrogen distribution to build on existing retail infrastructure for conventional fuels (Hydrogen Council, 2017).

Refuelling infrastructure for captive fleets provides a way to address the aforementioned underutilisation barrier. Thanks to higher utilisation rates, refuelling stations for captive fleets enable investments in refuelling infrastructure. As it leads to larger sales volumes in comparison with conventional hydrogen refuelling facilities, hydrogen-refuelling infrastructure for captive fleets allows the lowering of the price of hydrogen by diluting fixed costs on much higher volumes.

With the few exceptions of stations used for fleets, the set-up of a hydrogen station also implies a certain path dependency: small stations are more likely to be subject to higher capacity utilisation rates in the initial deployment phase when demand from hydrogen from transport vehicles is limited, given fairly long stock turnover rates. This complicates investment decision making, increases risks and adds to the barriers already mentioned for rapid hydrogen uptake in transportation

Emissions reduction potential

Fuel cell trucks are one of the few technology options capable of resulting in zero tailpipe emissions and deeply decarbonising heavy-duty, long-haul road freight transport. However, their capacity to do so depends heavily on the carbon intensity of the hydrogen production, transportation and distribution pathways. A review of key results for current production pathways is available in IEA (2015) and is briefly summarised in the following bullet points.

- Hydrogen produced with steam methane reforming from natural gas results in higher GHG emissions per unit of energy than petroleum-based fuels (higher by a factor of 1.35 to 1.4 for hydrogen transported in pipelines or in the gaseous phase in trucks, and a factor 1.7 to 1.8 higher for hydrogen transported by truck after liquefaction). The higher efficiency of FCEVs relative to conventional ICE diesel trucks reverses these results, leading to lower GHG emissions per km, but the life cycle emissions of hydrogen from natural gas steam methane reforming being used as an energy carrier for FCEVs do not

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lead to significant reductions in GHG emissions relative to the petroleum-based fuels used in ICEs.

- For hydrogen production (at the refuelling station) from electrolysis, the results strongly depend on the carbon intensity of the electricity used. Using today's European Union grid electricity mix, and including compression, yields emissions per unit of final energy almost three times higher than that of petroleum fuels. The balance is worse for coal-intensive power generation mixes and better for low-carbon power generation pathways. When hydrogen is produced from low-carbon electricity, biomass or fossil fuels with carbon capture and storage, the carbon content of hydrogen can be reduced to below 20 g CO_2-equivalent/MJ, about one-quarter of the well-to-wheel emissions from petroleum fuels.

Besides electrolysis from low-carbon electricity, other low-carbon hydrogen production technologies include:

- steam methane reforming using bio-methane or combined with carbon capture and storage
- gasification of biomass.

While steam methane reforming (SMR) and electrolysis are mature technologies, gasification and SMR with carbon capture and storage still need to be demonstrated on a large scale.

Enabling the deployment of hydrogen trucks

Enabling hydrogen to penetrate road freight transportation requires actions that target refuelling infrastructure deployment and vehicle technology costs. Improvements in hydrogen production technologies that decrease costs and increase energy efficiency would support the use of hydrogen in vehicles. In the case of centralised hydrogen production, there is also a need to address challenges in the hydrogen transportation and distribution network.

The build-up of sufficient hydrogen refuelling infrastructure is the first prerequisite needed to make the deployment of hydrogen-powered motor vehicles possible.

Reducing the cost of fuel cells and hydrogen storage tanks is also a major priority. RD&D is essential to keep achieving improvements, but it needs to be supported by technology deployment and the scale-up of hydrogen production to deliver cost savings from technology learning and economies of scale.

Hydrogen fuel cell vehicles have a high tank-to-wheel efficiency, but the thermodynamic efficiency of well-to-tank processes (i.e. hydrogen production, transport and conversion pathways) needs to be improved. Energy losses occur in several steps during hydrogen's production and distribution – including production (via electrolysis or steam reforming), transportation and refuelling. Hence, hydrogen production has to transition from the current rather carbon-intensive mix of production pathways to low-carbon production options.

- Electrolysis could avoid the risks associated with complex and costly hydrogen transport and distribution technologies, but its economic competitiveness would need to improve. To produce hydrogen from electrolysis at lower costs, the capacity utilisation rates of electrolysers would need to be maximised, and electricity would need to be available at a low cost. This could be achieved if nuclear energy were to become available at lower costs (which would also require overcoming other deployment barriers) or in the presence of energy from solar and wind resources with a high availability distribution across the day and the year (a situation that is currently limited in geographical scope).
- Centralised production from steam methane reforming with carbon capture and storage may be a viable strategy for limiting cost increases for hydrogen production, but it

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requires the deployment of costly and capital-intensive hydrogen transportation and distribution infrastructure. This is a major challenge to hydrogen deployment and use, particularly in light of high costs at low usage rates.

International co-operation in hydrogen production from renewable electricity sources should also be encouraged. Challenges include all steps of the production chain, from electricity generation to the electrolysis of water and the international transport of liquefied hydrogen.

Overcoming the barriers that still face hydrogen production and use in road freight transport also calls for co-ordinated effort across stakeholders to build a minimum number of stations, starting in main urban centres and the major axes of the road transport network. Examples exist in Germany and California, and similar co-ordinated initiatives need to emerge elsewhere (Hydrogen Council, 2017).

Considering that trucks have much smaller market volumes than cars and light commercial vehicles,[56] leveraging only on road freight transport to increase hydrogen uptake would limit the benefits that could be seized from economies of scale (achieving cost reductions in fuel cell and storage technologies requires large volumes of production). Deploying FCEVs in fleets of LDVs and buses will be necessary to drive costs downward. Advancing the energy transition also requires harmonised regional and sector-specific fuel cell and hydrogen standards that will allow for the realisation of economies of scale (Hydrogen Council, 2017).

As hydrogen's properties make it a powerful enabler for the energy transition, with benefits for both the energy system and end-use applications,[57] the uptake of hydrogen in transport would further have to be conceived as a concerted effort involving the rest of the energy system.

Comparing the costs of alternative vehicle and fuel technologies

Figure 26 shows the current costs per km for heavy-duty vehicles operating in major global markets and under a range of vehicle technology, fuel and infrastructure cost assumptions, taking into account a time horizon of five years of use and current fuel costs. The analysis compares conventional ICE diesel vehicles; diesel hybrids; trucks fuelled with natural gas; battery- and hybrid-electric hybrids operating over the majority (80%) of their vkm on electricity from catenary-based electric road systems (CAT-ERS); and hybrid electric hydrogen trucks (HFEV-Hybrid). Battery-electric and plug-in hybrid vehicles are excluded from Figure 26 for simplicity, given the focus on long-haul mission profiles.

Figure 26 also includes the infrastructure costs for natural gas, hydrogen and electric road systems (ERS). The assumptions used for the estimation of infrastructure costs aim to show the importance of frequencies of use of alternative fuels infrastructure (for hydrogen and natural gas, the 2015 cost estimates account for a capacity utilisation of the refuelling system ranging from 33% (in the case of captive fleets) to 4% (reflecting low usage in the early deployment phase). The assumptions in Figure 26 also assume that infrastructure would be shared with other transport modes.

Figure 26 confirms that CNG and LNG can be cost competitive in regions where the price gap between natural gas and diesel is highest, and where average mileages put a strong focus on fuel costs) in cases where infrastructure costs can be borne externally or are very effectively shared

[56] MFT and HFT sales combined have in recent years accounted for 6-7% of the sales of all road transport vehicles.

[57] Examples include the possibility to enable large-scale, efficient renewable energy integration, to distribute energy across sectors and regions and to act as a buffer to increase system resilience; the possibility to contribute to the decarbonisation of industry energy use; synergies with carbon capture and storage for the exploitation of fossil energy and the possibility to use it to decarbonise energy use in buildings.

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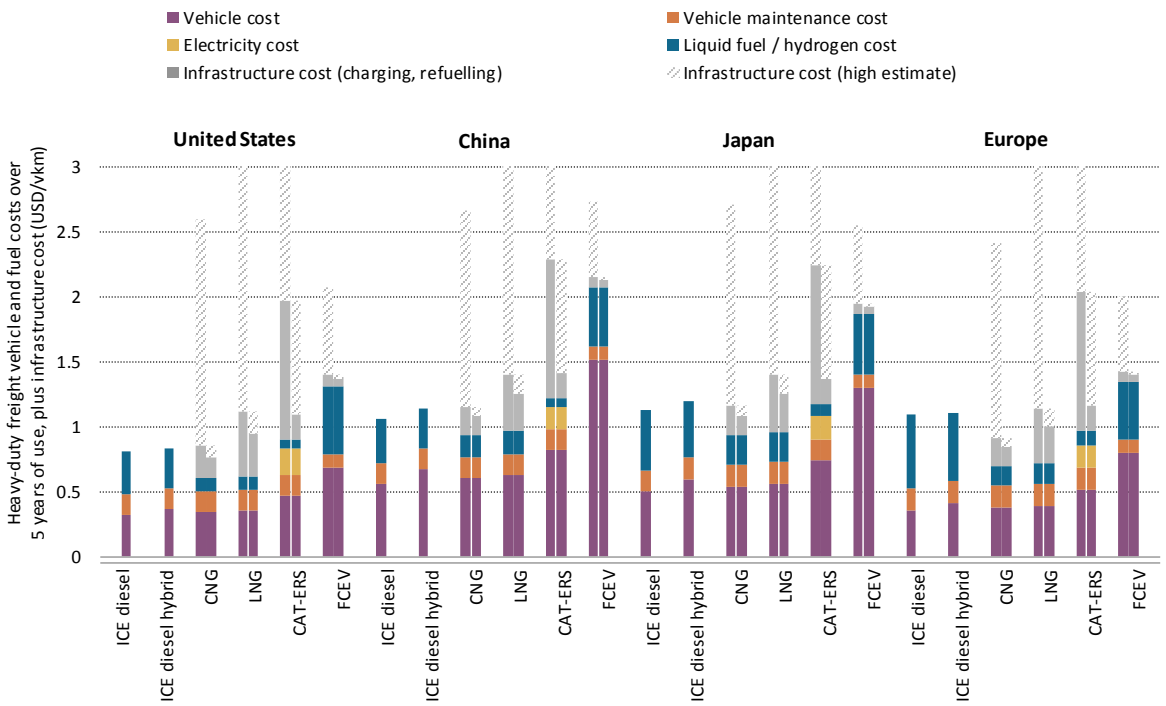
across fleets. The competitiveness of CNG and LNG is less favourable in China and Europe, given that the price gap between diesel and natural gas is narrower.

The hybridisation of diesel HFT trucks may prove an attractive option. Hybridisation clearly pays back over a vehicle's lifespan but is roughly at parity with conventional diesel ICE trucks when looking at the first five years of vehicle use. Hybrid HFTs are most cost competitive in the European Union, due to high fuel taxes and vehicle mileages. They are less competitive in China and Japan than in other regions due to the lower mileages compared with other markets, and in the United States, low fuel taxes undermine the competitiveness of hybrid HFTs.

Figure 26 • Heavy-duty freight vehicle and fuel costs over five years of usage, including infrastructure costs, 2015 (high- and low-infrastructure utilisation assumptions)



Notes: The key assumptions on heavy-duty vehicle costs and infrastructure are as follows.

Vehicles: The 2015 vehicle investment costs range from USD 120 000 for diesel ICEs, USD 160 000 for diesel ICE hybrids, USD 145 000 for natural gas vehicles, USD 220 000 for CAT-ERS and USD 490 000 for FCEVs. Gasoline, diesel and electricity prices are from the IEA Mobility Model, and the electricity price is USD 0.17 for all regions and cases.

Depreciation is assumed to be the same for all technologies. After five years, the residual value of a truck is 42% of its purchase value.

ERS: Electric road system infrastructure costs are based on USD 1.6 million/km and a frequency of use of 30 vehicles per hour or less (as cost estimates are very sensitive to the frequency of usage: using low frequencies leads to major increases in unit cost per km for CAT-ERS in 2015) in the higher cost estimate (bar on the left for CAT-ERS), and 160 to 30 trucks/hour in the lower infrastructure cost estimate (bar on the right).

Hydrogen: The 2015 hydrogen costs are evaluated using an electricity price of USD 0.01/kWh (and hence assuming that hydrogen is generated during periods when electricity supply is far in excess of demand), an electrolyser cost of USD 78/GJ, operating and maintenance costs of USD 8/GJ, an electrolyser usage rate of 7% across the year, a lifetime of 15 years and costs for the storage and refuelling system of USD 5.2/GJ of hydrogen delivery capacity.

For hydrogen and natural gas, the 2015 cost estimates account for a capacity utilisation of the refuelling system ranging from 33% (captive fleet case, grey shading in the figure) to 4% (higher estimate in the figure, bar on the left for FCEVs) or 33% to 50% in the lower infrastructure cost estimate (bar on the right). Infrastructure is not assumed to be shared with other transport modes.

Source: Vehicle travel per year, vehicle costs and fuel costs reflect assumptions used in the characterisation used in IEA (2017a), Mobility Model, June 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport.

Plug-in hybrid trucks using ERS consisting of overhead catenary lines (CAT-ERS) and hydrogen fuel cell trucks are the only technology options assessed here that could both eliminate tailpipe pollutant emissions and substantially reduce GHG emissions. However, their cost is significantly

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higher than that of fossil options. This highlights the need for RD&D investments and the necessity to scale up production to achieve cost reductions. In regions with high fuel taxes, such as the European Union and Japan, the cost competitiveness of alternative technologies is strengthened. Both the widespread adoption on highway corridors of CAT-ERS and the scale-up of FCEVs suffer from the chicken-and-egg issue, which implies very high costs to early adopters of the infrastructure needed to enable electricity and hydrogen in HFTs. Pilot and demonstration projects focusing on shuttle operations are the first step toward addressing this issue. As is the case for CNG and LNG, this calls for concerted action across various stakeholders to ensure that the deployment of trucks using electricity or hydrogen becomes possible.

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Long-term outlook and policy insights

What does the future hold for road freight transport? Will the long-standing historical relationship between global economic growth and road freight activity weaken, or will it require additional policy efforts for it to be overcome? What are the implications of existing policy efforts for reducing the future growth of fuel demand and emissions from road freight transport? Will it be sufficient for the future of road freight transport to be more efficient in terms of vehicles and the logistical system, and for alternatives to oil to be deployed at scale? Building on the analyses in Chapters 1 and 2, this chapter examines the long-term outlook for energy demand and emissions growth from road freight transport through the use of two scenarios. The first, the Reference Scenario, presents the outlook for future energy demand and CO_2 emissions growth to 2050 based on all policies affecting the outlook for road freight transport or those that have been announced. In doing so, it establishes a reference scenario of how road freight trends will play out in terms of the sector's share of global energy demand and emissions.

The chapter then moves into the description and analysis of the Modern Truck Scenario (MTS), which lays out a modernisation strategy for future road freight transport. The modernisation strategy aims to overcome some of the shortcomings identified in the Reference Scenario in terms of selected principal energy policy objectives, such as energy security and climate change. It envisions rapid adoption of the technological and system-wide measures for reducing the future energy and emissions growth that identified in Chapter 2 and lays out the benefits of this approach from an energy policy perspective. It further identifies the key policy requirements for realising such a scenario.

Defining the scenarios

The scenarios assessed in this study have been developed using the IEA Mobility Model (MoMo), which is the transport model of the IEA *Energy Technology Perspective* series. Developed over a period of nearly two decades, MoMo generates comprehensive and detailed region-by-region projections of transport sector developments and assesses their impacts on energy demand, greenhouse gas (GHG) emissions and the associated infrastructure and investment needs.[58] The latest historical data point of the model is 2015, and long-term projections are made in five-year time steps. In this study, the focus is on the long-term trends to 2050.

Global gross domestic product (GDP) is assumed to grow at an average annual rate of 3.1% between 2015 and 2050 (measured in terms of purchasing power parity [PPP]).[59] The bulk of global economic growth is projected to occur in emerging and developing economies: 80% of the growth in global economic activity to 2050 takes place in these countries. The world's population is projected to grow at a rate of 0.8%, although there is a high degree of variability among regions, with the majority of the growth occurring in developing countries. These assumptions remain the same across the scenarios examined in this chapter.

Reference Scenario

The Reference Scenario assesses the outlook for energy demand and emissions growth from road freight transport by considering all relevant policies and measures that are already adopted today or have been announced, even when the precise targets have yet to be fully defined. The scenario focuses on the specific policies and incentives that could affect the long-term outlook for road freight transport, including for improving the energy efficiency of

[58] For more details about MoMo, see www.iea.org/topics/transport/subtopics/mobilitymodelpartnership/.
[59] For a more detailed overview of key assumptions in the Reference Scenario see IEA (2017b).

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trucks, for facilitating improved logistical systems or selected technology enablers and for promoting the use of alternative fuels.

The projections for road freight transport in the Reference Scenario are embedded in the wider context of the long-term outlook for the energy sector.[60] This includes policies specific to individual parts of the energy sector, such as the power sector, the transport sector, and the industry and buildings sectors. However, it also includes broader policy efforts that may affect future patterns of energy consumption, such as the energy-related targets expressed through the Nationally Determined Contributions, submitted and then ratified by national governments as pledges in the United Nations Framework Convention on Climate Change Conference of the Parties (COP) 21 and adopted as part of the Paris Agreement.

Modern Truck Scenario

The Modern Truck Scenario envisions an entirely different future course of action. Its focus is on the ambitious but attainable deployment of technologies, policies and innovative business practices that deliver the same services as in the Reference Scenario but with radically reduced vehicle activity, less overall movement of goods, and reduced energy demand and emissions. The Modern Truck Scenario rests on three main pillars:[61]

- *Vehicle efficiency* (fuel economy) improvements that start immediately (e.g. with retrofits and driver training) and are spurred over the coming decades, primarily by tighter fuel economy standards and expansion of their geographic coverage. The standards are supported by differentiated vehicle taxation (both on vehicle purchases and operations, including fuel taxes) to incentivise the purchase and operation of efficient trucks.
- *Systemic improvements in road freight operations and logistics* that capitalise on the advancement of digital technologies and their application across all aspects of road freight, including supply chain and fleet management, collaboration across shippers and the optimisation of vehicle operations. The policy focus is on regulations and pricing policies that reward efficient operations in order to catalyse rapid uptake of these measures.
- *A shift to alternative fuels and alternative fuel trucks*. With a focus on the future deployment of alternative fuels that are low- or zero-emitting not only at the point of use but also across the entire supply chain,[62] both with regards to air pollutant and carbon dioxide (CO_2) emissions, as a means to address multiple energy policy goals. Where the deployment of fuel chain infrastructures is required (such as for electric or hydrogen trucks), co-ordination across multiple public and private actors and a dedicated stream of funding, including from taxes on vehicle travel (i.e. distance-based taxes) and/or fuel taxation, are assumed.

The measures in the Modern Truck Scenario were chosen to simultaneously facilitate the achievement of multiple energy policy objectives, with a focus on diversifying long-term energy supply, and reducing (or, where possible, eliminating) the release of GHG and air pollutant

[60] For a more detailed discussion of the long-term outlook for the energy sector in the Reference Technology Scenario, see 2017 Energy Technology Perspectives (IEA, 2017c).

[61] Additional potential for reducing energy and emissions growth from road freight lies in shifting activity to rail or inland maritime ships. As noted previously, such analysis is beyond the scope of this report.

[62] Alternatives to petroleum fuels need to ensure that GHG reduction and fossil fuel replacement takes places across the whole life cycle and not only for tailpipe emissions. This is especially important for electricity and hydrogen, leading to zero tailpipe emissions but potentially leading to high emissions of GHGs and other pollutants in production facilities, and biofuels. The latter do result in emissions at the tailpipe but may also be produced in ways that compensate for most of the GHGs released during combustion. Other sustainability goals for transport fuels and energy carriers include the minimisation of the competition for land needed for food production, and the minimisation of direct and indirect land use change that could lead to large GHG emissions, requiring a long time to be compensated, as well as the impacts on biodiversity, the use of water and other resources.

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emissions. The level of their adoption in the Modern Truck Scenario differs by region, depending on individual country characteristics.

Vehicle efficiency improvements

Increasing efficiency at the level of individual road freight vehicles is the first central pillar of the MTS. The efficiency improvement of the scenario meets the 35% improvement goal (against a 2015 benchmark) recently announced by the Global Fuel Economy Initiative (GFEI) for 2035 and includes further improvements in the following years. The improvement rate is greatest in developed regions and rapidly developing global markets, including, in particular, the People's Republic of China (hereafter, "China"), the European Union, Japan and the United States. In these countries and regions, new HFTs consume just more than half of the final energy in 2035 compared with vehicles entering the markets 20 years earlier, while the energy intensity of MFTs (per vehicle-kilometre [vkm]) is 40-45% lower.

The achievement of these efficiency improvements hinges on overcoming the barriers discussed in Chapter 2. Two main approaches can facilitate them:

- First and foremost, fuel economy policies, consisting of standards or regulations and differentiated taxes on vehicle purchases in response to market failures (see Chapter 1) are introduced in the short-term for road freight vehicles in all countries where they currently do not exist. The standards are progressively raised towards the 2035 goal globally, and beyond it in the following years.
- Second, to improve the business case for the required investment and to support climate goals as well as increased energy diversification, the Modern Truck Scenario assumes a stable and progressively increasing carbon price. The Scenario introduces this globally in 2020, and it reaches USD 500 (constant 2015 US dollars) per tonne of CO_2-equivalent (or USD 1.22 per litre of diesel-equivalent, on a well-to-wheel basis) by 2050.

Systemic improvements in road freight operations and logistics

The modernisation of road freight transport cannot focus on increasing the efficiency of individual vehicles alone. In order to fully to realise the efficiency potential of road freight transport, the second central pillar of the Modern Truck Scenario is the near complete realisation of all of the potential systemic improvements identified in Chapter 2 (Table 11). Their rollout is facilitated through policies that reward efficiency and collaboration as well as price signals and other mechanisms that internalise the externalities associated with road freight transport.

Alternative fuels

Promoting the adoption of alternative road freight vehicle fuels is the third central pillar of the MTS. Policy requirements differ depending on the fuel in question.

- The uptake of alternative liquid fuels in the MTS, for example, is achieved through dedicated research, development and demonstration (RD&D) support, and policies that promote reducing the carbon intensity of fuels and mandates. The latter is aimed at scaling up production for alternative fuel pathways that not only meet minimum sustainability requirements but also have good prospects for technology improvement. The prioritisation of drop-in options is also expected to speed up biofuel uptake by providing access to much wider markets than in the case of fuels that would require modifications to vehicles and fuel transport and refuelling infrastructure.
- For other fuels, in particular electricity and hydrogen, policy requirements are more comprehensive, given limited experience to date with the deployment of relevant technologies and infrastructures. The Modern Truck Scenario initially assumes RD&D support to foster cost saving for the relevant vehicle technologies. This is followed by the

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rollout of refuelling infrastructure, leveraging on revenues raised for the development of road transport networks[63] and financial support for the early adopters of plug-in electric and catenary-electric road systems enabled (hybrid)-electric and hydrogen trucks, using funding that could be provided by differentiated vehicle taxes.

The central prerequisite in the Modern Truck Scenario is that the revenues generated from conventional fuel use, truck purchase and operations are used to support the transition.

Trends in the Reference Scenario

Road freight activity

Economic growth and population growth are the main drivers of a robust projected increase in road freight activity over the coming decades. Global road freight activity (measured in tonne-kilometres) grows by 2.4-fold over today's level to 2050, concomitant with economic growth (Figure 27). The majority of the increase in road freight activity occurs in emerging and developing economies – between 2015 and 2050, emerging and developing economies account for nearly 85% of the global growth. By 2050, these countries constitute nearly three-quarters of global road freight activity (up from 55% today). By the early 2030s, China overtakes the United States as the country with the most road freight activity in the world, while India is the country with the largest annual growth rate (5.6%) among all countries analysed in detail in this study. Together, China and India comprise nearly 40% of the global growth in road freight activity to 2050. Activity growth in Africa to 2050 is also rapid, but it starts from a very low base (6% of global activity). Although it quadruples through 2050, trucking activity in Africa is still less than 10% of the global total by mid-century.

Global growth in road freight activity in the Reference Scenario is dampened by the combined impact of measures to improve logistics and streamline supply chains. Improvements to vehicle utilisation are expected to lead to increasing average truckloads, driven by growth in the vehicle activity shares run by HFTs in all regions. In developing regions, this effect outweighs the declining capacity utilisation of MFTs and the growth of the light commercial vehicle (LCV) stock. The net global impact is a reduction in total vkm by 10% in 2050, despite an increase in the total tonne-kilometres moved (due to improved vehicle utilisation) of about 6%.

Although policy support for such systemic improvements has generally been limited to date, increasing oil prices,[64] increasingly fierce competition at all levels of the freight supply chain, and some degree of consolidation of the trucking sector towards operators with larger fleets in all countries mean that the sector is likely to exploit logistics improvements that are relatively easy to implement in an effort to cut operation costs. In the Reference Scenario, online platforms increasingly help shippers, logistics service providers (LSPs), and carriers to manage and co-ordinate freight operations. Carriers and small operators can leverage real-time geographic information system (GIS) and routing algorithms as well as digital load matching to reduce travel activity. Gradual but limited improvements in truck autonomy occur; systems that enable platooning for fuel savings become increasingly viable first on highway operations, and, by the 2040s, autonomy becomes viable across a broader range of driving conditions. This requires the profession of driving trucks to evolve gradually although it does not disappear entirely: with the initial steps of automatisation, drivers handle the task of taking control of the vehicle in variable,

[63] Such funding could be raised by a variety of means, including fuel taxes and road pricing on trucks as discussed in Chapter 2. Road pricing becomes more relevant over time, as transport fuels begin to diversify and the revenues collected from taxes based on the well-to-wheel greenhouse gas emissions of fuels decline.

[64] The Reference Scenario assumes that oil prices grow by a factor of more than 2.5 over their level in 2016, exceeding USD 130 per barrel in 2050.

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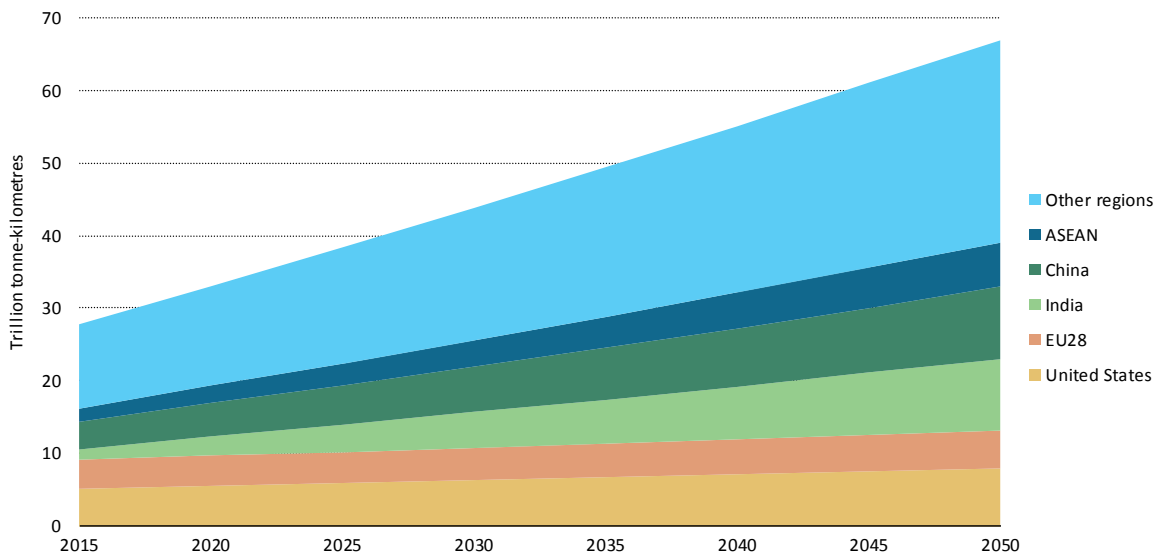
novel or unrecognised operational environments. The task then further evolves to manage single or multiple platoons of trucks.

Figure 27 • Road freight activity by region in the Reference Scenario, 2015-50.



Note: ASEAN = Association of Southeast Asian Nations; EU28 = European Union.
Source: IEA (2017a), Mobility Model, June 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

As global growth in road freight activity per capita broadly mirrors per capita GDP growth (a proxy for rising income levels, see Chapter 1 for a discussion of the drivers of freight activity), rapid economic and population growth in emerging and developing economies brings up their share of global tonne-kilometres (tkm) from road freight. The contribution of HFTs also increases over time. By 2050, three-quarters of global road freight activity is covered by HFTs, up from 63% today. This reflects a consolidation of the trucking market in many developing countries, accompanied by a shift away from small, individual trucks and companies with only a few vehicles towards carriers with larger fleets of bigger trucks. The share of road freight activity serviced by MFTs declines from one-third today to only 20% of the total in 2050 as the missions of these vehicles narrow in scope and are substituted either by HFTs (in regional and long-haul missions) or (only marginally) by LCVs (in urban operations).

To support such activity growth, the global stock of all trucks grows significantly over today's level in the Reference Scenario (Figure 28). From 2015 to 2050:

- The HFT stock increases by 2.6-fold to 64 million vehicles.
- The number of MFTs on the road grows by 60% over its current level, to more than 50 million vehicles.
- LCVs increase by 65%, reaching around 220 million vehicles.

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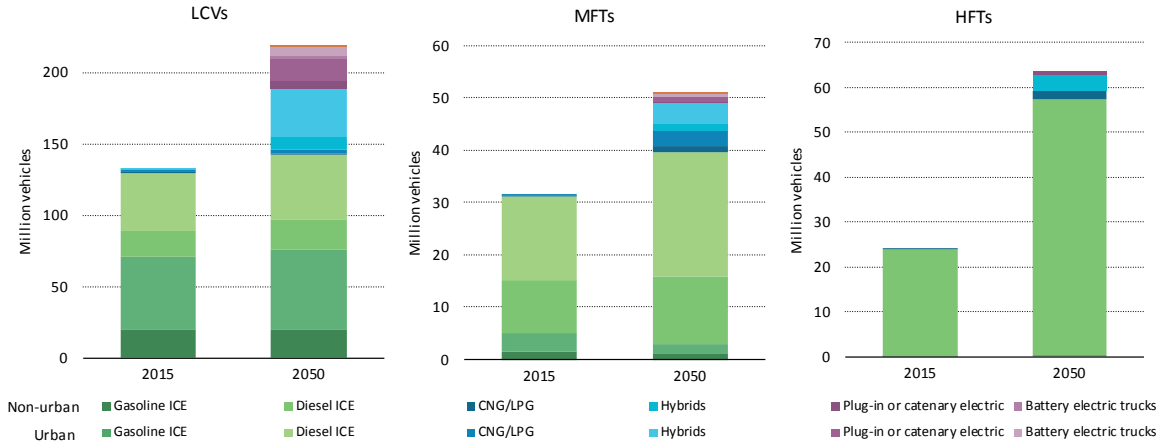
Figure 28 • Road freight vehicle stock in the Reference Scenario



Note: CNG = compressed natural gas; ICE = internal combustion engine; LPG = liquefied petroleum gas.
Source: IEA (2017a), Mobility Model, June 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

Energy demand from road freight vehicles

The strong rise in road freight activity through 2050 in the Reference Scenario brings about a significant increase in energy demand from the sector, which grows from 36 exajoules (EJ) in 2015 to more than 53 EJ in 2050.

Practically all the increase in road freight fuel demand in the Reference Scenario comes from emerging and developing countries (Figure 29). Although industrialised countries are responsible for about 16% of the increase in global freight activity to 2050, their fuel demand declines by 20% by 2050 as freight vehicle operations are further optimised and as the increasing fuel economy of trucks reduces vehicle fuel consumption. By 2050, the global average fuel intensity of road freight transport per tonne-kilometre is nearly 40% below what it is today.

The largest contributors to global energy demand growth from road transport in the Reference Scenario are Africa, the ASEAN region, China, India and the Middle East. India contributes nearly one-quarter to global energy demand growth, a share that is due to a major growth in trucking activity (40% greater tkm growth than China), a higher initial on energy intensity and a narrowing gap in power and other trucks attributes with China and the OECD, which counterbalances the fuel part of the economy improvements. China is the second-largest contributor to global road freight energy demand growth, accounting for around 10% of the global energy demand increase. The rate of energy demand growth in China, at about 1% per year, is significantly lower than its growth in freight activity, held back by a drop in energy intensity per tkm of nearly 50% thanks to increasing loads due to a greater reliance on progressively larger HFTs and fuel economy improvements. Road freight energy demand in China and India catches up with the global leader, the United States, by mid-century.

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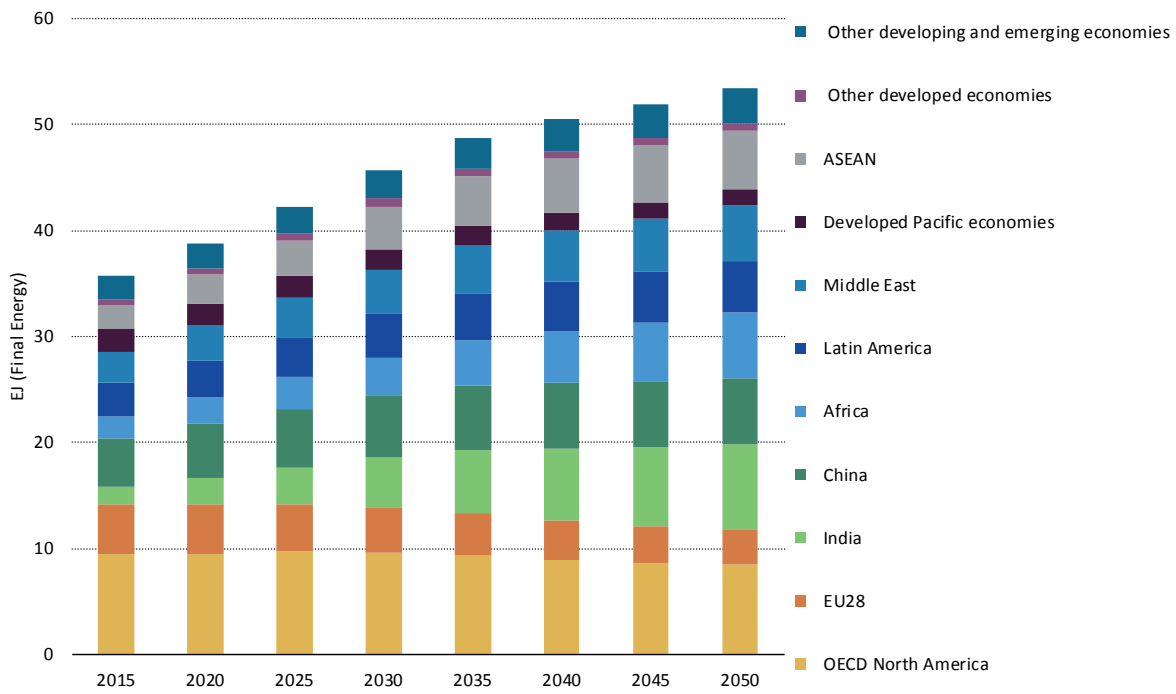
Figure 29 • Energy demand growth from road freight vehicles by region in the Reference Scenario, 2015-50



Source: IEA (2017a), Mobility Model, June 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

Much of the growth in road freight energy demand to 2050 in the Reference Scenario is satisfied by oil products. The road freight sector's weight on future oil demand growth is significant; it accounts for 40% of total global oil demand growth (across all sectors) to 2050. Oil consumption by road freight overtakes fuel demand from passenger r cars around 2030. Much of the growth in road freight oil demand is from emerging and developing countries, in particular in Asia: at 4.5 million barrels per day (mb/d), growth from road freight vehicles in Asia[65] alone is responsible for 90% of the freight transport sector's global oil demand growth. The composition of oil demand from road freight vehicles changes: a continued structural shift to larger and more efficient trucks accompanies not only economic development but is also driven by advances in logistics and supply chain results in a further shift toward diesel and away from gasoline.

Despite the continued significant reliance on oil products, some alternative fuels make marked inroads into the road freight vehicle fuel mix in the Reference Scenario. The share of oil in road freight vehicle use drops from 97% in 2015 to 84% in 2050. The two main fuels that make up for the remainder of the road freight fuel market are biofuels and natural gas. Biofuels exhibit the largest growth, in particular, conventional biodiesel, which grows to more than 3 EJ, displacing some 1.6 mb/d of oil by 2050. The main markets for biodiesel use in the Reference Scenario in 2050 are ASEAN countries, India, China and the United States, with demand values ranging between 0.4 EJ and 0.7 EJ, followed by Brazil, the European Union and Africa as a whole, all of which have consumption of slightly more than 0.3 EJ. Biomethane use also grows, although to a much more limited extent, to 0.7 EJ in 2050 and is used mostly in CNG and liquefied natural gas (LNG) truck fleets with regular operations and centralised refuelling stations, especially in China and the United States. Ethanol, produced via both conventional (0.25 EJ) and advanced (< 0.1 EJ) pathways enters the gasoline fuel pool to fuel mostly LCVs as well as a few smaller MFTs. Natural

[65] Including China, India, ASEAN member states and other developing Asian countries.

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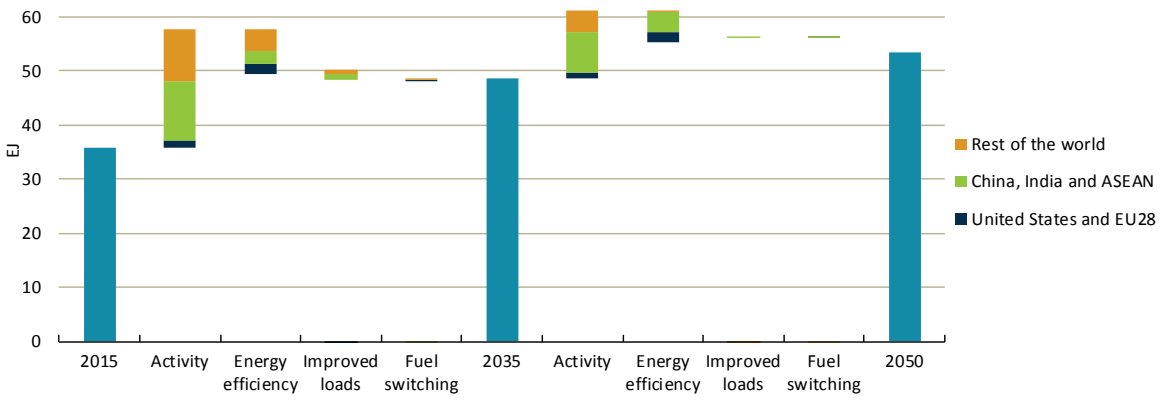
gas is the third-largest contributor to fuel demand from road freight vehicles in the Reference Scenario; its use rises to 2 EJ (up from more than 0.4 EJ today) and displaces around 1 mb/d of oil in 2050. With the current absence of large-scale deployment efforts beyond initiatives to support the build-up of some refuelling infrastructure, the use of natural gas in the Reference Scenario remains confined to countries where a substantial cost gap exists between natural gas and diesel, with the potential for fleets to leverage on this gap and reduce operating costs.[66] Regions with developed natural gas transmission and distribution networks, such as the United States (0.3 EJ in 2050) and China (0.3 EJ), are among the first to capitalise on such price differences. The Middle East also sees a rapid expansion in natural gas; after expanding its infrastructure in the 2030s, its road freight sector consumes more than the United States and China combined (0.7 EJ). The main outlets for road freight gas use in the Reference Scenario are captive fleets operating near residential or industrial natural gas distribution points, as well as urban fleets, in the attempt to reduce local pollutant emissions and the noise levels of trucks to comply with municipal limits.

As shown in the decomposition of the drivers of energy demand growth in the Reference Scenario (Figure 30), increases in global activity through 2035 are the main driver of increasing energy demand in road freight. The majority of this growth occurs in China, India and ASEAN member countries; indeed, the United States and the European Union contribute only 6% to this driver of increasing energy demand to 2035, after which point activity stabilises in these countries. Energy efficiency, realised through the penetration of new vehicle technologies and more efficient driving operations, offsets about 40% of this demand growth. Improved vehicle utilisation also offsets a small fraction of energy demand growth. After 2035, energy demand growth in the United States and the European Union has essentially stabilised. Between 2035 and 2050, the potential for efficiency technologies to offset activity growth in Asia and the rest of the world grows; more than 40% of the increases in energy demand due to activity can be offset by efficient truck technologies and operations.

Figure 30 • Decomposition of drivers of energy demand in the Reference Scenario



Source: IEA (2017a), Mobility Model, June 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

Further growth in road freight vehicle fuel demand is held back by two main factors: increasing energy efficiency and logistical improvements. For the former, the fuel economy of new MFT and HFT sales in the Reference Scenario improves by about 18%, between 2015 and 2035, and by

[66] The cost of industrial natural gas as a percentage of the cost of industrial diesel ranges from USD 0.01 per megajoule (MJ) in Asian transition economies (Kazakhstan, Turkmenistan and Uzbekistan) to USD 0.94 per MJ in Japan. Typically, natural gas costs in developed countries range from about 30-60% of the cost of diesel, but in many countries in Latin and South America, Africa, Central Europe and Asia, they range from 10-30%. As some of these countries, in particular the Asian transition economies and Middle Eastern countries, also have mature natural gas infrastructure, these are among the regions that could benefit from a transition to natural gas in captive truck fleets operating on industrial sites and in nearby cities.

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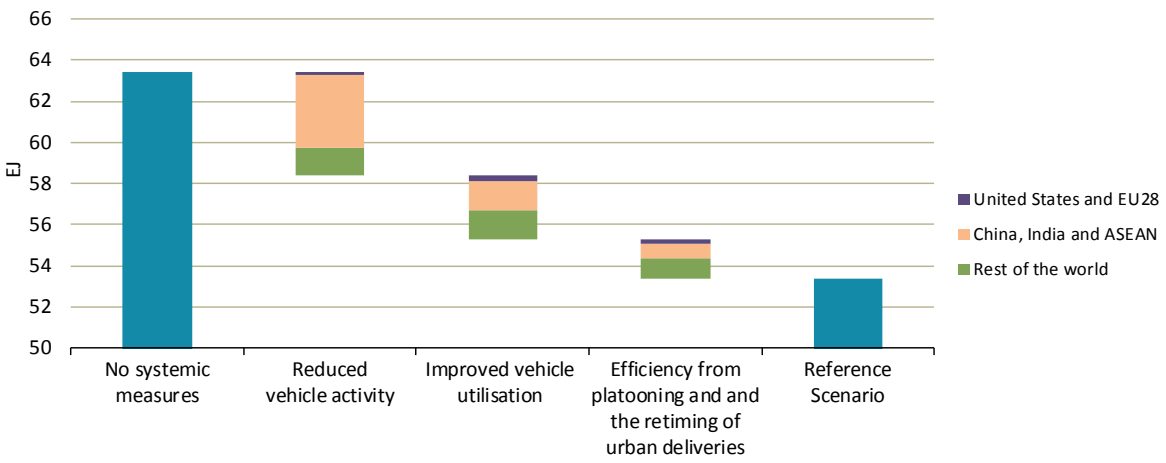
29% and 34% by 2050. These vehicle efficiency improvements are triggered by regulations, such as in Canada, China, Japan and the United States, as well as by rising oil prices, which gradually reduce payback periods, in many cases to less than a single year. The use of conventional hybrid trucks also grows, in particular in urban MFTs, followed by non-urban MFTs and in HFTs. Fuel economy improvements are generally greatest in developing and emerging economies in the Reference Scenario, reflecting the fact that vehicle fleets in these countries are generally older and less efficient. This signals a structural shift from small and relatively inefficient trucks to HFTs with greater service efficiency. Yet, the relatively vast potential for reducing fuel consumption from road freight vehicles remains unexploited in the Reference Scenario as, in the absence of further policy support, the deployment barriers remain too significant to be overcome. Although most of the efficiency potential could pay back over the lifetime of the trucks, the payback period often expands well beyond what is affordable by truck drivers (see Chapter 1).

The second dampening factor to vehicle fuel demand growth in the Reference Scenario is logistics improvements. As policy support is limited, only about half of the available logistics improvement potential that is easily accessible without major deployment hurdles is realised through 2050, and this reduces road freight fuel demand by around 16% (10 EJ) in 2050. Individually, each of these improvements has the potential to reduce energy use and direct emissions by anywhere from 1% to 7%. Their adoption helps to reduce overall vehicle activity, increase vehicle utilisation (or load factors), and improve on-road operational vehicle efficiency (MJ/vkm) over the coming half-decade (Figure 31). Their modest combined contribution to reducing fuel demand stems from the overlapping nature of many of the contributions (as in the case of improved vehicle utilisation and backhauling), non-additive contribution when the measures are combined, and some degree of rebound in activity stemming from reduced operational (fuel) costs.

Figure 31 • Contribution to energy use reductions from measures to improve efficiency in the Reference Scenario



Note: The y-axis begins at 50 EJ, hence the reduction in energy use by 2050 realised by technologies and systemic improvements is about 16%.

Source: IEA (2017a), Mobility Model, June 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

Table 16 shows the measures adopted in the Reference Scenario and their estimated maximum impacts on vehicle operations by 2050.[67] Realisation of these systemic efficiency improvements

[67] For a description of these measures, see the section on systemic improvements in Chapter 2 (opportunities to reduce energy use and emissions). Note that many measures only affect the operations of certain vehicle and mission types – for

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in the Reference Scenario comes with an assumed minimum co-ordinated public and private collaborative effort to collect basic data on freight operations as a means of understanding the current systemic inefficiencies as well as best practices. Only once the collection and public reporting of certain minimal data are effectively achieved can the full potential of the above (and other) measures be realised.

Reductions in freight activity from improved routing and last-mile efficiency measures come mainly in China, India and ASEAN member countries and collectively contribute to reducing energy use by about 5 EJ. Only 10% of the energy savings from improved vehicle utilisation, which save more than 3 EJ in 2050, come from the United States and the European Union; the remainder of the energy savings are evenly split between developing and emerging Asian countries and the rest of the world. The same geographical distribution is apparent in the impacts of on-road operational efficiency from platooning (in HFTs) and the retiming of urban deliveries (in LCVs and MFTs operating in urban settings). However, in this instance, the United States and the European Union collectively contribute 13% of the energy savings, and the Asian economies and the rest of the world each collectively contribute a roughly equal share of the nearly 2 EJ savings from these measures.

Table 16 • Systemic improvements in road freight realised in the Reference Scenario in 2050

Measure	Mission types	Parameters affected	Potential realised in 2050 (%)
Optimised routing	All LCVs, MFTs, HFTs	Activity (vkm)	3.2
Platooning	Non-urban MFTs, HFTs	Energy intensity (MJ/vkm)	7.3
Improved vehicle utilisation*	All LCVs, MFTs, HFTs	Utilisation (load factor)	5.4
Backhauling	All MFTs, HFTs	Utilisation (load factor)	1.9
Last-mile efficiency	Urban LCVs and MFTs	Activity (vkm)	2.3
Urban consolidate centres	Urban LCVs and MFTs	Activity (vkm)	0.8
Re-timing urban deliveries	Urban LCVs and MFTs	Energy intensity (MJ/vkm)	2.3

* Includes a shift to high-capacity vehicles.

Notes: Estimates of potential are applied as multipliers to the baseline projections for the vehicle mission types for which each specific measure applies. As the impacts of each measure are non-additive (e.g. due to overlaps in how they affect operations), the diminishing returns on each additional measure are modelled assuming multiplicative reduced efficacy of impact:

Total % improvement = 1 - (100% - Potential of measure A) * (100% - Potential of measure B) * … * (100% - Potential of measure N).

The percentages shown are the estimated impact of individual measures in 2050. The penetration of these measures is modelled as the linear uptake of this total potential between 2015 and 2050.

Source: Mobility Model, June 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport.

Greenhouse gas emissions

In the Reference Scenario, the combined deployment of logistics improvements, vehicle efficiency technologies, low-carbon fuels and well-to-wheel GHG emissions from the road freight sector constrains emissions growth. Although total activity grows almost threefold, GHG emissions increase by only just over 55% between 2015 and 2050 to 4.8 gigatonnes of CO_2-equivalent (Gt CO_2-eq) in 2050, indicating a degree of decoupling between emissions and activity growth. However, the growth in emissions from road freight is higher than other modes of transport; overall, road freight transport constitutes 43% of the total GHG emissions growth from the transport sector as a whole, more than any other transport mode. As a result, by 2050, road freight vehicles are responsible for 36% of transport-related GHG emissions (compared with 33% today). Over the projection period, road freight transport surpasses light-duty on-road

instance, platooning only results in improvements to the on-road fuel economy of highway operations. Hence, its impacts are only modelled for the portion of MFT and HFT driving that occurs on highways.

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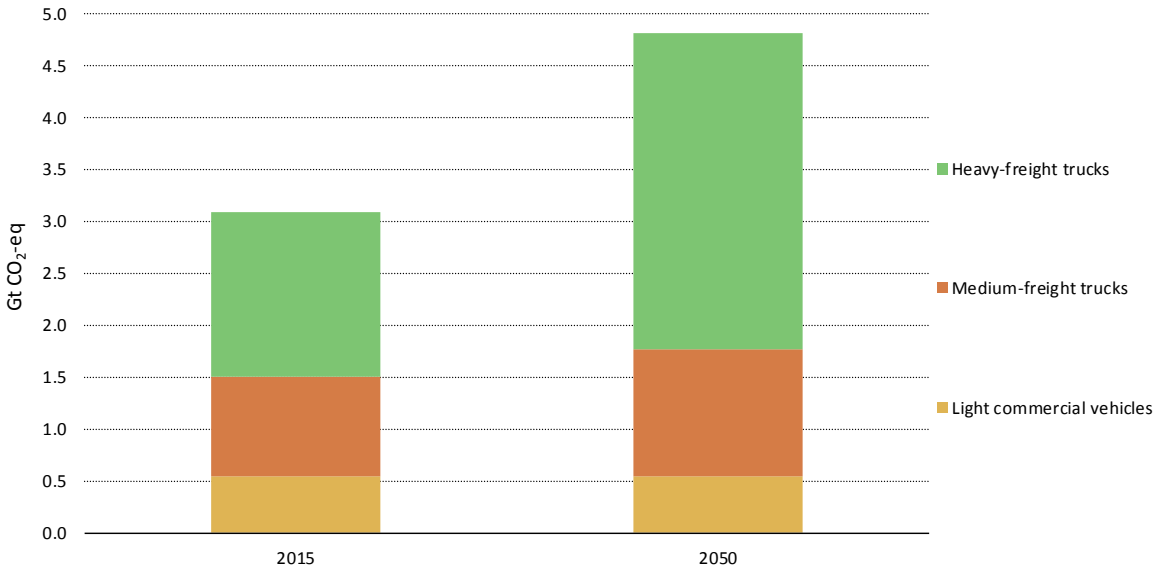
passenger transport to become the transport mode responsible for both the majority of energy consumption and GHG emissions by 2050.

The lion's share (85%) of GHG emissions growth between 2015 and 2050 comes from the increased activity of HFTs, which primarily fulfils regional and long-haul delivery services. MFTs make up 15% of the emissions growth and the emissions of LCVs remain essentially flat at a global level (Figure 32).

Figure 32 • Road freight vehicle GHG emissions by vehicle category in 2015 and 2050 in the Reference Scenario



Source: IEA (2017a), Mobility Model, June 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

Table 17 summarises the development of key metrics in road freight energy use and emissions in 2015 and 2050 in the Reference Scenario.

Table 17 • Trends in road freight in the Reference Scenario

Metric	2015	2050
Energy consumption (final energy - exajoules)	36	53
Oil consumption (final energy - exajoules) / (share in total final consumption)	35 / (97%)	45 / (84%)
Freight activity (trillion tonne-kilometres)	28	67
Well-to-wheel greenhouse gas emissions (Gigatonnes CO_2-equivalent)	3.1	4.8

Source: Mobility Model, June 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport.

Trends in the Modern Truck Scenario

The trends in the Reference Scenario suggest that the likely future path of road freight transport from today's perspective does not comply with multiple policy goals. From the perspective of fuel diversification, road freight transport is unlikely to realise major shifts from oil products in the long term, absent additional policy efforts beyond those currently in place and planned in the near future. With oil demand increasing by 5 mb/d to 2050, relative to today, the sector is likely to continue to be a major driver of global oil demand moving forward. From the perspective of climate change, the contribution of road freight transport to global CO_2 emissions, at 7% in 2015,

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might appear manageable. However, with the efforts to reduce emissions from the power sector and passenger transport in particular, the contribution of road freight transport to global energy-related GHG emissions increases to 9% in 2050 in the Reference Scenario.

But there is no inevitability to the trajectory of road freight transport. Many technologies already exist to curb oil demand and emissions growth from this sector (Chapter 2). Their adoption would bring about a modernisation of road freight transport and ensure that the long-term development of the sector is compatible with key energy and environmental policy goals. In the following section, we present the MTS, which takes action to such effect and presents the main implications on energy, emissions and other societal and economic aspects.

Key assumptions of the Modern Truck Scenario

The achievement of the Modern Truck Scenario rests on three main pillars:

- *vehicle efficiency improvements* that would need to start immediately and continue to be pushed over the coming decades
- *systemic improvements in road freight operations and logistics* that capitalise on the advancement of digital technologies and their application across all aspects of road freight, including supply chain and fleet management, collaboration across shippers and the optimisation of vehicle operations
- support for the use of alternative fuels and vehicle technologies enabling their use.

A suite of specific and targeted policy measures ensures their facilitation (Table 21), as discussed in the policy insights section of this chapter.

Broadly speaking, vehicle efficiency improves in the Modern Truck Scenario most rapidly in those countries that have already adopted fuel economy standards, reflecting the extension of the policy ambition of these early movers. The United States and Canada, having already set in progress the extension to Phase II standards that also cover trailers, are the global leaders and the only two countries in the MFT category with an annual improvement in fuel economy on a litres of diesel equivalent (lde) per 100 km basis of more than 3% between 2015 and 2035.

In the HFT category, many but not all countries achieve a 3% annual improvement in fuel economy between 2015 and 2035. The global leaders are the United States and Canada, countries throughout Europe (including the European Union and non-EU member Nordic countries as well as the EUG4 [France, Germany, Italy and the United Kingdom]), Japan and Korea. China also stands out as among the world leaders in quickly realising the opportunities of fuel economy improvements. Across much of the rest of the emerging and developing world, however, capital constraints continue to restrain the potential for rapid uptake of the best fuel economy technologies, and annual improvement averages around 2.1% across these regions.

Road freight activity in the Modern Truck Scenario

The Modern Truck Scenario rests on the assumption that nearly all the full potential of the systemic measures is realised, as public policy makers and businesses together aggressively pursue the creation of a framework that enables external collaboration across and up and down the supply chain (Table 18).

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Table 18 • Systemic improvements in road freight realised in the Modern Truck Scenario in 2050

Measure	Mission types	Parameters affected	Potential realised in 2050 relative to baseline regressions (%)
Optimised routing	All LCVs, MFTs, HFTs	Activity (vkm)	4.5
Platooning	Non-urban MFTs, HFTs	Energy intensity (litre/vkm)	11.3
Improved vehicle utilisation*	All LCVs, MFTs, HFTs	Utilisation (load factor)	9.0
Backhauling	All MFTs, HFTs	Utilisation (load factor)	3.8
Last-mile efficiency	Urban LCVs and MFTs	Activity (vkm)	3.8
Re-timing urban deliveries	Urban LCVs and MFTs	Energy intensity (MJ/vkm)	3.8
Urban consolidation centres	Urban LCVs and MFTs	Activity (vkm)	3.8
Co-modality	Non-urban MFTs, HFTs	Activity (vkm)	3.8
Crowd-sourced logistics	Urban LCVs and MFTs	Activity (vkm)	3.8
Co-loading	All MFTs, HFTs	Activity and utilisation	7.5**
Physical Internet	All LCVs, MFTs, HFTs	Activity and utilisation	18.8**

* Includes a shift to high-capacity vehicles.

** Impacts both vehicle activity (vkm) and utilisation (load factor). The impact of both measures on these parameters is assumed to be a 50:50 split so that in the case of co-loading, vehicle loads increase by 1.9% and total vkm declines by 1.9%.

Notes: Estimates of potential are applied as multipliers to baseline projections to the vehicle mission types for which each specific measure applies. The impacts of each measure are non-additive (e.g. due to overlaps in how they impact operations). The percentages shown are the estimated impact of individual measures in 2050, relative to the baseline vehicle and freight movement activity (vkm and tkm) and energy intensity (on-road fuel economy) projections.

Source: Mobility Model, June 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport

The combined impact of the measures to improve logistics and streamline supply chains brings about a reduction in road freight activity (tkm) of 13% by 2050, and a decline in vehicle activity of more than 20% relative to the Reference Scenario (Figure 33). The difference between the reduction in tkm and vkm is a measure of the impact of improved vehicle utilisation (i.e. of higher load factors as expressed in tkm/vkm) that can be realised by the above measures – by 2050, loads of MFTs and HFTs are about 14-15% higher in the MTS, with variations by region and vehicle type. While the vast majority of the total activity (tkm) reduction is realised for HFTs (simply because HFTs running long-haul operations account for the majority and a growing share of total tkm), MFT tkm activity declines are also appreciable, and LCV vkm and the load factors essentially offset each other, resulting in no appreciable tkm reduction. Vehicle activity reduction potential occurs to roughly the same degree across all the vehicle categories. On-road energy intensity (MJ/vkm) also declines due to more efficient urban operations (resulting from the retiming of urban deliveries) and, in highway driving, due to driver training, platooning and automation enabled by information and communications technologies.

The lower road freight activity brings reduces the growth of the global truck fleet, meaning that fewer trucks are required to deliver the same amount of goods. While the fleet grows by more than 75% over today's level in the Reference Scenario through 2050, fleet growth in the Modern Truck Scenario is restricted to less than 50% over today's level. The composition of the truck vehicle fleet also changes: the optimised supply chains with logistic hubs at city boundaries mean that HFTs have an even larger role in the long haul. LCVs take over much of the last-mile delivery in urban areas, increasing the share of both vehicle groups in the overall fleet at the expense of MFTs, which have a diminishing role.

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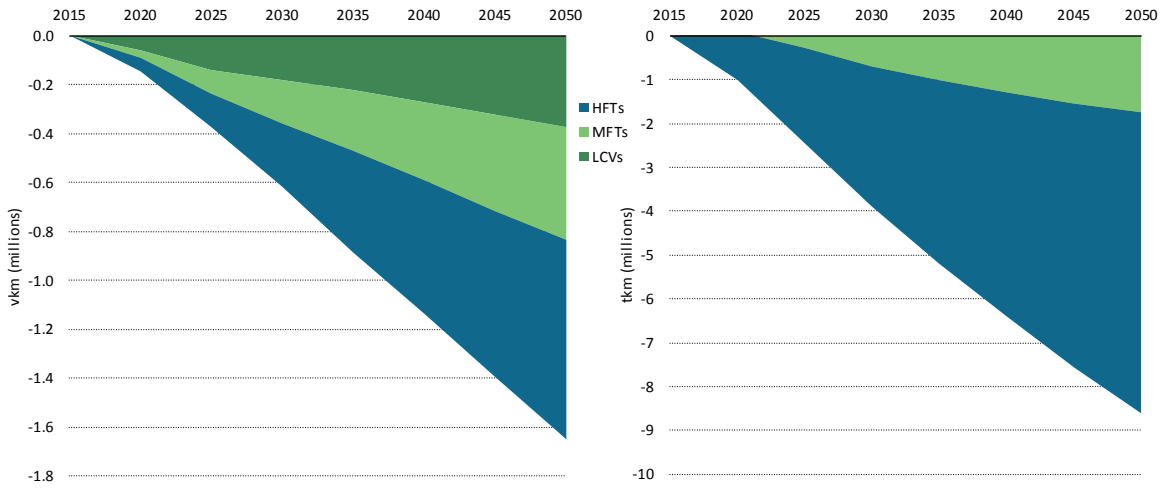
Figure 33 • Road freight activity reduction in the Modern Truck Scenario, relative to the Reference Scenario, 2015-50, in terms of vehicle-kilometres (left) and tonne-kilometres (right)



Note: Freight activity in tonne-kilometres in the LCV vehicle category is essentially unchanged – reductions in total annual vehicle-kilometres are almost perfectly offset by increased vehicle utilisation (load factors), resulting in no net change in tkm.

Source: IEA (2017a), Mobility Model, June 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

Energy demand from road freight vehicles in the Modern Truck Scenario

In the MTS, global fuel demand growth from road freight vehicles slows in the period through 2030 and then falls to 28 EJ in 2050, more than 20% below today's level and nearly half the energy demand in 2050 in the Reference Scenario. This global trend masks significant regional differences. In industrialised countries, road freight energy demand steadily declines to 7.5 EJ in 2050 in the Modern Truck Scenario because of increasing efficiency and systemic improvements. This is more than 50% below today's level and 6.5 EJ below the level reached in the Reference Scenario. Fuel demand savings are largest in countries where road freight fuel demand is already significant today and where activity growth is weaker. In North America, road freight energy demand falls to less than half of today's level to 4.5 EJ. In the European Union, demand is cut by 60%, to less than 2.0 EJ in 2050.

In developing and emerging economies, the strong growth in demand for goods keeps pushing energy demand from road freight vehicles higher through the mid-2030s, despite efforts to curb the increase in demand. From 2035 onwards, fuel demand growth begins to plateau and then slowly decline. By 2050, energy demand from road freight vehicles in these countries, at 20.4 EJ, is about 10% above today's level and nearly 50% (or 19 EJ) below the level reached in the Reference Scenario by 2050. Much of the energy demand savings occur in the fastest-growing markets: India contributes 16% of these energy savings and China an additional 11% of these savings. Established major energy consumers, such as North America, which makes up 16% of the savings, also contribute substantially to the savings (Figure 34).

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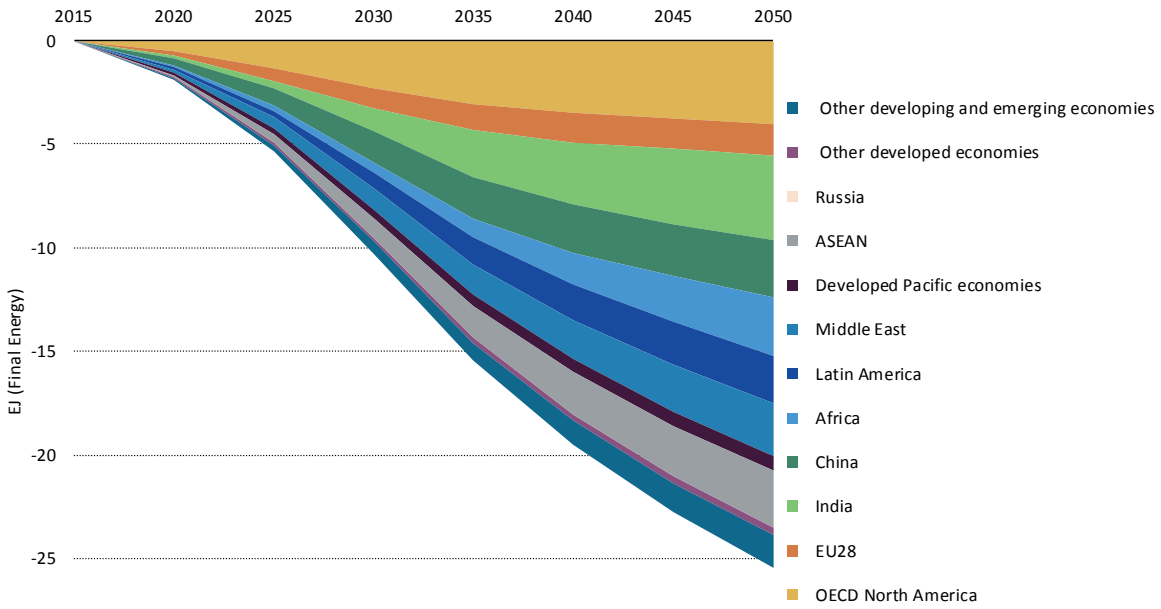
Figure 34 • Global energy demand savings in the Modern Truck Scenario relative to the Reference Scenario, 2015-50



Source: IEA (2017a), Mobility Model, June 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

As shown in Figure 35, relative to today, energy use in the Modern Truck Scenario declines from its 2015 level by 7.8 EJ, or by 22%. In 2050 in the Modern Truck Scenario, fuel demand from MFTs is 3.8 EJ (or 34%) lower than today, followed by LCVs at 3 EJ (or 45%). The decline in fuel demand from these two vehicle classes is because vehicle efficiency and logistics improvements are sufficient to counteract and exceed the impacts of rising global activity demand. In contrast, fuel demand from HFTs keeps rising through the mid-2030s in the Modern Truck Scenario – due to structural shifts to HFTs (long-haul and regional operations), activity growth is most rapid in this vehicle category – but begins to decline in the 2040s. By 2050, HFT fuel demand declines slightly and is 1 EJ (or 6%) lower than today.

Comparison with the trends of the Reference Scenario reveals a different picture. In light of the projected strong rise of long-haul freight transport and the current general lack of regulations on truck fuel economies, energy savings in 2050 for HFTs in the MTS, at more than 16 EJ compared with the Reference Scenario, are much larger than those for MFTs (6 EJ) and LCVs (3 EJ).

Even as improvements in routing and logistics result in an overall reduction in global freight activity, concerted investments in infrastructure and vehicles that rely upon low- and zero-carbon energy carriers lead to a radical shift in vehicle technologies in the MTS. Unlike in the Reference Scenario, where oil-derived fuels, in particular, diesel, remain the fuels of choice, the policy pillars assumed in the Modern Truck Scenario support the uptake of alternative fuels. In 2050, oil demand from road freight vehicles is nearly 16 mb/d lower than in the Reference Scenario, roughly equivalent to the current oil production of Canada and the Russian Federation (hereafter, "Russia") combined.

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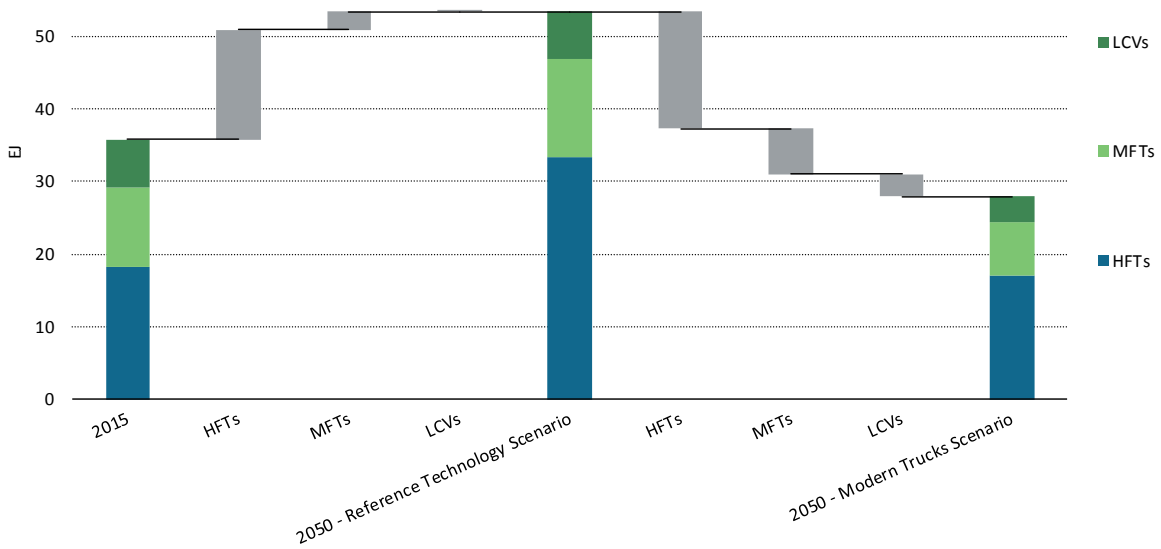
Figure 35 • Energy demand in 2015 and 2050 in the Reference Scenario and the Modern Truck Scenario



Source: IEA (2017a), Mobility Model, June 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

Advanced biofuels penetrate the liquid fuel pool rapidly in the MTS, in particular in the short-to-medium term, and displace 3 mb/d of oil by 2050. Bioethanol, biodiesel[68] and biomethane, in particular, substitute for gasoline and diesel, serving to reduce GHG emissions of conventional road freight vehicles (Figure 36). Ethanol grows moderately in the gasoline fuel pool, serving LCVs primarily. Conventional biodiesel is gradually phased-out in favour of waste- and residue-based renewable biodiesel (HVO), which by mid-century accounts for 42 billion lde of road freight fuel. As global supplies of HVO are likely to be insufficient to supply this volume, most of this biodiesel will have to come from biomass-to-liquid (BtL) processes, which will require further development to improve their efficiency and commercial viability. Biomethane is used first on captive urban fleets with a reliable supply of sustainable and cheap feedstock. Gradually, its use is extended to fuel some longer-distance HFT and regular operations. By 2050, biomethane supplies nearly 30 billion lde to road freight. Other advanced biofuels or even liquid or gaseous energy carriers produced with renewable electricity (Power-to-X) can complement this in the longer term, and drop-in fuels are expected to represent the majority of advanced, low-carbon non-fossil fuel pathways by mid-century.[69] In the MTS, biofuels and PtX pathways supply nearly 23% of total final energy demand in 2050.

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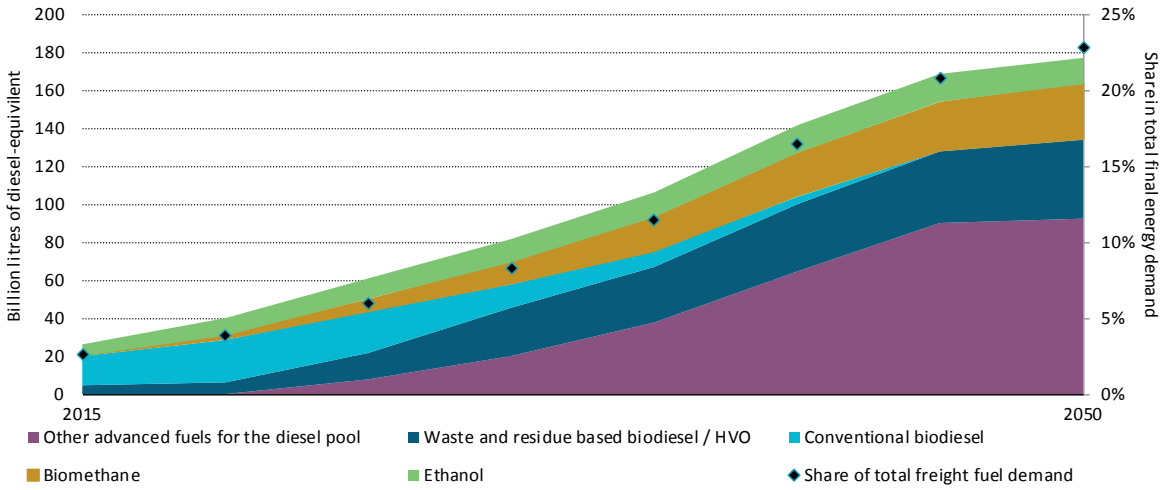
[68] Biodiesel includes renewable diesel, also referred to as hydro-treated vegetable oil (HVO). Renewable diesel can be produced from a range of feedstocks, including vegetable oils, used cooking oil and animal fat wastes.
[69] See, for instance, the IEA-RETD (2016) study on renewable power-to-gas.

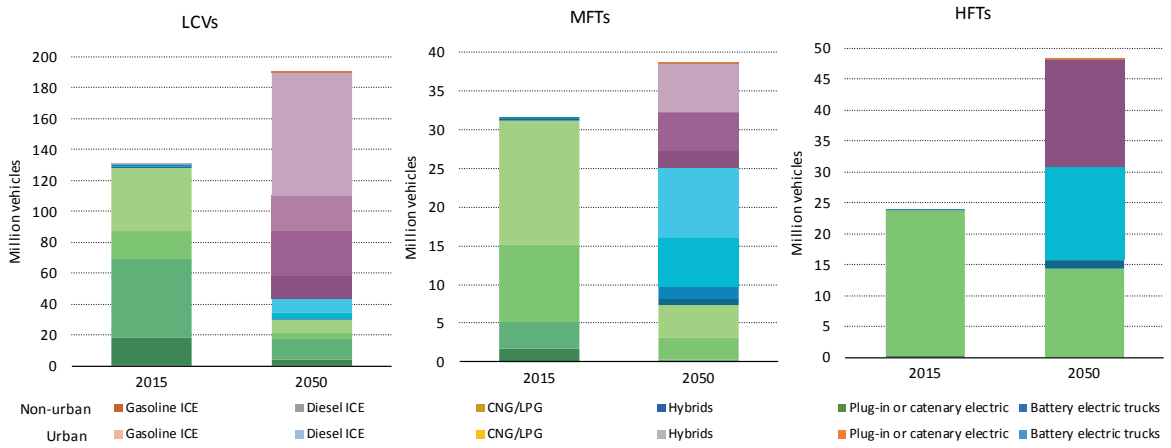
Figure 36 • Biofuels consumption in the Modern Truck Scenario



Source: IEA (2017a), Mobility Model, June 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

With increasing technology maturity and infrastructure rollout, however, other low-carbon alternatives, in particular, electricity, make increasing inroads in the Modern Truck Scenario. The uptake of alternative fuels in alternative fuel trucks varies by vehicle segment (Figure 37).

Figure 37 • Vehicle stocks and fleet technology shares in the Modern Truck Scenario, 2015-50



Notes: The uptake of electricity in HFTs is primarily derived from plug-in hybrid trucks using ERS. This is the technology used in the modelling to represent zero-emissions vehicles. If cost reduction barriers are overcome and low-carbon hydrogen production is scaled up, meeting demand that is not only confined to the transport sector, and despite drawbacks in terms of life-cycle efficiency, hydrogen also has the potential to be used in fuel cell vehicles and emerge as an alternative to ERS for zero-emission, long-haul road transport, as discussed in Chapter 2.

Source: IEA (2017a), Mobility Model, June 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

Hybridisation and electrification proceed most rapidly in the urban MFT fleets as both technologies are able to more effectively realise efficiency gains in short- to mid-distance transient operations. Hybrid trucks enter the truck fleet most rapidly in the MTS: by 2050, within the truck fleet, 7% of LCVs, 40% of MFTs and around 30% of HFTs use hybrid powertrains. Plug-in hybrids also grow in market shares. In the MTS, three-quarters of LCVs and 35% of MFTs are

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plug-in (or, in the case of MFTs, catenary-enabled) hybrid or battery electric by mid-century. In addition, 36% of HFTs are catenary-enabled electric trucks.[70]

Battery-electric truck and plug-in hybrids using ERS are used to represent zero-emissions vehicles. The main reasons for this are the greater resilience of cost assessment to variations in assumptions and the more concrete prospects for cost reductions on batteries, given the increasing interest and uptake of electric mobility on light-duty vehicles.

Figure 38 shows the estimated costs of alternative vehicle and fuel technologies over a five-year usage period at mid-century. Fuels are taxed in the Modern Truck Scenario according to their well-to-wheels GHG emissions at USD 500/t CO_2-eq (or USD 1.20 per litre of diesel-equivalent), which improves the competitiveness of alternative fuel and vehicle options. The fuel component of the costs of CNG and LNG trucks assumes the use of fossil-derived natural gas. If biomethane were instead used to fuel these trucks, the fuel costs would be appreciably lower given the superior life cycle emissions performance of many biomethane supply pathways. However, the availability of sustainable feedstocks for the production of biomethane is limited.

As a consequence of technology learning and economies of scale in vehicle components as well as improved utilisation through commercial adoption, the costs of catenary-enabled trucks running on electric road systems (CAT-ERS) and of fuel cell electric vehicles (FCEVs) can be brought down to the same range as conventional ICE diesel trucks. By mid-century, costs have the potential to be even lower than ICE diesel trucks. In the case of ICE diesel trucks, continued improvement in vehicle efficiency has been considered, as have the additional incremental costs of meeting increasingly stringent local pollutant (tailpipe) emission standards.

Figure 38 shows that both CAT-ERS and FCEVs can become economically competitive truck technologies by mid-century. The uncertainty surrounding the cost profile of FCEVs is, however, greater than for CAT-ERS vehicles.

If low-carbon hydrogen production is scaled up, meeting demand that is not only confined to the transport sector and despite drawbacks in terms of life cycle efficiency, more favourable prospects for cost reductions in fuel cell technologies are delivered thanks to successful technology deployment and the rollout of refuelling infrastructure. Hydrogen also has the potential to be used in fuel cell vehicles and emerge as an alternative to ERS for zero-emission long-haul road transport, as discussed in Chapter 2.

In order to achieve long-term cost competitiveness, zero-emissions infrastructure build-out will need to proceed first along the most heavily trafficked corridors and gradually extended to cover all major trunk roads. Hydrogen could indeed emerge as a viable option, especially in regions with low population densities, where the major roads do not have the frequency of service of heavy-duty truck use comparable to that seen today in European motorways.

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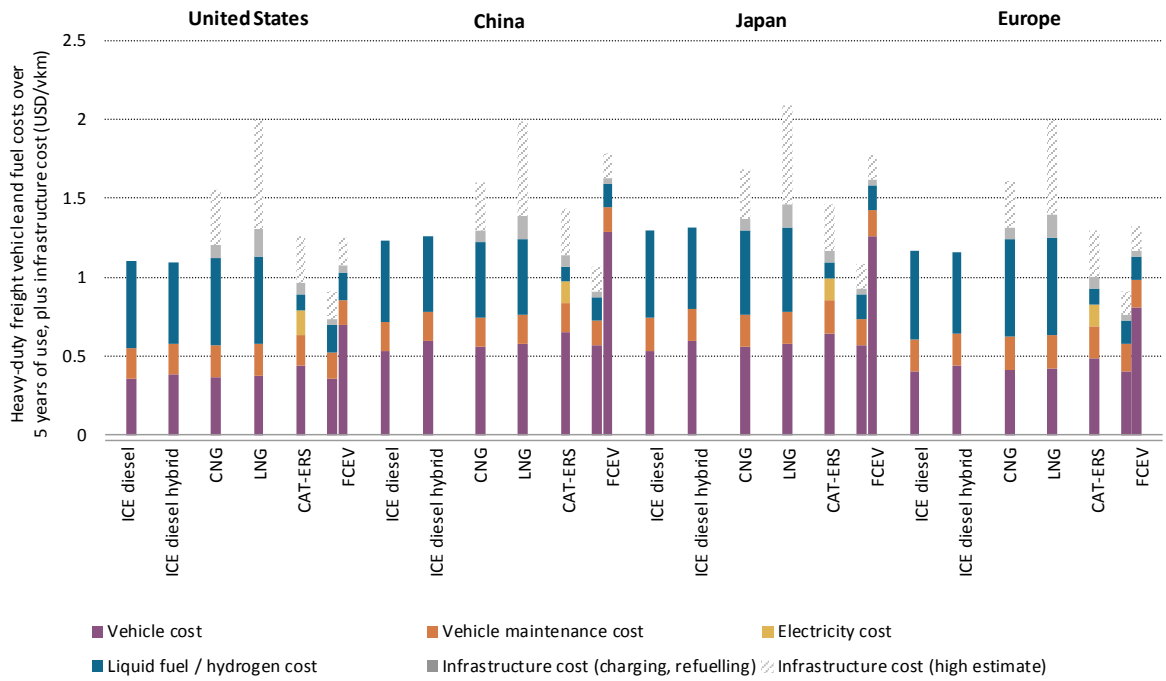
[70] Battery-electric truck and plug-in hybrids using ERS are used to represent zero-emissions vehicles. The main reasons for this are the greater resilience of cost assessment to variations in assumptions and the more concrete prospects for cost reductions on batteries, given the increasing interest and uptake of electric mobility on light-duty vehicles.

Figure 38 • Heavy-duty freight vehicle and fuel costs over five years of usage in 2050 in the Modern Truck Scenario, including infrastructure costs (with high and low infrastructure utilisation assumptions)



Notes: The key assumptions on heavy-duty vehicle costs and infrastructure are summarised below.

Vehicles: The 2050 vehicle investment costs range from USD 126 000 for diesel ICEs, USD 150 000 for diesel ICE hybrids, USD 140 000 for natural gas vehicles, USD 165 000 (low) to USD 180 000 (high) for CAT-ERS and USD 145 000 (low) to USD 420 000 (high) for FCVs. Gasoline, diesel and electricity prices are from the IEA Mobility Model, and the electricity price is USD 0.17 in all regions and cases.

Depreciation is assumed to be the same for all technologies. After five years, the residual value of a truck is 42% of its purchase value.

ERS: Electric road system infrastructure costs come down by 2050 to USD 0.6 million/km and a frequency of use 160 to 30 trucks/hour in the lower infrastructure cost estimate (bar on the right).

Hydrogen: The 2050 hydrogen costs account for large availability of electricity produced from renewables at an average cost of USD 0.07/kWh and a large capacity utilisation factor for electrolysers, leading to a 50% overall capacity utilisation rate. Storage and refuelling system costs equal USD 5.0/GJ of hydrogen delivery capacity. The capacity utilisation rate of the refuelling system ranges from 10% (top of the high-cost estimate – striped grey bar on the right column for FCEVs) to 50% (minimum infrastructure costs in the low-cost estimate – grey bar on the left column for FCEVs). These values are used, respectively, for the top of the high-cost estimate (striped grey bar on the right column for CAT-ERS) and for the bottom of the low-cost estimate (grey bar on the column for CAT-ERS).

Source: Vehicle travel per year, vehicle costs and fuel costs reflects assumptions used in the characterisation used in IEA (2017a), Mobility Model, June 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport.

Greenhouse gas emissions in the Modern Truck Scenario

Each of the measures outlined above contributes to reductions in GHG emissions in the MTS. Annual GHG emissions attributable to the road freight sector in 2050 in the Modern Truck Scenario are less than 30% those reached by mid-century in the Reference Scenario and about half their 2015 levels (Figure 39).

About 18% of cumulative GHG emissions reductions come about as a result of the reductions in truck vehicle activity, and an additional 12% of the cumulative emissions savings come through increased loads. Both are realised through the adoption of systemic improvements in the supply chain, which, in contrast with other measures, can begin to save fuel and

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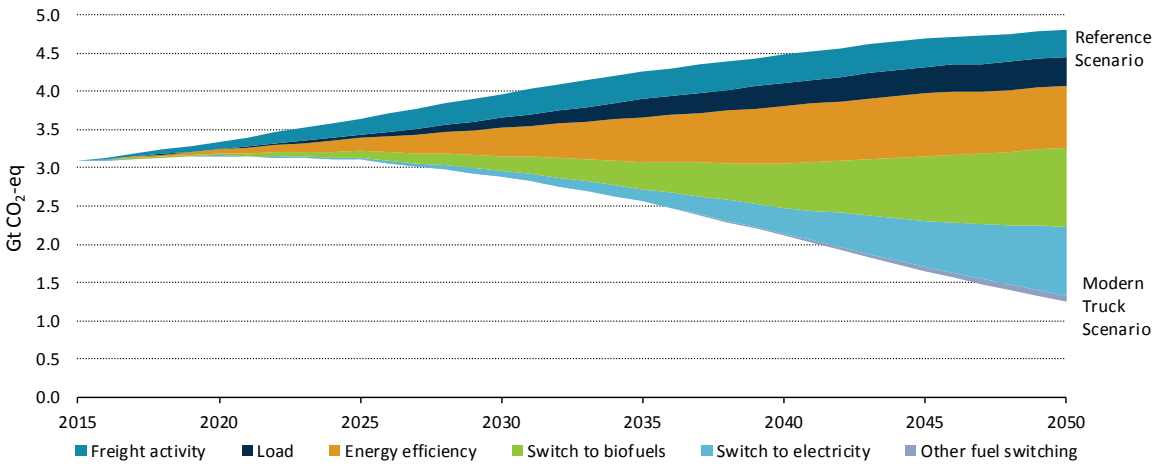
reduce emissions immediately.[71] Advanced biofuels contribute about one-quarter of cumulative GHG emission reductions, and a switch to electricity generated by low-carbon sources contributes an additional 16% (Figure 39).

Figure 39 • Contribution to GHG emissions reductions by measure in the Modern Truck Scenario, relative to the Reference Scenario



Source: IEA (2017a), Mobility Model, June 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

At 30% of cumulative GHG savings, energy efficiency is the largest contributor to emissions reductions. However, there are many mechanisms by which efficiency is realised in the Modern Truck Scenario. For example, while energy efficiency broadly refers to efficiency improvements of the vehicle, certain systemic measures (e.g. platooning, the retiming of urban deliveries and driver training) contribute to improving on-road vehicle efficiency. Aerodynamic retrofits and low rolling-resistance tyres can similarly lead to immediate improvements in vehicle efficiency. Over the timeline of truck stock replacements (i.e. in the order of one to two decades), fuel economy standards, along with other regulatory and fiscal policies, can drive the uptake of fuel-saving engine, powertrain and vehicle technologies. Beginning in the 2020s, the deployment of hybrids and electric trucks lead to pronounced improvements in vehicle efficiency (as detailed in Chapter 2).

In the Modern Truck Scenario, vehicle efficiency improves most rapidly in those countries that have already adopted fuel economy standards, reflecting the extension of the policy ambition of these early movers. With improvement rates close to 2.5% per year between 2015 and 2035, the United States and Canada, together with countries throughout the European Union, Japan, Korea and China stand out as global leaders in quickly realising the opportunities of fuel economy

[71] The estimates are in line with previous attempts to model the impact of similar measures: a recent estimate of the potential for logistics and operational efficiency (including only vehicle retrofits and fuel-efficient driving) to reduce CO_2 emissions in the United Kingdom by 2035 estimated cost-effective (from an end-user or firm perspective) potential reductions of 25% (within the range of 13-45%) (Greening et al., 2015). This estimate is similar to the savings realised in the Modern Truck Scenario by that year. However, it is fully conceivable that these estimates of the combined potential of adopting a wide portfolio of systemic improvements throughout the supply chain may prove overly conservative; if indeed all these measures were to be adopted, the reduction in total distances covered by trucks could decline by more.

On the other hand, given the overlap in the impacts of many of the measures, diminishing returns from the implementation of each additional measure are to be expected. Moreover, the cost reductions that would result from many of the efficiency-improving measures should be expected to lead to a rebound, both through greater demand for cheaper goods and through increased purchasing power overall.

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improvements. Across much of the rest of the emerging and developing world, capital constraints continue to restrain the potential for rapid uptake of the best fuel economy technologies: annual improvement ranges between 1.5% and 2.2% across these regions.

The contribution of ultra-low carbon and zero-emission technologies, modelled here as a switch to electricity, comes relatively late – these technologies begin to exert an impact in 2035 – and the contribution over the entire period is rather small (16%). However, the growing contribution of electricity by mid-century is reflected by the share of the emission reductions it accounts for in 2050 (as opposed to cumulatively from 2015-50): one-third of emission reductions in 2050 come from electrification.

Table 19 summarises the development of key energy and emissions metrics in the MTS. These can be contrasted against developments in the Reference Scenario (Table 17).

Table 19 • Trends in road freight in the Modern Truck Scenario

Metric	2015	2050
Energy consumption (final energy - exajoules)	36	27
Oil consumption (final energy - exajoules)/(share in total final consumption)	35 / (97%)	12 / (44%)
Freight activity (trillion tonne-kilometres)	28	58
Well-to-wheel greenhouse gas emissions (gigatonnes of CO_2-equivalent)	3.1	1.2

Source: Mobility Model, June 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport.

Investment needs: Saving money by hauling smarter

The incremental costs of advanced vehicle technologies, in particular, electric and hydrogen trucks, as well as their supporting infrastructure, are substantial (Chapter 2). Nevertheless, the reductions in vehicle-kilometres travelled that can be realised through the systemic improvement reduce the stock of trucks needed and result in overall savings in expenditure on trucks and fuel. Vehicle purchase investments could be cut over 2015-50 by USD 7.4 trillion, or 12% of total truck purchase expenditure in the Reference Scenario. Vehicle operations and maintenance costs could be cut by USD 3.1 trillion, or 19% relative to the Reference Scenario. The largest savings, however, come from reduced fuel costs: modernisation of the road freight sector could save upwards of USD 35 trillion in fuel outlays over the period 2015-50. This sum represents nearly half (48%) of the total fuel costs in the Reference Scenario.

The costs of building infrastructure are dwarfed by the above savings. For instance, assuming that electric road systems would need to cover 3-10% of national highway and major truck road systems, then investment needs for the construction, operations and maintenance of these systems would range from about USD 1 trillion to USD 5 trillion.[72] In addition, savings from reduced total road infrastructure requirements resulting from the smaller truck fleets, while not included in these cost estimates, could be substantial.

[72] As discussed in the technology cost assessment, hydrogen fuelling infrastructure could cost less than the infrastructure needed for electric road systems, especially in low density regions, provided that the hurdles facing production and distribution of low-carbon hydrogen are overcome. The total cost of the hydrogen pathway also depends on successfully achieving low unit costs of production for vehicle technologies. The prospects for this to occur seem more uncertain than for ERS, and depend on the market uptake of fuel cell technologies in a wide range of transport modes and applications, including light-duty vehicles.

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Policy insights – The long haul to modernise road freight transport

Road freight transport is an important energy sector. It has a key role to play in contributing to economic activity, and it is a significant driver of oil demand. Since 2000, road freight transport has contributed around 80% to global oil demand growth, making the sector the second-largest source of oil demand following passenger cars. Road freight consumed roughly the same amount of oil as the entire industry sector. With its heavy dependence on oil, road freight transport is also an important source of carbon dioxide (CO_2) emissions, and accounts for about 7% of global emissions from energy production, transformation and use. It also contributes to air pollution: although a high share of road freight activity takes place outside of urban areas, today lorries, vans and trucks are important sources of air pollutant emissions.

Such observations are true today, but their resonance will grow in the coming decades. The fuel consumption of passenger light-duty vehicles has been progressively regulated over the past few decades across more and more regions: more than 80% of cars sold on global markets are already subject to fuel economy standards today, and hybrid and electric cars are increasingly making inroads into the sales mix of cars. For most countries, though, regulations to curb the oil demand growth of road freight transport is limited mostly to light commercial vehicles. Fuel economy standards for heavy-duty trucks (including MFTs and HFTs) to date exist only in four countries: Canada, China, Japan and the United States. The consequence is that road freight transport is likely to continue to drive up global oil demand in the coming decades. In the Reference Scenario, they account for more than 35% of global oil demand growth to 2050. As a result, the sector also becomes increasingly important from the perspective of CO_2 emissions.

Current trends appear unsustainable given that road freight transport appears unlikely to meet key energy policy objectives such as fuel diversification and the reduction of CO_2 emissions and air pollutants. However, as demonstrated in the Modern Truck Scenario, there are ways to modernise road freight transport and reduce future energy and emissions growth from the sector. Some of the options are near term and readily available. Others are longer term and require dedicated and foresighted policy commitment. In the following, we explore some of the policies that could help to bring about a future like the one depicted in the MTS, while ensuring that road freight transport can continue to play its key role in fuelling economic growth.

Key elements for modernising road freight transport

A variety of options exists to modernise road freight transport. They span a wide range, from incremental changes to vehicle technologies to more fundamental changes in the energy carriers used by road freight vehicles, and a transition to entirely different road freight transport systems. These are three main realms that contribute to modernising the sector:[73]

- improving vehicle efficiency
- implementing systemic improvements in road freight operations and logistics
- shifting to trucks that rely on alternative fuels.

Not all possible options to modernise road freight respond to energy policy objectives in the same way. While generalising is difficult and much is country-dependent, it is possible to categorise the various options in an attempt to determine how they fare against policy goals. Table 20 summarises these conclusions. It shows how energy efficiency and systemic

[73] As mentioned previously, additional potential for reducing energy and emissions growth from road freight lies in a modal shift to rail or inland maritime ships. An analysis of the potential of this modal shift is beyond the scope of this report.

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improvement deliver indirect benefits toward diversifying the energy supply, how natural gas provides only minor benefits toward reducing greenhouse gas emissions, and how liquid biofuels are not very different from petroleum fuels in terms of reducing air pollution.

Table 20 • Impact of measures to modernise road freight on the energy system, economy and environment

		Energy supply diversification	Climate change	Air pollution
Energy efficiency		Substantial potential to contribute indirectly (through reducing aggregate energy use)		
Systemic improvements				
Alternative fuels	Natural gas		20% lower tank-to-wheel emissions offset by methane slip and leakage	
	Biofuels		Need for low well-to-wheel emissions and minimization of land use change	Assumes use of high quality drop-in fuels
	Electricity		Requires low-carbon fuel supply pathways	
	Hydrogen			

Key	Impact
	Highest
	Positive
	Neutral / no improvement

In essence, the Modern Truck Scenario, a long-term vision for modernising road freight transport, can have important co-benefits for the achievement of different energy policy goals. Full achievement requires a long-term commitment to such modernisation efforts, given the fundamental rethinking of road freight that is inherent to some of its elements. These include some aspects of systemic improvements and the switch to specific alternative fuels, namely electricity and/or hydrogen, capable of decarbonising the segments of the sector where energy demand is expected to grow the most (i.e. regional and long-haul operations of HFTs). Its long-term achievement rests also on the near-term priorities, the implementation of which can facilitate the long-term modernisation of road freight transport. In the following, we first focus on the required near-term actions and then elaborate on the various policy tools (and the role of different stakeholders) for the long-term modernisation of road freight.

Policy priorities

Not all elements of the Modern Truck Scenario are easily implemented. Some fuel and vehicle technologies are still at the research, development and demonstration (RD&D) stage. In some cases, such as in building electric road system (ERS) or hydrogen production and fuelling networks, the required efforts are based on co-operation across multiple stakeholders and policy makers. We identify three key enablers that present no-regret opportunities from an energy policy perspective, one for each category of potential improvements:

- *Adopting policies targeting vehicle efficiency, including fuel economy standards and differentiated taxes on vehicle purchase.* The two policies complement each other: the former regulatory policy ensures that all new truck sales achieve minimum efficiency performance, and the latter fiscal measure favours the best performing models, pushing further improvements. For MFTs and HFTs taken together, the fuel use per kilometre of new vehicle registrations needs to be progressively reduced by 35%, relative to a 2015 baseline, by 2035. To achieve this, fuel economy standards for heavy-duty vehicles (HDVs) need to be broadened far beyond its current application in only four countries to

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cover all the HDV main vehicle markets. Once heavy-duty fuel economy policies are in place, their stringency needs to be successively raised, accounting for cost reductions delivered by technological progress.

- *Supporting widespread data collection and information sharing*: Data gathering and information sharing are key prerequisites to realising some of the potential that underlies systemic improvements of freight logistics, including the sharing of assets and services. Policy makers should take a proactive role in supporting data collection and sharing platforms by promoting closer collaboration among all stakeholders, including government, citizen groups and corporate actors operating across the supply chain. Toward these ends, public policy can build on the experience of Green Freight Programmes (see Chapter 1).
- *Promoting the deployment of alternative fuels and the vehicles that use them*: The use of alternative fuels requires different types of policy involvement, depending on the fuel in question (natural gas, biofuels, electricity or hydrogen) and the state of technological maturity. Their deployment typically requires support across four areas: RD&D, market uptake of alternative fuel vehicles, adequate access to charging or refuelling infrastructure and the availability of alternative fuels.

Adopting fuel economy standards and differentiated vehicle taxation

Two key policies, fuel economy standards and differentiated vehicle taxation, can promote rapid energy efficiency improvements in new sales of road freight trucks.

Fuel economy standards

Fuel economy standards for HDVs require careful design and implementation, with a view to the variety of different truck types, operations and sizes. This renders the implementation process somewhat more challenging than for passenger cars. Standard setting also requires close consultation with a variety of different stakeholders, including manufacturers as well as operators, to ensure the cost-effectiveness of such policies and labelling efforts to ensure maximum transparency. Fortunately, experience with the development and implementation of such policies already exists. This experience can aid the development and expansion of fuel economy policies for heavy-duty vehicles in countries and regions where they do not yet exist.

Policy efforts currently in place or under development rely on computer simulation models to calculate the energy consumption and CO_2 emissions of different vehicle configurations, mission profiles and drive cycles. The two most well developed models are the Greenhouse Gas Emissions Model GEM (US EPA, 2016b) used in North America and the Vehicle Energy Consumption Calculation Tool VECTO (JEC, 2016) used by the European Union. The use of these simulation models is best suited for regions that already apply international regulations on type approval of vehicle components, including heavy-duty vehicle engines. Applying these tools in other countries will require modifications to parameters that specify vehicle characteristics to reflect regional and national duty cycles and vehicle technologies.

Software tools such as GEM and VECTO rely on inputs acquired from physical testing of vehicle components and engines. These tools characterise physical parameters including engine performance, aerodynamic drag of the vehicle, and rolling resistance of the tyres. Data acquisition is an important prerequisite for validating the accuracy of the models. As in the case of fuel economy standards for light-duty vehicles, test procedures and data acquisition processes, grounded on accurate component testing, are needed to assess the energy use and emissions of heavy-duty vehicles.

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The adaptation of existing software tools or the development of similar applications where they do not yet exist is likely to result in long lead times before fuel economy regulations can come into force. In these cases, the combination of engine tests and tyre labelling standards is an effective interim step to capture near term cost-effective efficiency opportunities.

Despite the challenges posed by the complexity of HDV fuel economy standards, their application across the main vehicle markets needs to be broadened. Over time, fuel economy standards that successively rise in stringency, building upon previous gains, can provide effective guidance for manufacturers and operators alike about the long-term pathways for increasing the energy efficiency of road freight vehicles. In countries where heavy-duty fuel economy policies are already in place, their stringency will need to be successively raised, building upon the technology advances of the previous standards and cost reductions delivered by technological progress.

Differentiated vehicle taxation

Differentiated taxation on vehicle purchases, also known as "feebates" (the combination of fees and rebates), is already applied on light-duty vehicles. Feebates have demonstrated their effectiveness at accelerating the uptake of low-carbon technologies, thereby reducing fleet average GHG emissions (Brand, Annable and Tran, 2013; IEA, 2017c), steering market responses toward lower total costs of vehicle ownership and use. They can also be used as a technology policy instrument. By fostering the market uptake of technologies that are not yet cost-competitive, they enable cost reductions in these technologies from technology learning and economies of scale. Although purchases of heavy-duty freight vehicles are not typically taxed, there is no reason why revenue-neutral feebate programmes should not be applied to the truck market.

Promoting widespread data collection and information sharing

Some of the potential for systemic improvements in road freight transport and logistics can be realised by individual operators alone, such as through the widespread use of the Global Positioning System (GPS), together with optimisation and intelligent algorithms. However, the real potential can be harvested only if data on truck operations is systematically gathered and rules for data sharing between different operators are established, e.g. to protect confidential and proprietary data. The better system can be designed to facilitate logistics improvements (i.e. the more operators and other stakeholders are included), the more effective its implementation will be for reducing fuel demand and emissions growth.

Expanding the regional scope and the number and range of companies (including shippers and other companies involved not only in road freight but also in international shipping, freight aviation and rail deliveries) participating in green freight programmes (GFPs) can increase the market and social pressure on companies to adopt more sustainable practices. These programmes not only highlight the practices of the best-performing companies but also serve as a means for the dissemination of best practices.

Scaling up the benefits that have already been achieved by Green Freight Programmes will require more engagement from policy makers and other stakeholders involved in road freight transport. Policy makers can take a proactive role in promoting the establishment of widespread data collection and sharing platforms to enable improvements in freight logistics through closer collaboration, including the sharing of assets and services.

This process can start with the establishment of voluntary reporting schemes for shippers and other large companies operating in the supply chain. There are two types of data that could usefully be reported. In the case of activity data, shippers should be encouraged to report on aggregated tkm, vkm and energy consumption to GFPs and governments. In order to protect the commercial and intellectual property of companies involved in this process, engagement with all

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stakeholders is needed to ensure that the rules of data exchange are multilaterally defined and transparent for everyone, the protocols needed for data collection and information sharing are royalty-free, and corporate requirements for the protection of confidential information are safeguarded.

In the case of CO_2 emissions reporting, leading companies can first be encouraged to advertise their green credentials within GFPs. This, combined with the wider application of best practices that have emerged in GFPs, can pave the way for supranational and national public authorities to encourage widespread CO_2 emissions reporting and move toward mandatory reporting requirements. This is the final step in incentivising more sustainable and lower-emitting practices, not only in road freight but also throughout the entire logistics and supply chain.

Supporting alternative fuels and vehicles

Support for alternative fuels and vehicles should cover four main areas: RD&D; market uptake of alternative fuel vehicles; adequate access to charging or refuelling infrastructure; and the availability of alternative energy carriers. Descriptions of each follow below.

Research, development and deployment (RD&D)

RD&D support narrows the performance and cost gaps between incumbent and alternative technologies. The required support depends on the level of technology maturity. Broadly speaking, it is required for each of the following technologies: advanced biodiesel production via thermochemical (BtL) pathways; hydrogen production, refuelling and vehicle technologies (including fuel cells and storage systems); electricity storage in vehicles using batteries; and the demonstration of electric road systems (ERS) to enable the use of electricity for long-haul freight transport on roads. R&D support also accelerates the development of alternative heavy-duty road vehicles, in particular the vehicles that would use ultra-low and zero-emissions fuels.

Market uptake of alternative fuel vehicles

As vehicle technologies move out of RD&D stage, deployment support will be necessary to ensure that vehicles that rely on alternative fuels – including trucks able to operate on biofuels and methane, but also hydrogen and FCEVs and electric trucks using ERS – become increasingly available. This in turn can support the required initial growth in the demand for alternative fuels.

Differentiated vehicle taxes, feebates and zero-emission vehicle mandates (ZEV mandates) can stimulate the deployment of efficient and low-emission vehicle technologies through fuel switching, thereby mobilising investments that are necessary to achieve cost reduction thanks to technology learning and economies of scale.

Differentiated vehicle taxes and feebates can be designed to not only tax inefficient and highly emitting vehicles, but also use the revenues collected from these taxes to subsidise the purchase of vehicles with superior fuel economy or local pollutant emissions performance.

In the case of heavy-duty vehicles, ZEV mandates are well suited to vehicles using electric motors and powered by direct power supply, including electric batteries and hydrogen fuel cells. ZEV mandates are regulations that require vehicle producers to sell a minimum share of ultra-low or zero-emission vehicles. They are currently based on a system of tradable credits, which provides market flexibility to manufacturers. Pioneered by California for the light-duty vehicle market (CARB, 2017c) and now also applied to medium-duty vehicles (ICCT and DieselNet, 2016), they are currently enforced in several other states in the United States (UCS, 2016) as well as Canada's Quebec province, and are now being considered in China (Electrek, 2016). Expanding such systems to other major vehicle markets will mobilise the investment necessary for the transition to the MTS.

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Access to refuelling infrastructure

Methane, hydrogen and electricity use in road freight will also require an early focus on infrastructure development, a prerequisite to enable market uptake for vehicles using these energy carriers.

Support in the initial stages of technology scale-up is particularly important. This will require substantial funding from the public sector, or through public-private partnerships (PPPs), especially in the initial phase, when the demand for alternative fuels is constrained by the limited number of alternative fuel vehicles. A dedicated funding stream could ensure a consistent and long-term signal of reliable return. Revenues generated from fuel taxation and vehicle travel (i.e. distance-based taxes), typically used to finance the development of the road network, could be allocated to building out alternative fuel infrastructure. Industry collaborations can also facilitate the development of refuelling infrastructure.

Availability of alternative fuels

Taxing transport fuels based on their well-to-wheel GHG emissions can be an important facilitator for the uptake of low-carbon fuels. It can encourage innovations by the private sector to reduce emissions incurred across the supply chain, regardless of the fuel type. As highlighted in the discussion on biofuels, taxes could also consider other environmental, economic and social impacts, including natural resource availability and sustainability.

Biofuel mandates and low-carbon fuel standards can promote the commercialisation of advanced biofuels. In the case of road freight transport, the focus should be on bringing drop-in biofuels for the diesel fuel pool onto the market. Both mandates and low-carbon fuel standards should take into account sustainability criteria, favouring only technologies that exceed defined performance thresholds and therefore ensuring technology neutrality.

IEA analysis shows that the additional energy demand that would come about due to a transition to electric trucks is sizeable but manageable, and it suggests that prospects for the mid- to long-term availability of electricity are encouraging. Nevertheless, shifting to low-carbon electricity generation, as needed in the Modern Truck Scenario, requires strong carbon pricing measures, complemented by technology support measures to reduce investment risks (IEA, 2017c). At certain times and locations, the impacts of more electric vehicles on grid capacity can be sizeable (IEA, 2017e). This is an issue not only for electric cars, but also for the electrification of road freight transport, and requires solutions that optimise the utilisation of available grid capacity or through a systematic upgrade of the electricity grid.

In the case of hydrogen, carbon pricing is also essential for ensuring that life cycle emissions conform to the emission reduction needs of the MTS. Well-to-wheel GHG pricing can ensure that hydrogen production is based on renewable energy sources and, if it relies on fossil fuels, is equipped with carbon capture and storage. Given the limited experience with large-scale production, technology support measures to reduce investment risks have greater relevance for hydrogen production and distribution than they do for electricity.

Complementary measures

The modernisation of road freight transport is likely to require consultations among the major stakeholders and a high level of co-ordination between governments and the other actors involved, given the requirement for often high, upfront investments (such as for the rollout of dedicated infrastructures). Industry has a role to play, in particular when it comes to tapping the potential for systemic improvements. From the perspective of implementation, deploying a suite of tools by different levels of government as well as by other actors will foster this change. Table 21 lists the most relevant instruments available, including those discussed above, as well as other financial and regulatory measures.

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Table 21 • Policy measures supporting the modernisation of road freight

Policy measure	Actors	Authority level	Vehicle efficiency	Systemic improvements	Alternative fuels
Heavy-duty fuel economy standards: geographical expansion and gradual tightening	Government	National and supranational	XX		X
Differentiated vehicle taxes	Government	National and supranational	XX	X	XX
Low interest loans for energy efficient trucks	Commercial banks	--	X		
RD&D support to accelerate the development of technologies enabling energy efficiency improvements	Government	Local and municipal	X		X
Green financing to mobilise investment for the deployment and market uptake of energy efficient technologies	MDBs, commercial and national banks	–	XX	X	X
Accelerated vehicle replacement schemes to remove only older vehicles that are still being driven	Government	National, local and municipal	X		X
Green freight programmes: expansion of the regional and sectoral scope, and corporate membership	GFPs	--	XX	XX	
Voluntary annual reporting of road freight operations (e.g. aggregate vkm, tkm and fuel consumption)	Government, GFPs	National and supranational		XX	
Mandatory CO_2 emissions reporting	Government; GFPs	National and supranational	XX	XX	XX
Rules and regulations to promote external collaboration	Government	National and supranational	XX	XX	XX
Standardisation of truck sizes and regulation of operations of high-capacity vehicles	Government	National and supranational **Ideally global**	XX	XX	
Standards for ultra-low and zero-emissions infrastructure	Government	National and supranational	X		XX
Support for the deployment and use of alternative fuels infrastructure	Government, PPPs	National and supranational	X		XX
Biofuel mandates and low-carbon fuel standards	Government	Regional, national and supranational	X		XX
Differentiated distance-based pricing based on GHG emissions	Government	National and supranational	XX	X	XX
Tax transport fuels based on life-cycle GHG emissions	Government	Regional, national and supranational	XX	XX	XX
Stringent standards for pollutant emission and fuel quality *	Government	Regional, national and supranational	X	XX	XX
Access restrictions in urban areas based on vehicles' environmental performance (with a focus on air quality) and/or regulations that affect the cost or limit the availability of license plates for conventional vehicles	Government	Local and municipal	X	XX	XX
Measures to increase the cost of access to urban areas (e.g. usage fees for specific portions of the road network), differentiated on the basis of vehicles' environmental performance (focusing on air quality)	Government	Local and municipal	X	XX	X

* Regulations targeting local pollutants may have different impacts on vehicle efficiency because the relationship between fuel economy and pollutant emissions performance is not straightforward, and there are often trade-offs. To the extent that hybrids and (hydrogen-) electric trucks can achieve ultra-low or zero tailpipe emissions, these policies also promote vehicle efficiency.

Notes: GFP = green freight programme; MDB = multilateral development banks; PPP = private-public partnerships.

"XX" indicates a direct and major impact on a given category of improvement (i.e. vehicle efficiency, systemic improvements and alternative fuels); "X" denotes some impact (either minor or indirect).

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Following is a brief description of the policies and measures shown in Table 21 not yet described, placed into five broad categories:

- regional or global standards, protocols and frameworks
- measures to alter price signals
- financial incentives that promote energy efficiency
- initiatives to improve the availability, quality, and reliability of data
- air pollutant emissions policies.

Regional or global standards, protocols and frameworks

Setting global standards will require co-operative efforts. One of the main areas concerns the **regulation of the operations of high-capacity vehicles**. As discussed in Chapter 2, the simultaneous application of performance-based standards and the Intelligent Access Program, as pioneered in Australia, can enable the efficiency gains of using high-capacity vehicles while avoiding some of their potential drawbacks, including the potential for infrastructure damage, potential compromises to safety, and a reverse modal shift. Similarly, national and supranational **standards for ultra-low and zero-emissions infrastructure** will need to be established as trials and demonstration projects of catenary-enabled electric trucks and hydrogen fuel cell trucks move into the initial stages of deployment.

Much as the standardisation of container sizes in international shipping into 20-foot equivalent units enabled previously unrealisable efficiency gains, so, too, can efforts to **harmonise trucks sizes globally** support the vision of modular and seamless integration that is a core component of the physical Internet (Montreuil, Ballot and Tremblay, 2015). While achieving global alignment across a broad range of national and international vehicle and engine manufacturers may be difficult, the potential economic and societal gains are significant.

The prevalence of imports of used trucks and engines in developing countries underscores the importance of a global policy regime. The faster efficient and low-emissions technologies can be diffused in industrialised countries, the more quickly their advantages can be realised in developing countries.

Measures to alter price signals

Taxes based on the carbon content of fuels are an important enabler of the use of alternative fuels, as described earlier. In addition, fuel taxes narrow the cost differential between incumbent vehicle technologies and their more efficient alternatives (including vehicles using alternative energy sources, especially if produced with low life cycle emissions). As they increase the cost of transportation, fuel taxes also incentivise systemic improvements. **Distance-based pricing schemes with CO_2 differentiated taxation,** such as the programme recently proposed by the European Commission (EC, 2017), provide a potent price signal that applies in the operational phase (which accounts for the majority of GHG emissions). They can also serve as a revenue stream to finance the infrastructure that would be required by the ultra-low and zero-emissions alternative energy technologies (electricity and hydrogen).

Financial incentives that promote energy efficiency

Standards and differentiated vehicle taxation are critical policy enablers of energy efficiency. But additional complementary measures exist and often take the form of some type of financial support. These include low-interest RD&D support, green financing, loans for energy efficient trucks, and accelerated vehicle replacement schemes.

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RD&D support can accelerate the development of energy efficiency technologies in the pre-commercial stages. **Green financing** in the form of preferential lending terms for vehicle and component manufacturers that meet specific performance requirements can promote the scale-up and deployment of energy efficient technologies that research makes available. **Low-interest loans for energy efficiency technologies** can help bring down the cost barrier for energy efficiency investments. The can be promoted by green freight programmes (GFPs). Through their benchmarking of the efficiency and fuel savings of technologies and practices in specific and highly variable contexts, GFPs can also provide a reputable third-party assessment of the payback potential of these technologies and practices. More broadly, GFPs can play a crucial role in establishing protocols for technology verification. This is an essential requirement for enabling green financing for capital investments in more efficient technologies. One of the other potential hurdles for green financing is the perception of lending institutions of the poor credit risk of many small and capital-constrained companies. Financial assistance from MDBs, such as the World Bank and Asian Development Bank, could change the calculations considerably. Banks and GFPs could work together to streamline the loan application process. Banks should make the process as simple as possible and clearly define the benefits.

Many countries have implemented accelerated vehicle replacement schemes (see Table 10 at the end of Chapter 1), often as part of an economic stimulus package. These can be effective measures for improving air quality, as well as reducing oil demand and CO_2 emissions. These schemes need to be designed in a targeted manner to ensure that they remove only older vehicles that are still being driven among the vehicles in the rolling stock and replace these with more efficient and lower emitting vehicles, thereby leading to reduced emissions of CO_2 and local pollutants. Retiring vehicles that travel little provides minimal benefits (Fraga, 2011).

Initiatives to improve the availability, quality, and reliability of data

Measures to promote systemic improvements in road freight transport and logistics – including data gathering; rules for data sharing; extending the regional and sectoral scope; and scaling up the achievements of green freight programmes (GFPs) – have been outlined above. In addition to the solutions already discussed, and possibly as an interim step, governments can also encourage vertical and horizontal co-operation among companies by setting rules and regulations that promote external collaboration. As in the case of widespread systemic improvements, these should include legislation to protect companies' commercial and intellectual property, but also to harmonise and, whenever practical, remove barriers that restrict collaboration across national borders and non-aligned regional regulatory frameworks.

Air pollutant emissions policies

As examined in the recent IEA report *Energy and Air Pollution* (IEA, 2016b), the public health impacts of energy-related pollutant emissions are considerable. There is both scope and a clear public health case for **air pollutant emission standards** where they do not already exist, or for raising their stringency where they do not live up to international best practices. In countries with stringent standards, it is important to ensure that tested emissions reflect real-world emissions. Incorporating the lessons learned from experience in the next stages of regulations can also help to enforce the setting of standards in countries aiming to catch up to the global best standards.

In regions where fuel quality hinders the uptake of more efficient and less pollutant-emitting vehicle technologies, **mandates to improve fuel quality** are an immediate priority. Stricter standards on pollutant emissions (and fuel quality) increase the cost of compliance for technologies based on the combustion of fuels due to the need to use exhaust after-treatment controls. They favour alternative technologies by narrowing the cost differential they have with diesel internal combustion engines (ICEs). Given the efficiency advantage of some of these

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alternatives over diesel ICEs, these measures also promote energy efficiency. They also promote those alternative fuels that lead to lower pollutant emissions (including natural gas and biomethane, electricity and hydrogen).

Considerable leverage to minimise air pollutant emissions exists at the municipal level. Municipal governments are directly accountable to a concentrated constituency of citizens, all of whose interests tend to be aligned when it comes to the health, safety and quality of life implications of road transport. In this context, the political consensus for improvement is well disposed to promote technologies and operations that minimise the adverse impacts of urban freight (and passenger) transport.

Low- and zero-emissions zones function by either **restricting access** or **levying taxes** on vehicles that get access. In the effort to reduce local air pollutant emissions, they favour access by low-emitting vehicles. This promotes those alternative fuels that lead to lower pollutant emissions (including natural gas, biomethane, electricity and hydrogen). Given the efficiency advantage of some of these alternatives over diesel ICEs, measures that promote alternative fuels may also promote energy efficiency. As they increase the cost of access to urban areas, they also incentivise solutions (such as consolidation centres) that deliver the same services in urban regions with less activity, thereby promoting systemic efficiency. These measures are especially important as enablers of the market uptake of vehicle technologies that use alternative fuels.

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Acronyms, abbreviations and units of measure

Acronyms and abbreviations

3PL	third-party logistics
4PL	fourth-party logistics
ACEA	European Automobile Manufacturers' Association
ACEEE	American Council for an Energy-Efficient Economy
AFID	Alternative Fuels Infrastructure Directive
AMT	automated manual transmission
ANL	Argonne National Laboratory
ASEAN	Association of Southeast Asian Nations
ATA	American Trucking Association
ATRI	American Transportation Research Institute
BET	battery-electric truck
BEV	battery-electric vehicle
BtL	biomass-to-liquid
BTS	Bureau of Transportation Statistics
CARB	California Air Resources Board
CAT-ERS	catenary-enabled trucks running on electric road systems
CEC	Commission of the European Communities
CNG	compressed natural gas
CO_2	carbon dioxide
COP21	21st Conference of the Parties (UNFCCC)
DFM	digital freight matching
DfT	Department for Transport, United Kingdom
EBA	European Biogas Association
EC	European Commission
ECCJ	Energy Conservation Center, Japan
ERS	electric road system
EU28	European Union
EUR	euro
FCEV	fuel-cell electric vehicle
FCV	fuel-cell vehicle
FQD	Fuel Quality Directive
GDP	gross domestic product
GFA	Green Freight Asia
GFE	Green Freight Europe
GFP	green freight programme
GHG	greenhouse gas
GIS	geographic information system
GPS	Global Positioning System
GVW	gross vehicle weight
H_2	(diatomic) hydrogen (an energy carrier)
HCV	high-capacity vehicle
HDV	heavy-duty vehicle (includes both MFTs and HFTs)
HFT	heavy-freight truck
HVIP	Hybrid and Zero Emission Truck and Bus Voucher Incentive Project

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HVO	hydro-treated vegetable oil
IAP	Intelligent Access Program
ICCT	International Council on Clean Transportation
ICE	internal combustion engine
IEA	International Energy Agency
ILUC	indirect land use change
LCV	light commercial vehicle
LNG	liquefied natural gas
LPG	liquefied petroleum gas
LRR	low rolling resistance
LSP	logistics service provider
LUC	land use change
MDB	multilateral development bank
MFT	medium-freight truck
MIIT	Ministry of Industry and Information Technology
MoMo	Mobility Model
MSW	municipal solid waste
MTS	Modern Truck Scenario
MY	model year
NHTSA	National Highway Traffic Safety Administration
NOx	nitrogen oxides
OECD	Organisation for Economic Co-operation and Development
OEM	original equipment manufacturer
PBS	performance-based standard
PLDV	passenger light-duty vehicle
PM	particulate matter
PPP	purchasing power parity
PPP	public-private partnership
PtX	power-to-X
RD&D	research, development and demonstration
RFS2	Renewable Fuel Standard scheme
RTS	Reference Technology Scenario
SMR	steam methane reforming
SO_2	sulphur dioxide
TPS	tyre pressure system
TTW	tank-to-wheel
UCC	urban consolidation centre
UCO	used cooking oil
UNFCCC	United Nations Framework Convention on Climate Change
US DOE	US Department of Energy
US EPA	US Environmental Protection Agency
USD	US dollar
V2I	vehicle-to-infrastructure
V2V	vehicle-to-vehicle
WHR	waste heat recovery
WHVC	world harmonised vehicle cycle
WTT	well-to-tank
WTW	well-to-wheel (total life-cycle) emissions

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Units of measure

°C	degree Celsius
bcm	billion cubic metres
bhp-hr	brake horsepower-hour
CO_2-eq	CO_2-equivalent units (based on 100-year global warming potential)
EJ	exajoule
g CO_2-eq/MJ	gramme of carbon dioxide-equivalent per megajoule of fuel
g CO_2/km	gramme of carbon dioxide per kilometre
GJ	gigajoule
Gt	gigatonne
$GtCO_2$	gigatonne of carbon dioxide
$GtCO_2$-eq	gigatonne of carbon dioxide-equivalent
Gtoe	gigatonnes of oil-equivalent
kg	kilogramme
km	kilometre
lb	pound
lde	litre of diesel-equivalent
l/100 km	litres per 100 kilometres
mb/d	million barrels per day
MJ	megajoule
Mpa	megapascal
mph	miles per hour
Mt	megatonne
t	tonne
tkm	tonne kilometre
vkm	vehicle kilometre
Wh/L	watt-hour per litre

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Typeset and printed in France by IEA, July 2017

Cover design: IEA. Photo credits: © GraphicObsession.

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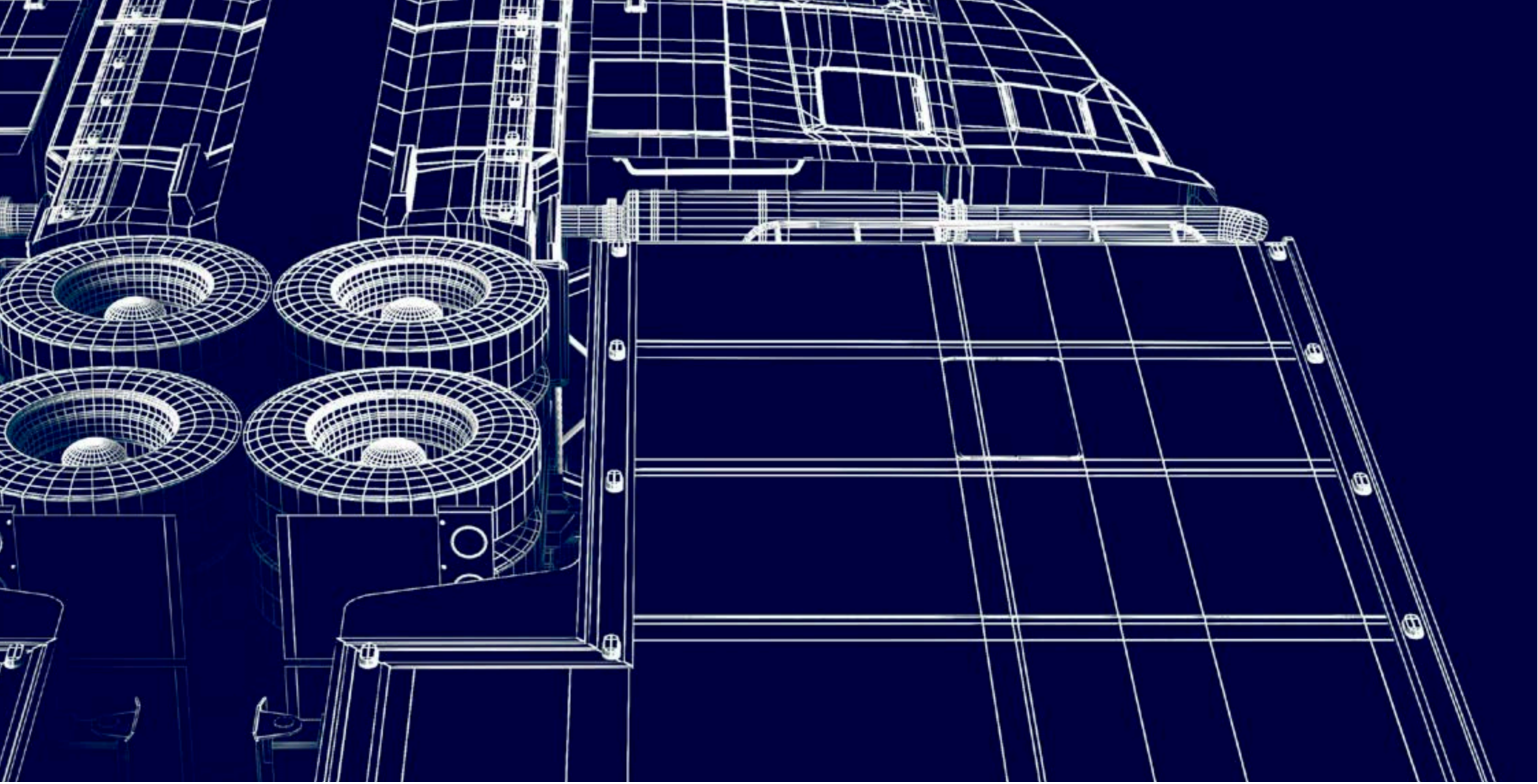

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