Chapter 6
Transport Transition Concepts

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Abstract Detailed background for all transport scenarios and development pathways including all key parameters, and story-lines for the 5.0 °C, 2.0 °C and 1.5 °C transport scenario pathways. Mode specific efficiency improvement over time for road-, rail- and aviation transport technologies. Explanations of all vehicle technologies are included in the scenarios, along with the rationale for their selection. Description of key technology parameters for all relevant transport modes such as energy demand per passenger, and per freight tonne. Detailed regional breakdown for developments in regard to transport energy demand for ten world regions and all transport modes are provided.

6.1 Introduction

Global transport accounted for 23% of total anthropogenic CO_2 emissions in 2010 and those emissions have increased at a rapid rate in recent decades, reaching 7 Gt in 2010 according to the IPCC Fifth Assessment Report (Sims et al. 2014). The reason for this steady increase in emissions is that passenger and freight transport activities are increasing in all world regions, and there is currently no sign that this growth will slow down in the near future. The increasing energy demand in the transport sector has mainly been met by greenhouse gas (GHG)-emitting fossil fuels. Although (battery) electric mobility has recently surged considerably, it has done so from a very low base, which is why, in terms of total numbers, electricity still plays a relatively minor role as an energy carrier in the transport sector.

Apart from their impacts on climate, increasing transport levels, especially of cars, trucks, and aeroplanes, also have unwanted side-effects, including accidents, traffic jams, the emission of noise and other pollutants, visual pollution, and the disruption of landscapes by the large-scale build-up of the transport infrastructure.

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However, road, rail, sea, and air transport are also an integral part of our globalized and interconnected world, and guarantee prosperity and inter-cultural exchange. Therefore, if we are to cater to people's desire for mobility while keeping the economy running and meeting the Paris climate goals, fundamental technical, operational, and behavioural measures are required immediately.

In this transport chapter, we discuss potential transport activity pathways and technological developments by which the requirement that warming does not exceed pre-industrial levels by more than 2.0 °C or 1.5 °C can be met—while at the same time maintaining a reasonable standard of mobility.

For our transport scenario modelling, the global warming limits of 2.0 °C and 1.5 °C were translated into transport CO_2 budgets. We structured our scenario designs around the following key CO_2-reducing measures[1]:

- Powertrain electrification;
- Enhancement of energy efficiency through technological development;
- Use of bio-based and synthetically produced fuels;
- Modal shifts (from high- to low-energy intensity modes) and overall reductions in transport activity in energy-intensive transport modes.

These measures are outlined in more detail in the subsequent chapters.

6.2 Global Transport Picture in 2015

The world final energy demand in the transport sector totalled 94,812 PJ[2] in 2015, according to the IEA Energy Balances (IEA 2017a, b, c). Based on this estimate, we used TRAEM (Sect. 3.3 to model the freight and passenger transport performance in our transport model with statistical data and energy efficiency figures.

The following paragraphs outline the 2015 transport structure modelled in TRAEM, which is the starting point for the subsequent scenario building until 2050.

As can be seen from Fig. 6.1, road passenger transport had the biggest transport final energy share of 51% in 2015. Most of this comprised individual road passenger modes (mostly cars, but also two- and three-wheel vehicles), which accounted for 45% of all end energy in the transport sector. In total, road transport (passenger and freight) accounted for around 90% of total final energy demand for transport.

The majority of total passenger–km (pkm) in passenger transport (around 85% of total pkm) is contributed by road transport modes. Freight is much more rail-oriented, and has a 42% share of total tonne–km (tkm), as shown in Fig. 6.2. The tkm share is much larger than the energy share arising from the much higher energy efficiency of railways compared with trucks.

Figure 6.3 shows the powertrain split of all transport modes in 2015 (by pkm or tkm respectively). With a few exceptions, the majority of modes were still heavily dependent on conventional internal combustion engines (ICE). A small number of buses had electric powertrains, which were mainly trolleybuses and increasingly

[1] See also Teske et al. (2015).

[2] International aviation and navigation bunkers are not included in this figure.

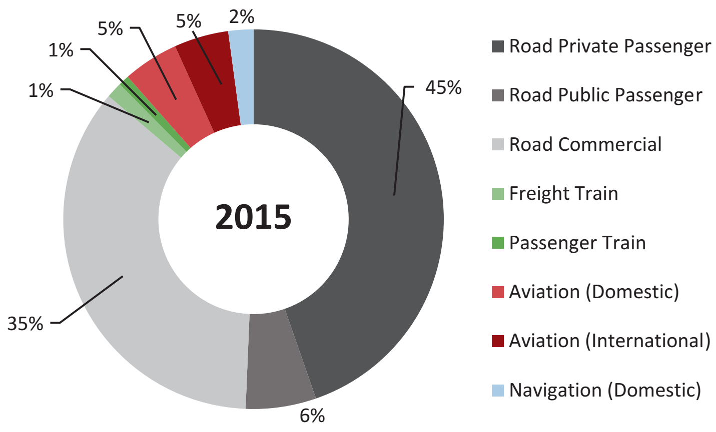


Fig. 6.1 World final energy use by transport mode in 2015

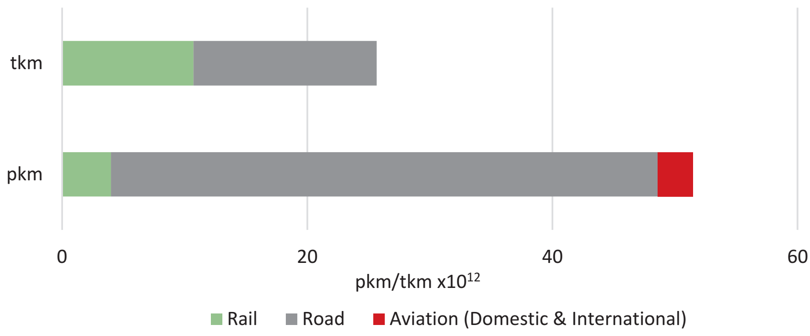


Fig. 6.2 Transport mode performances of road, rail, and aviation

also battery-powered electric buses, predominantly in China. China also has a particularly large number of electric two- and three-wheel vehicles. Almost all battery electric scooters worldwide were in China. Passenger rail was electrified to a large extent (e.g., metro and high-speed trains), whereas freight trains were predominantly not electrified.

OECD America and OECD Europe together make up nearly half the total energy demand (Fig. 6.4), and China is almost on the same level as OECD Europe, although it has about twice as many inhabitants as OECD Europe.

6.3 Measures to Reduce and Decarbonise Transport Energy Consumption

This section describes the measures required to reduce the final energy demand and decarbonise the transport sector. A variety of actions will be required so that the transport sector can conform to the <2.0 °C or 1.5 °C global warming pathways. The

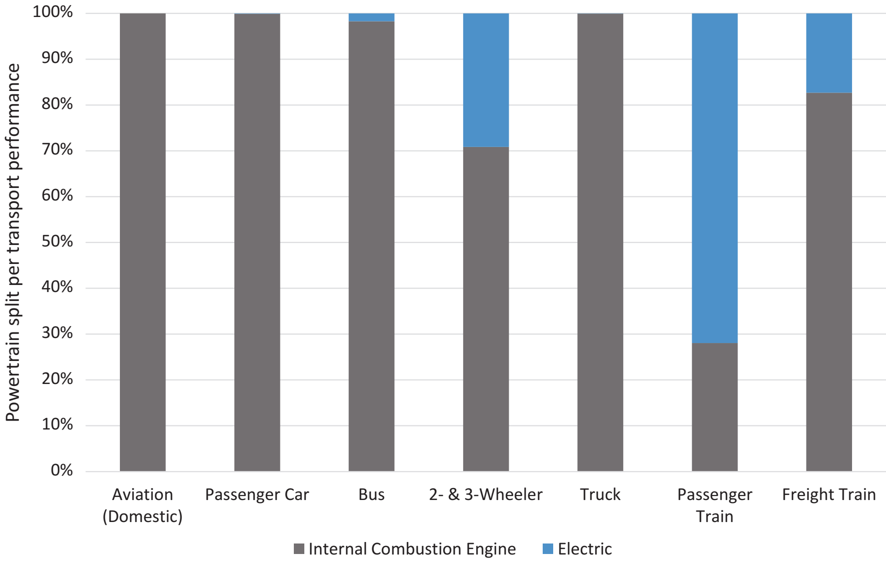
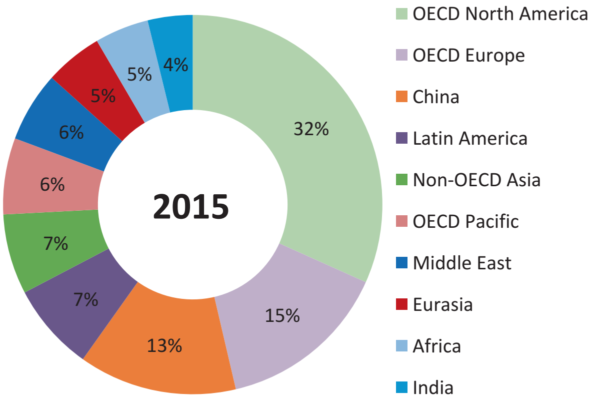


Fig. 6.3 Powertrain split for all transport modes in 2015 by transport performance (pkm or tkm)

Fig. 6.4 Final energy use by world transport in 2015 according to region



set of actions described can be clustered into technical and operational measures (e.g., energy efficiency increases, drivetrain electrification); behavioural measures (e.g., shifts to less-carbon-intensive transport carriers and an overall reduction in transport activity); and accompanying policy measures (e.g., taxation, regulations, urban planning, and the promotion of less-harmful transport modes). This study focuses on the 2.0 °C and 1.5 °C Scenarios and sets out the differences between these scenarios and the business-as-usual 5.0 °C Scenario.

We found that urgent and profound measures must be taken because the emissions reduction window will soon close. Therefore, temporary reductions in fossil-fuel-related transport activities (in terms of pkm and tkm of passenger cars, trucks, and aviation) in OECD countries seem nearly unavoidable until the electrification (based on renewable energy production) of the transport sector undergoes a breakthrough.

6.3.1 Powertrain Electrification

Increasing the market penetration of highly efficient (battery and fuel-cell) electric vehicles, coupled with clean electricity generation, is a powerful lever and probably also the most effective means of moving toward a decarbonised transport system. All electric vehicles have the highest efficiency levels of all the drivetrain options. Today, only a few countries have significant proportions of electric vehicles in their fleets. The total numbers of electric vehicles, particularly in road transport, are insignificant, but because road transport is by far the largest CO_2 emitter in overall transport, it offers a very powerful lever for decarbonisation. In terms of drivetrain electrification, we cluster the world regions into three groups, according to the diffusion theory (Rogers 2003):

- *Innovators*: OECD North America (excluding Mexico), OECD Europe, OECD Pacific, and China
- *Moderate*: Mexico, Non-OECD Asia, India, Eurasia, and Latin America
- *Late adopters*: Africa and the Middle East.

Although this clustering is rough, it sufficiently mirrors the basic tendencies we modelled. The regions differ in the speed with which novel technologies, especially electric drivetrains, will penetrate the market.

6.3.1.1 The 5.0 °C Scenario

The 5.0 °C Scenario follows the IEA Current Policies Scenario (IEA 2017a) until 2040, with extrapolation to 2050. We model only minor electrification over all transport modes (see Fig. 6.5), with passenger cars and buses making relevant gains in *electric vehicle* (EV) shares. For example, we project a share of 30% for *battery electric vehicles* (BEV) in China by 2050 due to foreseeable legislation and technological advancements in that country (Cui and Xiao 2018), whereas for the world car fleet, the share is projected to increase to only around 10%. The growth in the share of the commercial road vehicle fleet and of the fleet of two- and three-wheel vehicles held of electric powertrains will be small, as will be the increase in further rail electrification. Aviation and navigation (shipping) will remain fully dependent on conventional kerosene and diesel, respectively.

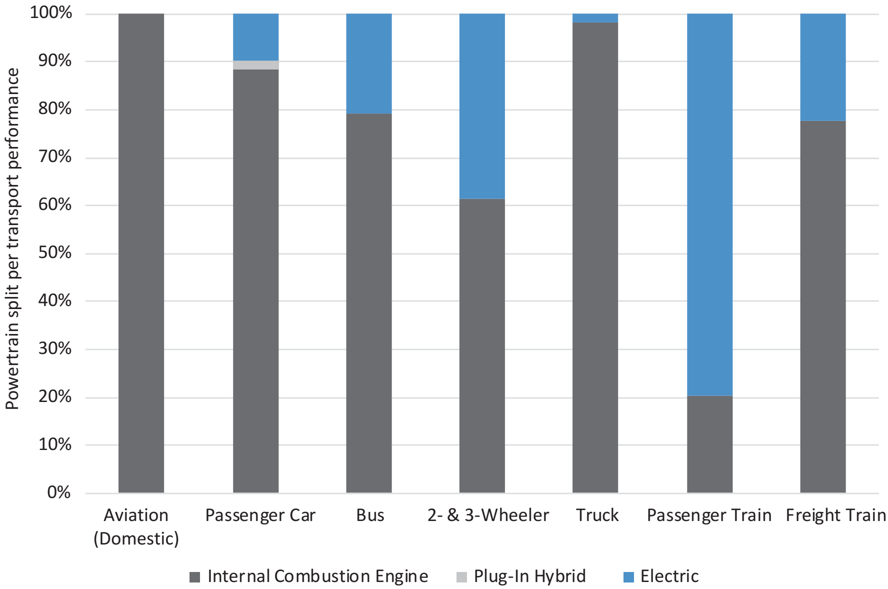


Fig. 6.5 Powertrain split for all transport modes in 2050 under the 5.0 °C Scenario in terms of transport performance

6.3.1.2 The 2.0 °C Scenario

Based on the low market share of BEV observed today (2018), minimal progress in electrification until 2020 is assumed in the 2.0 °C Scenario. Moving towards 2030, the *innovator* regions will experience strong electrification, encouraged by purchase incentives, EV credit systems, and tightened CO_2 fleet emission targets. Passenger cars and light commercial vehicles are projected to achieve shares of BEVs in the regional stocks between 21% and 30%, whereas heavy commercial vehicles and buses will attain even higher EV fleet shares of between 28% and 52% by 2030. This will require a massive build-up of battery production capacity in the coming years. Electric city buses and some trolley trucks will make a significant contribution to this development. Two- and three-wheel vehicles will be nearly completely electrified (batteries and fuel cells) in a couple of regions. OECD Pacific will head the *fuel-cell-electric vehicle* (FCEV) market introduction, which will account for up to 6% of passenger cars and light commercial vehicles by 2030, with Japan and South Korea the main market drivers. Higher shares of FCEV in *innovator* regions are more likely in the bus and heavy truck sector, which reach up to 10% in 2030. In 2050 in the innovative regions, only a minor proportion of vehicles will have ICE (up to 9%). Passenger cars and light commercial vehicles will predominantly be electrified, with a BEV share of around 80%. FCEV will also gain a significant share of 17% in OECD Pacific and OECD North America.

Looking ahead to 2050, 60–70% of buses and heavy trucks will probably be (battery) electric, whereas FCEV will increase their market share to around 37%. The proportion of buses and heavy trucks that will be BEV in 2050 will be around 60–70%. Two- and three-wheel vehicles will be nearly fully electrified in all regions (80–100%).

In the *moderate* regions, the BEV share of road transport vehicles is set in a range of 1–15%. Except for Latin America, the *moderate* regions will have an ICE share of 83% or less for passenger cars. For example, India is progressing with its current electrification strategy and up to 14% of its passenger cars will be battery-powered by 2030. It is likely that ICE will dominate buses and trucks in the *moderate* regions in 2030. Fuel-cell cars now have small shares of 1–2%. Non-OECD Asia is positively influenced by its *innovator* neighbour region, OECD Pacific. In the 2.0 °C Scenario, *moderate* regions will reach BEV shares of up to 67% for passenger cars and light commercial vehicles and between 54% and 65% for buses and heavy trucks by 2050. Compared with the *innovator* regions, the *moderate* regions will not experience a significant uptake of FCEVs. Africa and the Middle East will remain mostly dependent on ICE in 2050, with shares of around 90%. Only slow electrification will occur in Africa, with small and cheap BEVs (Fig. 6.6).

As an example of how different the electrification speeds will be across the world regions, Fig. 6.7 shows the uptake of electric and fuel-cell drivetrains in buses and two- and three-wheel vehicles, region by region, in terms of pkm. In 2015, a substantial proportion (15%) of China's buses were already electrified. OECD Pacific and OECD Europe will follow, with substantial electrification after 2020, as will India, Non-OECD Asia, and Eurasia after 2030. The remaining regions will electrify their fleets predominantly after 2035. Fuel-cell drivetrains will not begin to penetrate the market to a significant extent until 2025. We project a fleet that is 40–70% electric (battery and trolley) and 10–30% fuel-cell electric by 2050 in the 2.0 °C Scenario.

Figure 6.8 plots the projected electrification of passenger and freight rail in terms of final energy demand. Substantial electric passenger rail was present in OECD Europe, OECD Pacific, and China in 2015, and substantial electric freight transport in OECD Europe and Eurasia. In most other world regions, freight transport by rail predominantly relied on diesel locomotives.

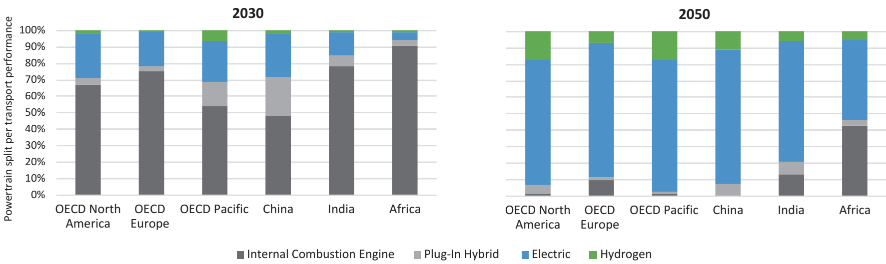


Fig. 6.6 Powertrain split (fleet) of passenger cars in selected regions in 2030 (*left*) and 2050 (*right*) under the 2.0 °C Scenario

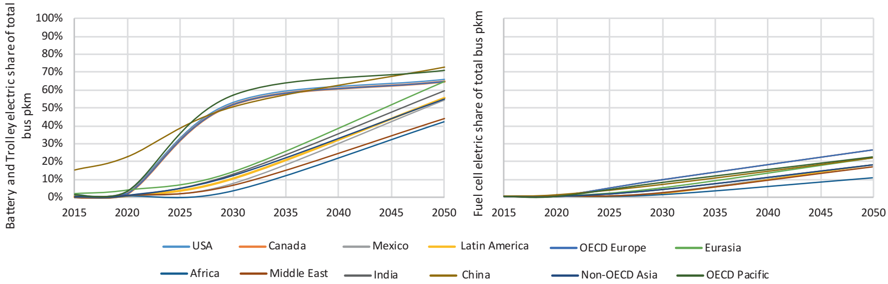


Fig. 6.7 Battery and trolley electric bus share of total bus pkm in the 2.0 °C Scenario (*left*) and fuel-cell electric bus share of total bus pkm in the 2.0 °C Scenario (*right*)

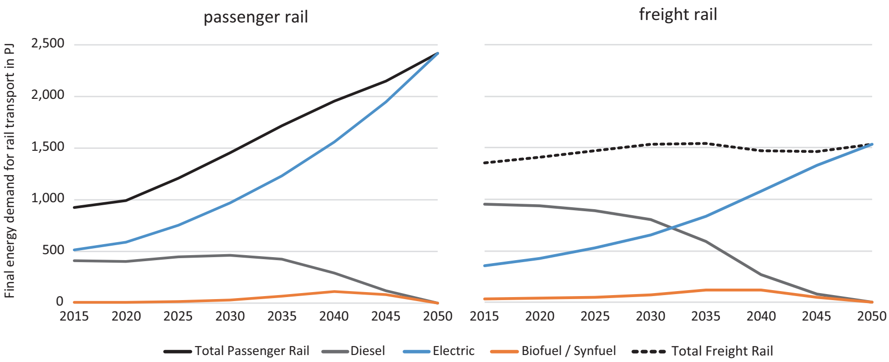


Fig. 6.8 Electrification of passenger rail (*left*) and freight rail (*right*) under the 2.0 °C Scenario (in PJ of final energy demand)

In most world regions, nearly all rail traffic is projected to be electric after 2040 in the 2.0 °C Scenario. Total diesel consumption in rail operations is projected to increase slowly until 2030, mainly because railway vehicles have long lifespans, and once diesel cars are put into operation, they are not replaced overnight. Furthermore, line electrification usually requires several years of planning and construction.

Aviation will probably remain predominantly powered by liquid fossil fuels (kerosene and bio- and synfuel derivatives) in the medium to long term because of limitations in electrical energy storage. We project a moderate increase in domestic pkm flown in electric aircrafts starting in 2030, with larger shares in OECD Europe because the flight distances are shorter than, for example, in the USA (Fig. 6.9). Norway has announced plans to perform all short-haul flights electrically by 2040 (Agence France-Presse 2018).

However, no real electrification breakthrough in aviation is foreseeable unless the attainable energy densities of batteries increase to 800–1000 Wh/kg, which would require fast-charging capable post-lithium battery chemistries.

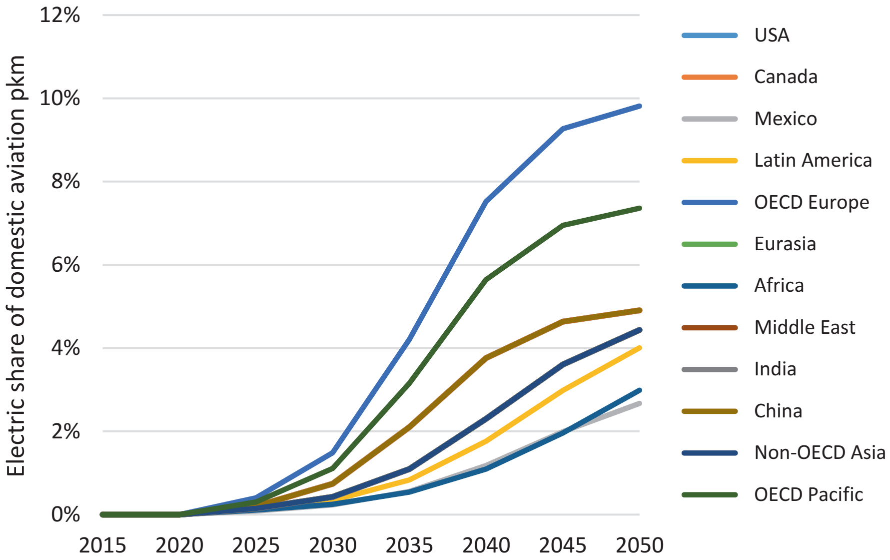


Fig. 6.9 Electricity-performed pkm in domestic aviation under the 2.0 °C Scenario

6.3.1.3 The 1.5 °C Scenario

In the 1.5 °C Scenario, an earlier and more rapid ramp-up of electric powertrain penetration is required than in the 2.0 °C Scenario and the *innovative* regions will be at the forefront. The *moderate* regions will also need to electrify more rapidly than in the 2.0 °C Scenario, but will end up with only a minimally higher share by 2050. In the passenger car sector in particular, plug-in hybrid electric vehicles (PHEVs) will ensure a sharp reduction in conventional combustion engine vehicles between 2030 and 2050. In the *late adopter* regions, there is no difference between the 2.0 °C and 1.5 °C Scenarios. The phasing out of internal combustion engine (ICE) vehicles will occur more quickly under the 1.5 °C Scenario than under the 2.0 °C Scenario (Fig. 6.10).

6.3.2 Mode-Specific Efficiency and Improvements Over Time

In passenger transport, trains and buses are much more energy efficient per pkm than passenger cars or aeroplanes. This situation does not change fundamentally if only electric drivetrains are compared (Fig. 6.11). It is apparent that railways and especially ships are clearly more energy efficient than trucks in transporting freight (Fig. 6.12). The 2015 figures are the starting point for a more detailed discussion, mode by mode, later in this chapter, and these figures are the basis for the rationale of our discussion in terms of modal shift (Chap. 6, Sect. 4). The efficiency data are

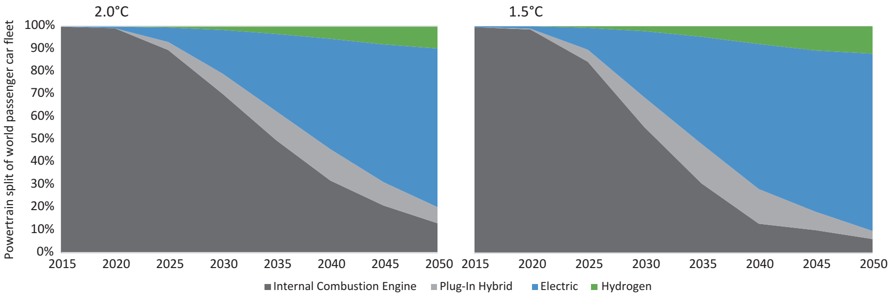


Fig. 6.10 Powertrain split of the world passenger car fleet in the 2.0 °C Scenario (*left*) and 1.5 °C Scenario (*right*)

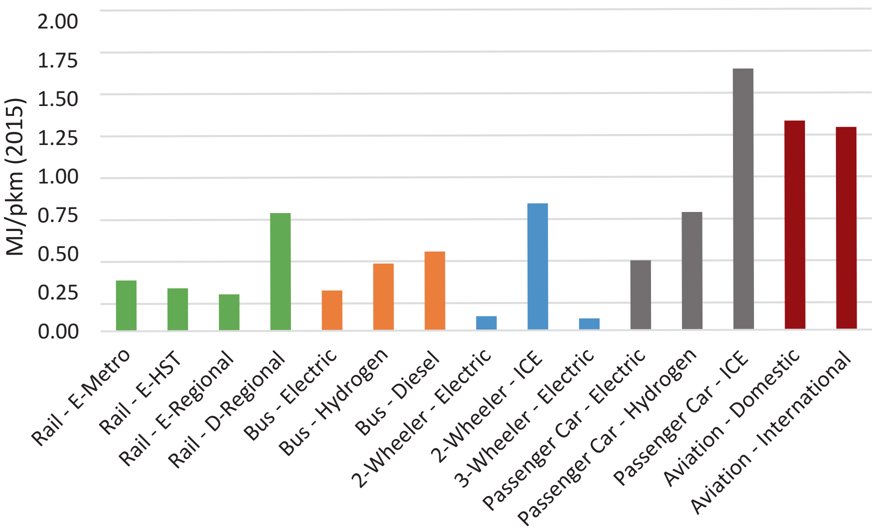


Fig. 6.11 Final energy demand in urban and inter-urban passenger transport modes in 2015 (world averages)

based on literature-reported and transport operator information. The efficiency levels in terms of pkm or tkm depend to a large extent on the underlying capacity utilization of the vehicles, which differs between world regions. The numbers are average values and differences are evaluated at the regional level.

In addition to powertrain electrification, there are other potential improvements in energy efficiency, and their implementation will steadily improve energy intensity over time. Regardless of the types of powertrains and fuels used, efficiency improvements on the MJ/pkm or MJ/tkm level will result from (for example):

- Reductions in powertrain losses through more-efficient motors, gears, power electronics, etc.;
- Reductions in aerodynamic drag;

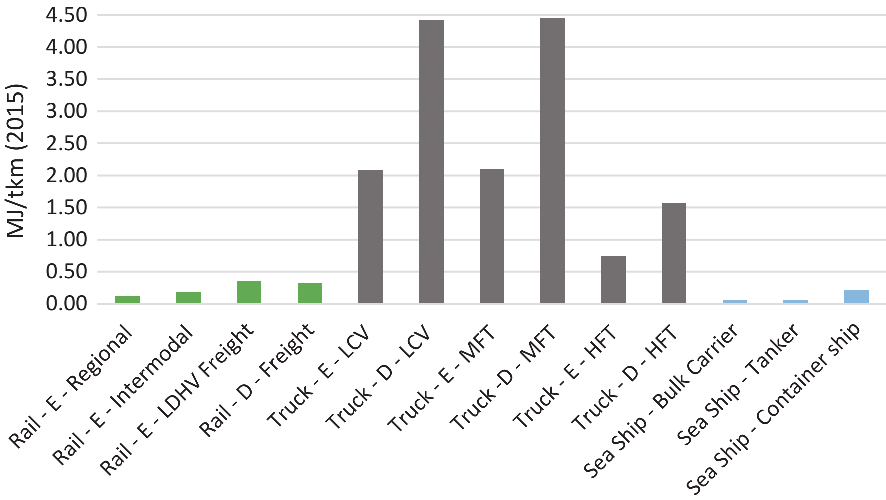


Fig. 6.12 Final energy demand in freight transport modes in 2015 (world averages)

- Reductions in vehicle mass through light-weighting;
- The use of smaller vehicles;
- Operational improvements (e.g., through automatic train operation, load factor improvements).

The measures are discussed in the following mode-specific sub-chapters.

6.3.3 Road Transport

6.3.3.1 Passenger Cars

As of 2017, 99% of the passenger cars produced worldwide were estimated to be equipped with an ICE: the majority of them gasoline or diesel (95%), 3.4% hybrid electric vehicles (HEV), and 0.7% PHEV (BCG 2017). Only about 0.9% of the cars sold were pure battery electric vehicles (BEV). There are several options for energy efficiency improvements. The fuel consumption reduction potential of petrol engines as a result of engine improvements and hybridization is around 25–30%, and it is around 15–20% for diesel engines (van Basshuysen and Schäfer 2015). Maximum efficiencies of 38–40% can be reached by ICE (Schäfer 2016), whereas electric drivetrains have efficiencies of 80–85% (including [re]charging losses). Besides the reduction in engine losses, both lightweight construction and reductions in rolling resistance will result in additional fuel savings.

Hybrid systems increase the complexity of powertrains, resulting in higher masses and higher costs, but they offer additional fuel-saving potentials. Energy can thus be recovered by recuperation during braking in hybridized and all-electric

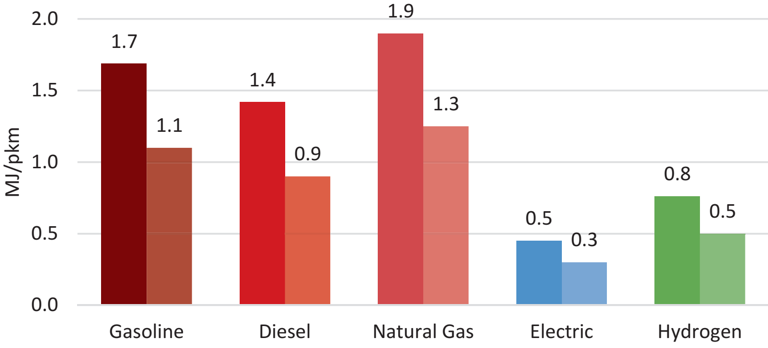


Fig. 6.13 World average energy consumption development for passenger cars per powertrain in 2015 (*left*) and 2050 (*right*)

vehicles. In BEV and FCEV, advanced battery technologies can reduce the overall vehicle mass. However, post-lithium technologies, such as lithium–sulfur and solid-state batteries with increased energy densities and lower systems masses compared with today's Li-ion battery technologies, will probably not enter the transport sector before 2030 (Schmuch et al. 2018).

In total, we project a 1% increase in annual efficiency on a per passenger/km basis (the same for all drivetrains) for the 5.0 °C and 2.0 °C Scenarios. The efficiency improvements for 2050 in the 2.0 °C Scenario will be achieved in 2040 under the 1.5 °C Scenario (Fig. 6.13).

6.3.3.2 Light and Heavy Freight Vehicles

Like passenger cars, trucks are currently driven almost exclusively by conventional ICE. With a market share of 84% of diesel-fuelled vehicles in 2015 (IEA 2017c), the global fleet of trucks was predominantly operating on diesel (IEA 2017b). In some regions, such as the Middle East, trucks are also powered by gasoline to a considerable degree. Electric drivetrains will enter the truck sector gradually in coming years because of changes in exhaust emissions legislation and because the higher efficiency of electric drivetrains compared with ICE will offer economic advantages to road carriers (Fig. 6.14). Compared with diesel-powered trucks, fuel-cell electric drivetrains in trucks can substantially reduce the energy intensity per tkm, and allow higher operating ranges than battery-powered trucks. To achieve rapid improvements in energy efficiency in the truck sector, the hybridization of diesel powertrains, especially those operating in stop-and-go intensive urban environments, is promising (Burke and Hengbing 2017; Lischke 2017). However, after 2030, the hybrid diesel powertrain will be seen merely as a transitional technology before the advent of fully electric powertrains (overhead catenary, battery electric, and fuel-cell electric). Therefore, the development of battery recharging and hydrogen refuelling infrastructures will require massive investments in coming years. In

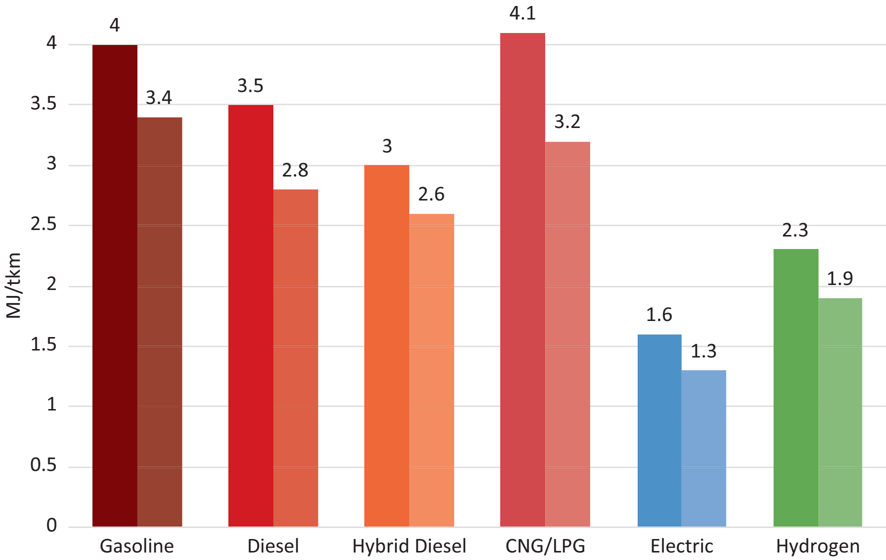


Fig. 6.14 Average global energy intensities of truck drivetrain technologies in 2015 and 2050

the commercial sector, it is likely that many electrical charging stations will be set up on the private grounds of logistics operators. The market growth of BEV in the truck sector will require considerable public spending on the installation of overhead catenary lines along major highways for trolley trucks (hybridized with diesel, fuel cells, or batteries). The first pilot lanes are being developed in Germany, Sweden, and California (USA) (Siemens 2017).

6.3.3.3 Buses

State-of-the-art city buses operate on ICE (diesel or gas) or are trolley buses (all-electric or hybridized with an additional battery or diesel motor). Diesel hybrids have entered the city bus market and constitute a large proportion of the bus fleets in a range of cities today. The short distances between stations, small operating radii, and moderate daily mileages make the use of batteries in city buses a viable option, complemented by fuel cells for routes with higher ranges or difficult terrains. Battery electric buses are between the prototype/experimental stage and a mature technology. In China, battery electric buses are already an integral part of public bus transport systems, and the city of Shenzen has had a 100% electric bus fleet since 2016 (over 16,000 battery electric buses) (Sisson 2018). Fuel-cell electric buses still lag behind battery electric buses in terms of numbers, but are increasing. In 2017, about 80 fuel-cell electric buses were in operation in Europe (Element Energy Ltd. 2018) and 26 in the USA (Eudy and Post 2017). Full battery operation is more difficult to achieve in regional and long-distance buses and coaches, so the

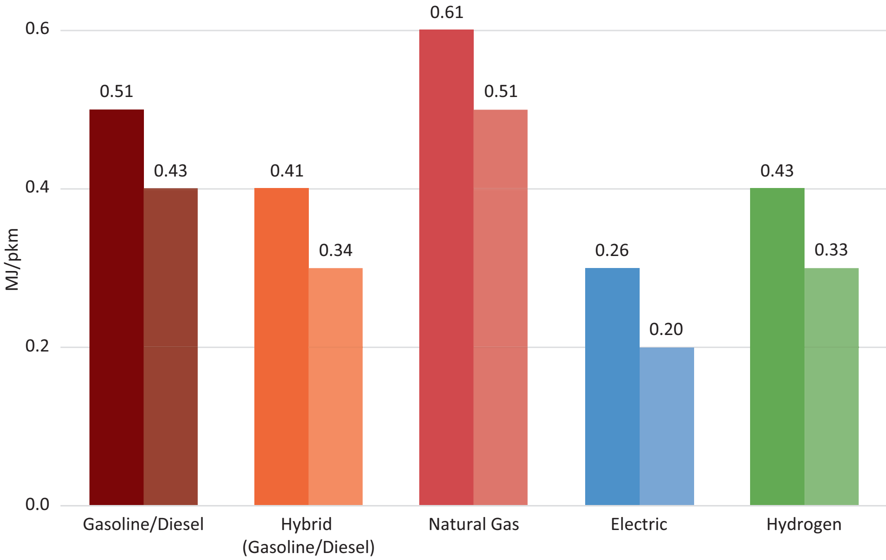


Fig. 6.15 Average global energy intensities of bus drivetrain technologies in 2015 (*left*) and 2050 (*right*)

uptake of full battery electric and also fuel-cell powertrains will be slower than in city buses. Diesel-powered buses will remain in the market longer, complemented by diesel hybrid powertrains. Ultimately, fuel-cell-powered inter-urban coaches will probably be more common than fuel-cell-powered city buses. In our model, we divided the regions into *innovators* (i.e., China and OECD countries) and all the other regions lagging behind the innovators. We also identified a clear trend towards electrification.

We project a 0.5% (diesel, diesel-hybrid and natural gas) to 0.8% (electric and fuel cell hydrogen electric) increase in efficiency on a per passenger per km basis in all three scenarios (Fig. 6.15).

6.3.3.4 Two- and Three-Wheel Vehicles

Two-wheel vehicles are probably the most important component of everyday traffic in large parts of Asia and Africa. The drivetrain efficiencies of e-scooters are reported to be 1.2–3 kWh/100 vehicle–km. China is by far the biggest market for electric scooters in the world, with more than 200 million electric scooters on the road by 2015, that translates to an electric share of about 70%.

Three-wheel vehicles (also country-specifically called ‘rickshaws’ or ‘tuk-tuks’) have at least two, and usually three or more seats, and are often overloaded in daily traffic. India alone is reported to have 2.5 million rickshaws on the road, each travelling 70–150 km/day (Abu Mallouh et al. 2010). Most three-wheel vehicles are fuelled by gasoline and some by liquid petroleum gas (LPG), although some com-

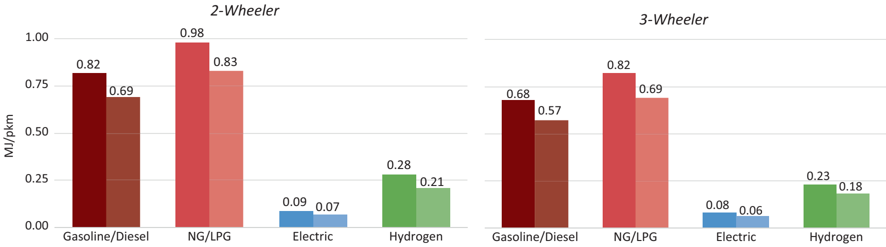


Fig. 6.16 Average global energy intensities of two-wheel vehicles (*left*) and three-wheel vehicles (*right*) by drivetrain technology in 2015 (*left bar*) and 2050 (*right bar*)

munities incentivize the conversion of two-stroke engines to battery electric three-wheel vehicles. Electric tuk-tuks are increasingly emerging in South-East Asia, together with battery swap stations and solar-powered rickshaws (Moran 2018; Reddy et al. 2017). Thailand has announced that it plans to convert all existing two-stroke-powered tuk-tuks to battery electric powertrains within 5 years (Coconuts Bangkok 2017). In India, too, plans are repeatedly announced to electrify all new two- and three-wheel vehicles within the next two decades (Ghoshal 2017).

The efficiency of battery electric drivetrains is much better than that of conventional two-stroke engines in two- and three-wheel vehicles (Fig. 6.16). We project a 0.5% annual increase in efficiency on a per pkm basis (the same for all drivetrains) in all three scenarios.

6.3.3.5 Rail Transport

No other transport mode is more suited to operate electrically than railways. Urban rail systems, for instance, are invariably electric. Electric trains consume about 60–70% less energy than diesel trains when their final energy use is compared (on catenary and tank levels, respectively). According to the International Railway Association, about 32% of the worldwide rail network was electrified in 2015 (UIC 2017). However, in terms of transport performance (pkm or tkm), the ratio of electric to diesel is higher because electrified rail lines usually experience more traffic than non-electrified lines. The electrification of rail lines with overhead catenaries has been the state-of-the-art technology for decades and new lines are almost exclusively equipped with overhead power lines right from the start.

However, line electrification, especially of existing lines, is often difficult to achieve due to unsettled and complex right-of-way issues, narrow tunnel diameters, or simply because line electrification is not economically viable due to low line utilization. The use of on-board batteries for mixed electrified/non-electrified lines and shunting operations and the use of fuel-cell hybrid powertrains for longer lines with little or no electrification whatsoever could be feasible fully electric alternatives to diesel power or full-line electrification. (Fuel-cell electric trains have not been modelled in this research).

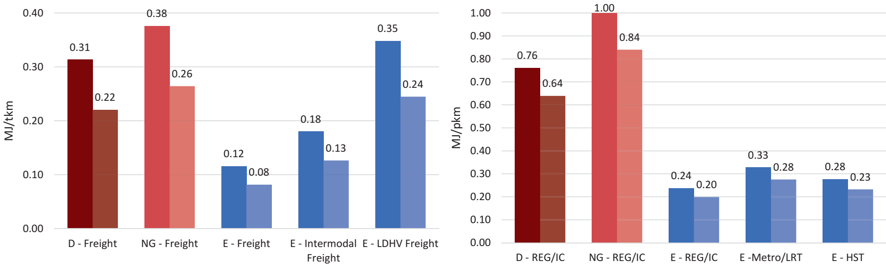


Fig. 6.17 MJ/tkm of freight rail trains (*left*) and MJ/pkm of passenger rail trains (*right*) for 2015 (*left*) and 2050 (*right*)

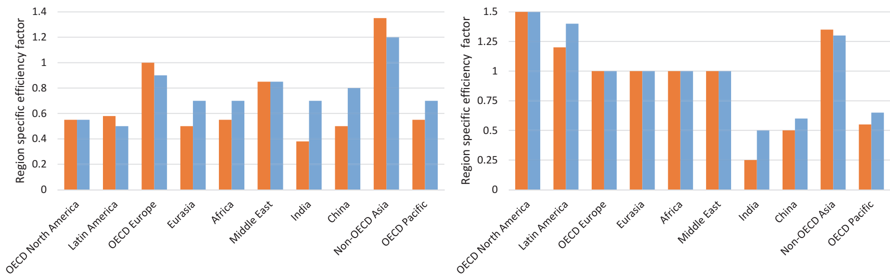


Fig. 6.18 Region-specific MJ/tkm and MJ/pkm in 2015 and 2050 for freight rail trains (*left*) and passenger rail trains (*right*)

We project a 0.5% annual increase in efficiency on a per passenger per km basis and a 0.8% annual increase in efficiency on a per tonne per km basis (the same for all drivetrains) in all three scenarios (Fig. 6.17).

The actual efficiency depends on the type of train and the world region. These differences are considered in every transport sub-model and are exemplified in Fig. 6.18 for freight and passenger trains.

6.3.3.6 Water and Air Transport

Inland navigation will probably remain predominantly powered by ICE in the next few decades. Therefore, we did not model the electrification of inland navigation vessels. However, pilot projects using diesel hybrids, batteries, and fuel cells are in preparation (DNV GL 2015). We assumed the same increase in the share of bio- and synthetic fuels over time as in the road and rail sectors.

In aviation, energy efficiency can be improved by measures such as winglets, advanced composite-based lightweight structures, powertrain hybridization, and enhanced air traffic management systems (Madavan 2016; Vyas et al. 2013). We project a 1% annual increase in efficiency on a per pkm basis.

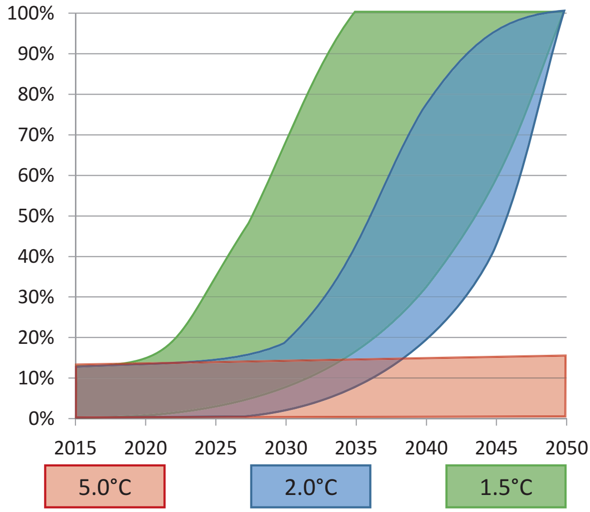


Fig. 6.19 Shares of bio- and synfuels in all world regions under all scenarios

6.3.4 *Replacement of Fossil Fuels by Biofuels and Synfuels*

The use of biofuels in the transport sector offers a potential lever to reduce the CO_2 emissions from fossil fuels. Biofuels can be used either as a direct drop-in or as admixtures to fossil fuels. Biofuels are widely used, especially in Latin America (e.g., E85 in Brazil, a blend of 85% ethanol and 15% gasoline). Biofuels will be replaced by synthetic fuels (synfuels) within the next few decades.

In the three scenarios, we use region-specific shares of bio- and synfuels to replace fossil fuels such as diesel, gasoline, and kerosene. Figure 6.19 shows the scenario-specific band-widths. In the 5.0 °C Scenario, Latin America will increase its proportion of bio- and synfuels to around 15%, whereas in the Middle East, Mexico, and Eurasia will even not reach a 0.5% share by 2050. Bio-fuel and especially synfuel shares will remain constant in the 5.0 °C Scenario, whereas they will increase in the 2.0 °C Scenario between 2030 and 2050 and in the 1.5 °C Scenario from 2020 onwards.

6.3.5 *Operational Improvements and Novel Service Concepts*

In addition to technical improvements, such as the energy efficiency savings described in previous chapters, behavioural changes can potentially reduce energy demand and help decarbonise the transport sector as a whole. These measures include, among other things, the efficient operation of vehicles, for example by increasing the occupancy rates of moving vehicles, reductions in mileages, and reductions in vehicle stocks.

6.3.5.1 Passenger Transport

The classic fixed boundary between private and public transport will blur in the future as novel platforms and sharing concepts emerge. This trend will potentially reduce the number and usage of privately owned vehicles. Private car ownership is generally becoming less a ‘must’ for many people in the car-oriented OECD regions. Driven by digitization, app-based cars and ride-sharing concepts are emerging. They include traditional car sharing (e.g., Zipcar), free-floating car sharing businesses (e.g., car2go), and ride-hailing mobility concepts (e.g., Uber, lyft). In Europe, private ride-sharing mobility platforms, such as *BlaBlaCar*, are seen as alternative passenger car usership schemes. All shared-use mobility concepts have in common that they reduce the vehicle stock and increase occupation rates on trips. To own a car is no longer considered a status symbol, but has become simply a mode of transport in the Western world.

Flexibility and passenger-friendly usability is becoming increasingly important to users of public transport. Various app-based on-demand mobility services are currently being tested in pilot projects—for example, in the German city of Schorndorf (Brost et al. 2018). Under these business models, innovative vehicle concepts are tested for suitability. Automated battery electric (mini) buses can make public transit more flexible. Their modularity also allows them to connect to other modes of transport, such as rail and air transport, and thus opens up fundamentally new transport chains that are more energy efficient than traditional passenger car usage. However, decision-makers and transport planners must consider the potentially detrimental rebound effects of highly personalized automated mobility (Pakusch et al. 2018). For example, an increase in total energy consumption may occur as a result of the higher transport demand arising from transport options that are seen as more attractive than more-energy-efficient mass transit systems or cycling. Therefore, novel transport concepts could cancel out the gains in energy efficiency on a per vehicle level.

6.3.5.2 Freight Transport

The automatization of road freight traffic can reduce fuel consumption. The technology for partially automated trucks is already available and being tested to make it widely available. In the Society of Automotive Engineers (SAE) automation level 3 (SAE 2018), (multi-brand) truck platooning has become possible, which is a driver-assistance technology (Janssen et al. 2015). With communication between the first truck and the following trucks, the control of the following vehicles is handed over to the leading vehicle. Thus, the following vehicles are driving in the slipstream and lower air drag is achieved, which can reduce energy consumption by up to 5% (Daimler 2018).

In urban freight transport, last-mile delivery concepts based on light commercial vehicles can help reduce fuel consumption. By fragmenting the transport routes into the main leg and urban traffic (last mile), different vehicle types and modes can be used more efficiently for specialized transport tasks. Like light commercial vehicles (electric), cargo bikes could shape the urban freight traffic of the future as they do already today in many countries in Asia.

Further novel logistic concepts, such as the use of drones for delivery and decentralized production using 3D printers, will help to reduce the overall transport demand and thus energy consumption through more-efficient operational solutions.

6.4 Transport Performance

We outline achievable 2.0 °C and 1.5 °C Scenario paths that will allow us to achieve very ambitious emission reduction targets. The levels of pkm and tkm for every world region in 2015 were calibrated against statistical data, the literature, and our own estimates when concrete data were not available.

To complement the anticipated technologically driven mode-inherent improvements in efficiency that we took as the input for our modelling in the previous sections of this chapter, we now describe the scenario assumptions in terms of the transport mode choices and transport demand. The main idea is to model low-emission pathways that shift from fossil-dependent, low-energy-efficiency modes toward more-energy-efficient and electrified modes. We also look at the general level of performance of transport modes and suggest region-specific development pathways. We first outline the scenario-specific pkm and tkm pathways to 2050 and then discuss the rationales for the mode choices that will result in the transport performance projections.

For the 5.0 °C Scenario, we extrapolate current trends in transport performance until 2050. In relative terms, the transport performance of all transport carriers will increase from current levels. Aviation, passenger car, and commercial road transport are particularly projected to grow strongly (Fig. 6.20). These modes consume more energy than trains, ships, and buses, as discussed in Sect. 6.3.2. Even if the full efficiency potential of these transport modes is realized, energy intensity per pkm or tkm will remain higher than that of trains, ships, or buses.

In the 2.0 °C Scenario and 1.5 °C Scenario, we project a strong increase in rail traffic (starting from a relatively low level) and a slower growth or even a reduction in the use of the other modes in all world regions (Fig. 6.21). The next two sections describe the specific changes and developments for each type of passenger and freight transport.

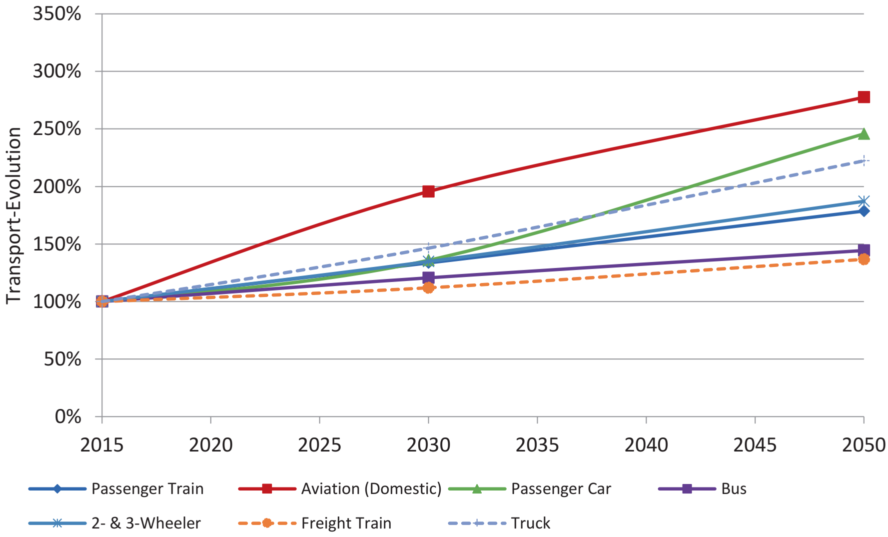


Fig. 6.20 Relative growth in world transport demand (2015 = 100% pkm/tkm) in the 5.0 °C scenario

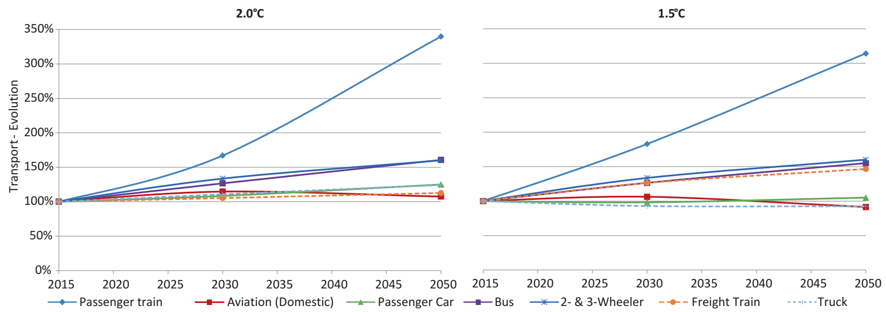


Fig. 6.21 Relative growth in world transport demand (2015 = 100% pkm/tkm) in the 2.0 °C Scenario (*left*) and 1.5 °C Scenario (*right*)

6.4.1 Passenger Transport Modes

To reduce transport-related CO_2 emissions, a shift towards low-energy-intensity modes of transport is required for both ambitious climate-protection scenarios. Travelling by rail is the most energy-efficient form of transport, and therefore we suggest a strong shift from domestic aviation to trains, especially high-speed trains and magnetic levitation trains. The assumed shifts from domestic aviation to trains are shown in Table 6.1. The mode shift potential differs, depending predominantly on the country-specific distance between origin–destination pairs. The shifts from international aviation to trains were not analysed because the potential is lower

Table 6.1 Pkm "per km" shift from domestic aviation to trains (in %)

	2015	2020	2025	2030	2035	2040	2045	2050
2.0 °C scenario	0	0	0.5–0.75	0.7–1.1	1–1.7	1.4–2.5	1.9–3.8	2.7–5.7
1.5 °C scenario	0	2	4	6	8	10	12	14

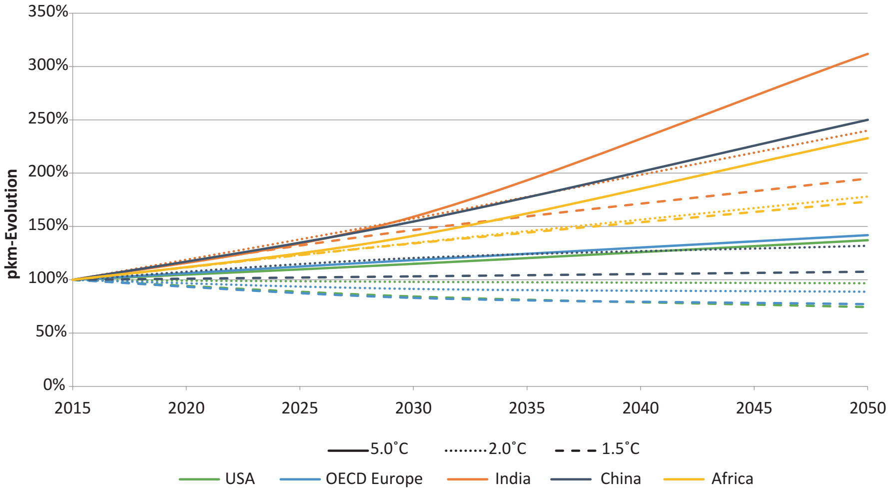


Fig. 6.22 Regional pkm development

(although not zero). The maximum global shift from domestic aviation to trains will be stronger in the 1.5 °C Scenario than in the 2.0 °C Scenario.

In the urban context, investments in public transit systems and limitations on the use of private cars are cornerstones of a more-energy-efficient transport system. The increased use and integration of homes and offices, and video conferencing can reduce traffic. With further urbanization, two- and three-wheel vehicles are suitable for travelling small distances quickly. A shift to small and medium cars and away from larger cars and SUVs will also allow lower energy intensity. Whereas occupancy rates remain steady for the passenger car sector in the 2.0 °C Scenario, in the 1.5 °C Scenario, we assume a significant increase in occupancy rates. Ultimately, pkm will stabilize, whereas vehicle–km (vkm) will decline in response to incentives such as high-occupancy vehicle lanes and novel ride-sharing services.

Figure 6.22 shows the development of pkm in all scenarios for sample world regions. In the 2.0 °C Scenario, pkm in the OECD countries will predominantly remain on the same level in 2050 as in 2015 due to saturation and sufficiency effects. In all the other world regions, we project a growth in pkm, reflecting economic catch-up processes in the developing world induced by increases in population and

GDP. As can be seen for the 1.5 °C Scenario, India, which represents a strongly growing economy, will double its pkm by 2050, whereas OECD areas, such as the USA and Europe, will experience a decline. Although China is expected to experience continuous economic growth over the next few decades, pkm will rise slowly compared with that in the 5.0 °C Scenario.

Pkm in absolute numbers in 2050 will be highest in the 5.0 °C Scenario. It will also increase in the 2.0 °C and 1.5 °C Scenarios, but at a slower rate (Figs. 6.23 and 6.24).

Looking more closely at the 2.0 °C Scenario, the transport modes will evolve differently in the world regions, both quantitatively and in relative terms (Fig. 6.25) due to the diverse mobility patterns. For example, Africa has a high bus share in total pkm today, whereas OECD Europe has a high passenger car share (LDV), but pkm must decrease by 2020 and in subsequent years to meet the CO_2 reduction targets because fleet electrification will not be able to keep up. In parallel, rail pkm

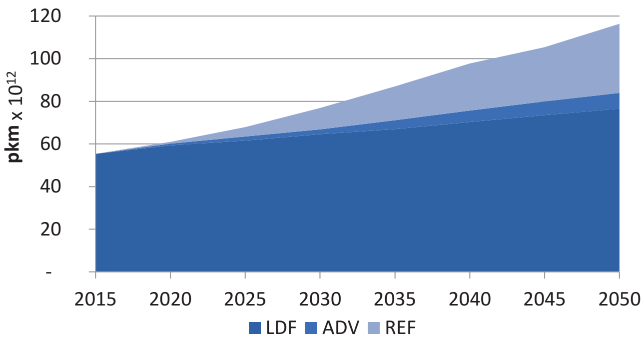


Fig. 6.23 World pkm development in all scenarios

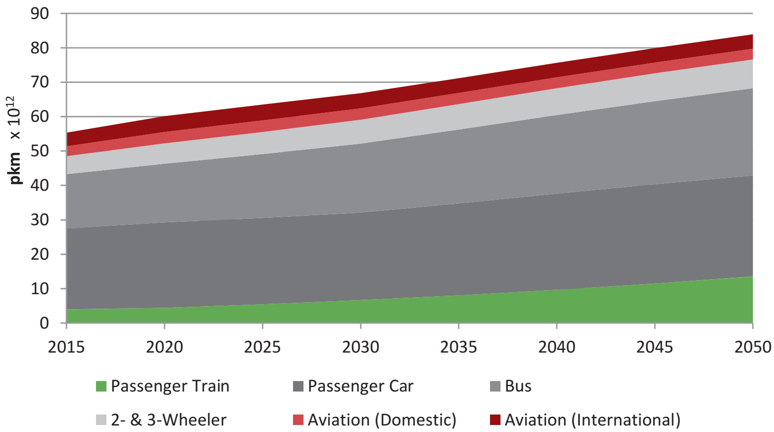


Fig. 6.24 World pkm development in the 2.0 °C Scenario

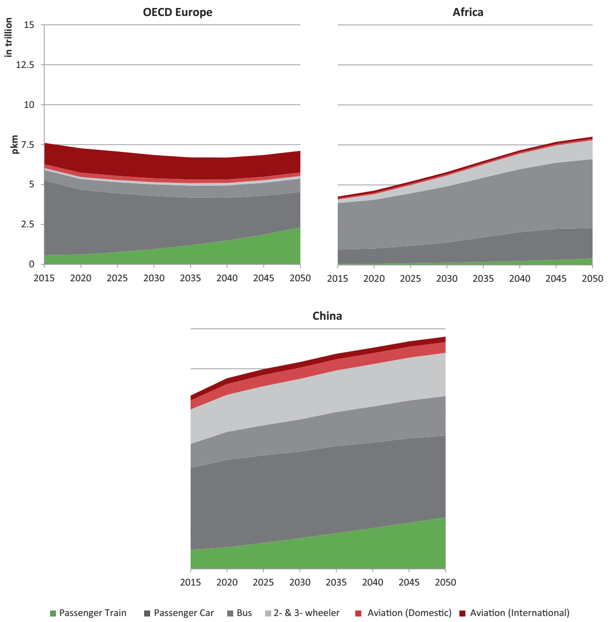


Fig. 6.25 Pkm development in OECD Europe (*left*) Africa (middle), and China (*right*) in the 2.0 °C Scenario

will increase strongly until 2050 and this will compensate, in part, the decline in passenger car pkm. Population and GDP are very likely to catch up in Africa and will result in a sharp rise in mobility demand. We project that most of this rise to be covered by informal and formal public transport systems, with buses and minibuses. In China, the pkm split among modes is more balanced. All modes are projected to rise in pkm in the future.

6.4.2 Freight Transport Modes

Total freight activity is modelled to increase strongly in the 5.0 °C Scenario and more slowly in the 2.0 °C Scenario (Fig. 6.26). In the 1.5 °C Scenario, freight transport activity in 2050 is projected to remain at the 2015 level. Freight intensity will stagnate or decrease in the 1.5 °C Scenario in the OECD countries and increase in other regions, such as China and India (Figs. 6.26 and 6.27).

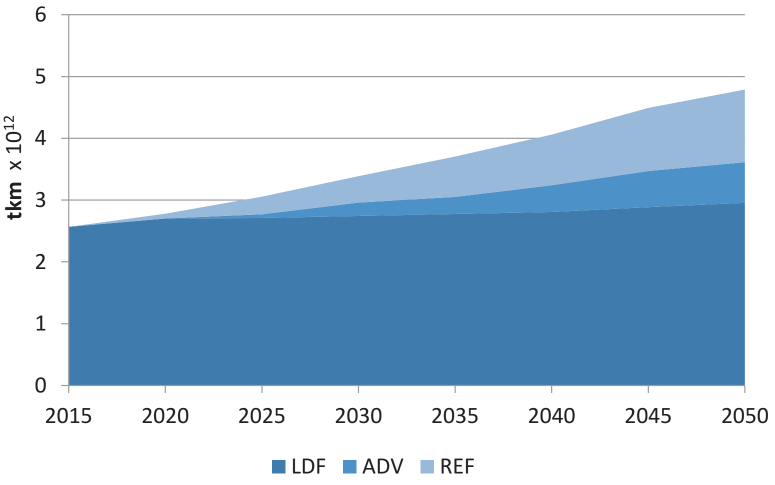


Fig. 6.26 World tkm development in all scenarios

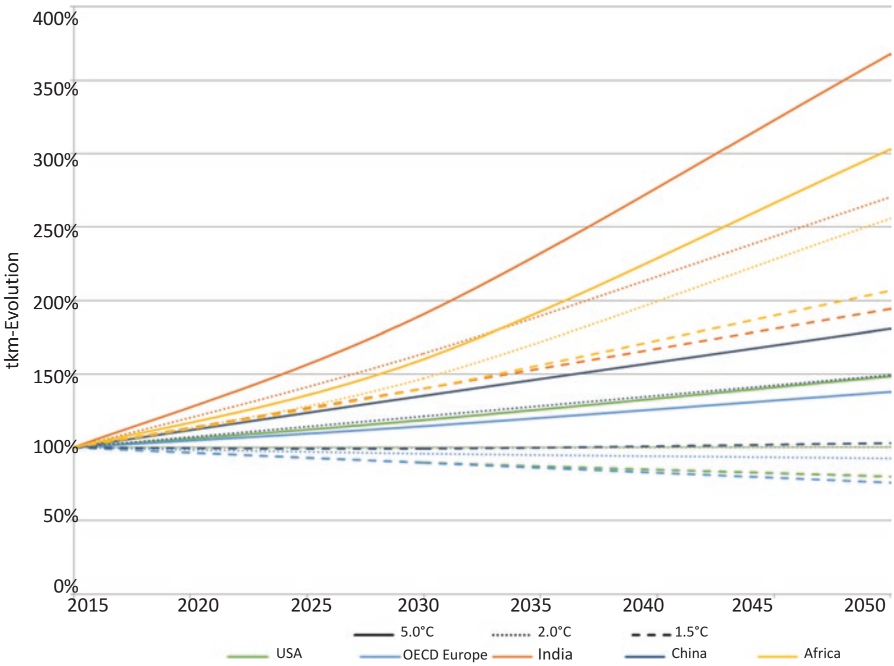


Fig. 6.27 Regional tkm development

Table 6.2 Global tkm shifts from truck to train in the 2.0 °C and 1.5 °C Scenarios (in %)

	2015	2020	2025	2030	2035	2040	2045	2050
LFT (2.0)	0	0	0	0	0	0	0	0
LFT (1.5)	0	1	4	6	7–8	9–10	11–12	13–14
MFT (2.0)	0	1	2	3	4	5	6	7
MFT (1.5)	0	2–3	5–10	9–14	13–18	13–19	13–19	13–18
HFT (2.0)	0	3	5	8	10	13	15	18
HFT (1.5)	0	2–3	8–18	12–22	16–27	16–27	16–27	18–27

We modelled the shift from high-energy-intensity modes to low-energy-intensity modes, especially from road to rail freight. This will require substantial investments in additional rail infrastructure. Table 6.2 shows the assumed global tkm shift from truck to train in the 2.0 °C and 1.5 °C Scenarios. Heavy freight trucks (HFT) are more likely to operate over long-haul distances, and are therefore more suitable for the shift to rail freight than light freight trucks (LFT) or medium freight trucks (MFT). In the 2.0 °C Scenario, we assume an average shift of 18% for HFT, whereas in the 1.5 °C Scenario, the shift is projected to reach up to 27%. The ramp-up of shift potential is slow, because the provision of rail and terminal infrastructures and rolling stock will require considerable time.

We modelled tkm for truck (road) and rail freight transport. In the 5.0 °C Scenario, transport activity is projected to increase clearly until 2050. In the 2.0 °C and 1.5 °C Scenarios, this increase will be slower and the tkm on rail will exceed the road tkm in numbers by 2050 (Fig. 6.28).

In the 2.0 °C Scenario, road tkm will decrease in the OECD countries and stagnate or increase slightly in China (Fig. 6.29). Rail tkm is projected to increase in all other world regions (Fig. 6.29). Rail tkm in China will temporarily decrease slightly because of an anticipated medium-term decline in coal transport (Fig. 6.30).

In 2015, rail's share of total tkm differed between regions, but will increase in the 2.0 °C Scenario in all regions except India, where road tkm will increase more than rail tkm (Fig. 6.31).

Energy Scenario Results

Our scenario modelling involves merging the transport performance for all modes and powertrains with specific energy demands, and yields the accumulated demands for electricity, hydrogen, gas, and liquid fuels across all world regions between 2015 and 2050. The transport energy scenario results are outlined in Chap. 8.

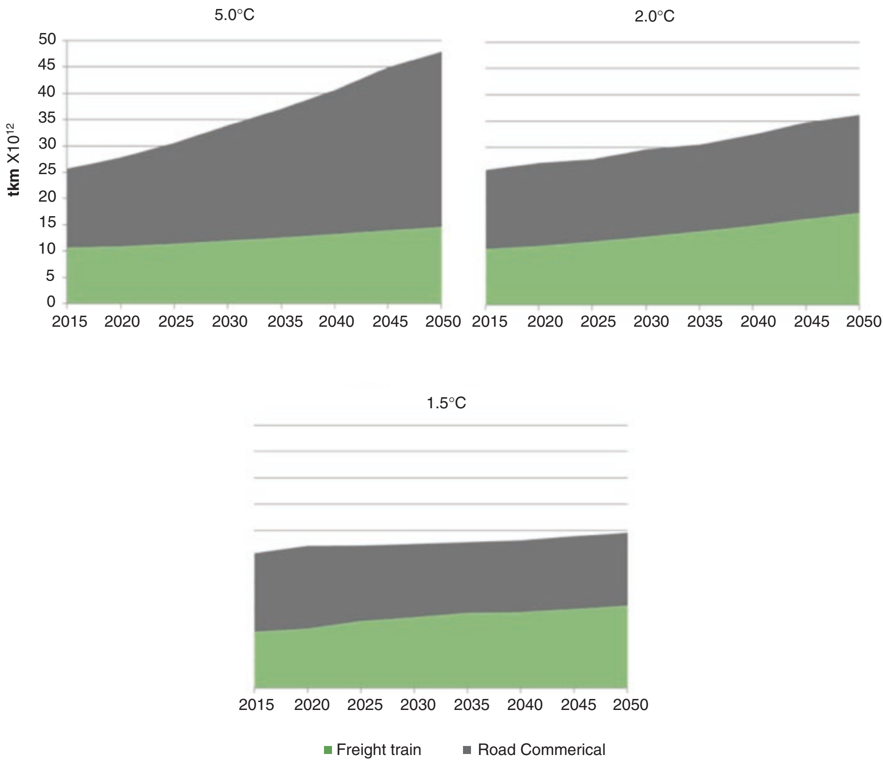


Fig. 6.28 World tkm development in the 5.0 °C, 2.0 °C, and 1.5 °C Scenarios

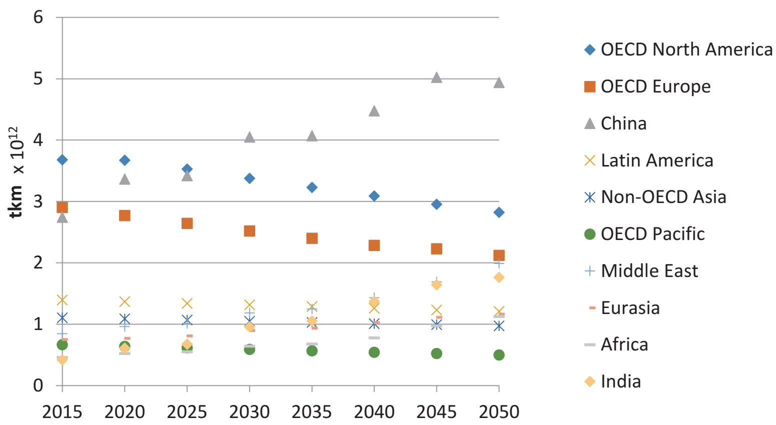


Fig. 6.29 Road tkm in the 2.0 °C Scenario

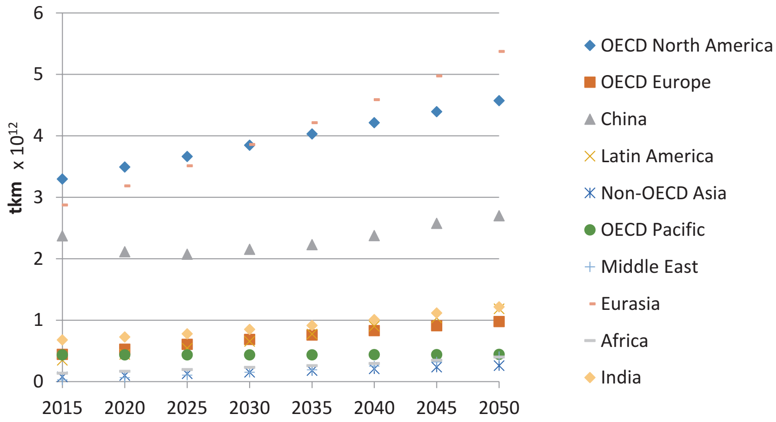


Fig. 6.30 Rail tkm in the 2.0 °C Scenario

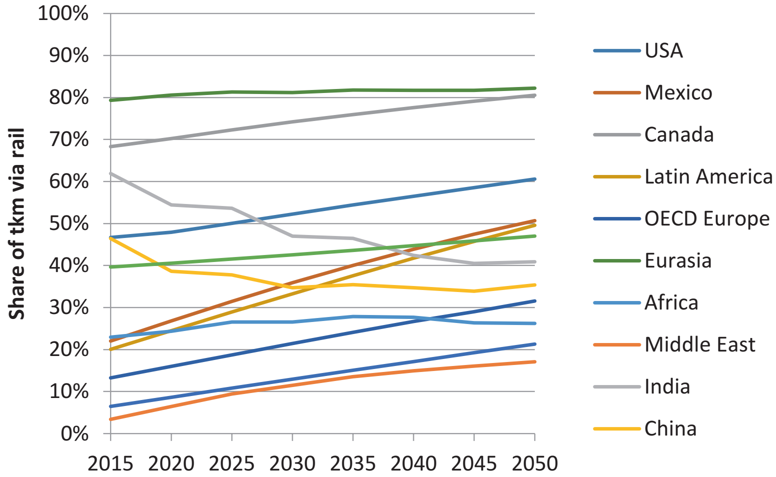


Fig. 6.31 Share of rail tkm in total rail + road tkm in the 2.0 °C Scenario

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