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The Role of Rail in Decarbonizing Transport in Developing Countries

MARTHA LAWRENCE AND
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MOBILITY AND
TRANSPORT
CONNECTIVITY SERIES

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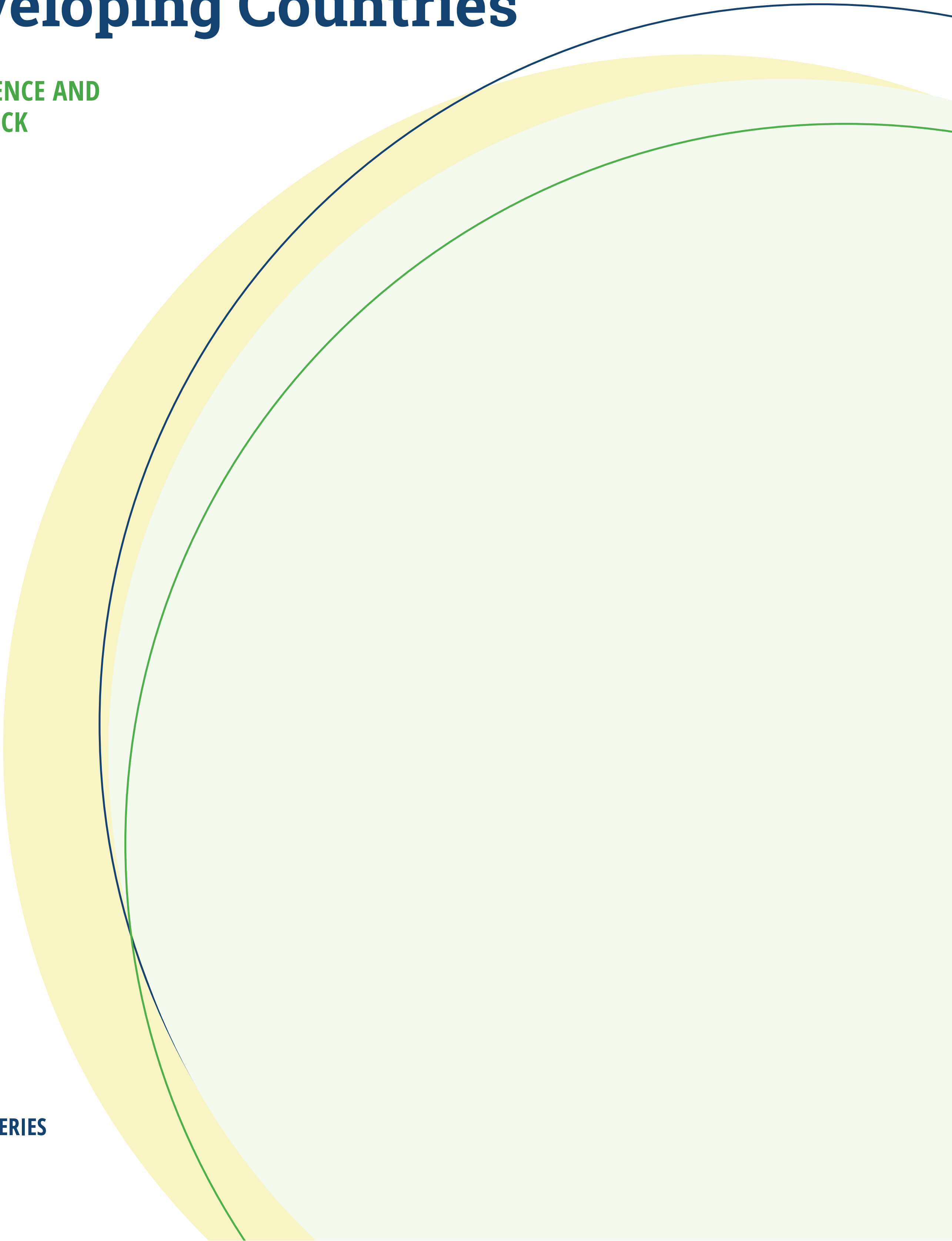

MOBILITY AND
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Foreword

Transport is an imperative for economic and social development. It is the physical, social, and economic network that connects people to opportunities, goods to markets, and communities to prosperity. Improving the quality of transport infrastructure and services can help emerging economies address poverty and reduce inequality.

As emerging economies invest in their transport systems, they are faced with a difficult decision: Do they follow the traditional development of fossil-fuel powered, road-vehicle dependent transport systems—despite the now clear environmental consequences—or do they forge a new development path for the transport sector consistent with global sustainable development and climate goals? While the policies, infrastructure, and technologies that make up the traditional development pathway for the transport sector might be well defined and present the path of least resistance, the many consequences of road vehicle dependent transport systems—including social exclusion, traffic fatalities and injuries, local air pollution, and the emissions of climate-warming greenhouse gases (GHGs)—show this trajectory to be too costly to continue to replicate.

While more complex, a development trajectory that encourages multimodal and integrated transport systems could prove better for economic and social development while also contributing to climate action. Emerging economies with less mature transportation systems have the flexibility to explore new ways to leverage more sustainable infrastructure, policies, and technologies to leapfrog the transport system development of higher-income countries and limit the sector's GHG emissions before they grow. By pursuing a low-carbon transport development trajectory, emerging economies can avoid lock-in to traditional, high-externality transport systems and circumvent the expensive retrofitting and replacing process that higher-income countries will be experiencing in the next few decades.

The World Bank's Decarbonization of Transport flagship activity brings together the expertise of numerous international specialists and World Bank staff to identify and characterize low-carbon transport system development pathways for lower-income countries. Starting from the economic and social development goals of emerging economies, the flagship activity sets out to define policy actions, infrastructure investments, and technologies that can help build safer, more efficient, more inclusive, more resilient—and also greener—transport systems. The flagship activity identifies the fundamental challenges faced by passenger and freight transport systems in low- and middle-income countries and key "win-win" actions for development and climate action in the transport sector.

Nicolas Peltier
Director, Transport Global Practice
The World Bank

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This report was developed as part of the World Bank's Decarbonization of Transport flagship activity led by Cecilia Briceno-Garmendia (Lead Economist) and Bianca Bianchi Alves (Senior Transport Specialist) with guidance from Nicolas Peltier (Director, Transport Global Knowledge Unit) and Binyam Reja (Practice Manager, Transport Global Knowledge Unit). Sara Sultan, Jonathan Davidar, Leszek Tymoteusz Zemke, Erin Scronce, and Xavier Bernard Leon Muller provided invaluable communications and dissemination support. Kara Watkins edited the report and Oleksiy (Alex) Manuilov designed the report.

About the Authors

Martha Lawrence is the Leader of the Railway Solutions Area and Co-Leader of the Global Solutions Area on Logistics at the World Bank. She had been a team leader and technical expert for the World Bank's railway lending and technical assistance programs in China, Europe, India, Sub-Saharan Africa, and Central Asia. She has over 40 years of experience in the railway sector, with extensive knowledge in railway restructuring, railway finance, and transport regulation. Ms. Lawrence led the development of the World Bank's resource on railway reform: *Railway Reform: A Toolkit for Improving Rail Sector Performance*. She is an author of numerous World Bank reports on railways, such as *Railways in Developing Countries: A Global Review, Modern Railway Services in Africa: Building Traffic—Building Value, China's High Speed Rail Development, and Attracting Capital for Rail Development in China*. She has prepared business, restructuring, and financing plans for railways worldwide and advised private sector investors on over US$8 billion in structured lease financing of transit rolling stock and infrastructure. Ms. Lawrence holds a BA in economics from Northwestern University and an MBA in finance and transportation management from Northwestern University.

Richard Bullock has over 40 years of experience in the railway sector, covering costing and pricing, project analysis, railway restructuring, and regulatory issues. He has worked on over 50 railways worldwide. Before becoming an independent consultant, Mr. Bullock served as a director of Travers Morgan Australia and, in addition to the World Bank, has worked on projects for several other international institutions. Mr. Bullock has an MA in mathematics from Cambridge University and an MA in operational research from Brunel University.

Abbreviations and Acronyms

°C	degrees Celsius
CO_2e	CO_2 equivalent; describes all greenhouse gases in a common unit. For any combination of types of greenhouse gas, indicates the amount of CO_2 which would have the equivalent global warming impact.
CNG	compressed natural gas
COPERT	Computer Program to calculate Emissions from Road Transport
DEFRA	Department for Environment, Food and Rural Affairs (United Kingdom)
DMU	diesel multiple-unit passenger train
EMU	electric multiple-unit passenger train
EC/EU	European Commission/European Union
FHWA	Federal Highways Administration (United States)
g CO_2e	grams of carbon dioxide equivalent
GHG	greenhouse gas
GR	Georgian Railways
gtkm	gross ton-kilometer, transport of 1 metric ton of goods+equipment for 1 kilometer
HFO	heavy fuel oil
HS2	high-speed line in the United Kingdom
HSR/HST	high-speed railway/high-speed train
IEA	International Energy Agency
IRI	international roughness index
ITF	International Transport Forum
JICA	Japan International Cooperation Agency
KCJ	Kereta Api Indonesia Commuter Jabotabek
KWh	kilowatt-hour
LCE	life-cycle emissions
LNG	liquified natural gas
LPG	liquified petroleum gas
MJ	megajoule
MT	Mato Grosso
MU	multiple-unit passenger train
ntkm	net ton-kilometer; transport of 1 metric ton of goods for 1 kilometer
pkm	passenger-kilometer
PKPE	Polskie Koleje Państwowe Energetyka (energy subsidiary of Polish Railways)
PR	Pakistan Railways

PTKAI	PT Kereta Api Indonesia
RFI	radiative forcing index
RSSB	Rail Standards and Safety Board (UK)
SP	Sao Paulo
TEU	twenty-foot equivalent unit (container)
tkm	ton-kilometer, transport of 1 metric ton 1 kilometer
TOD	transit-oriented development
TREMOD	transport emissions model (Germany)
TTW	tank-to-wheel, measured in metric tons
UIC	International Union of Railways
U.K.	the United Kingdom
U.S.	the United States
wh/kg	watt-hour per kilogram
WTW	well-to-wheel, measured in metric tons

Note
Throughout the report, the word 'ton' is used to indicate metric tons or tonnes (equivalent to 1000 kilograms) unless otherwise specified.

Executive Summary

Railways support green development. Governments in developing countries seek to provide transport infrastructure and services to enable inclusive economic development. Rail offers low-cost transport for high-volume corridors with a small land footprint, enhancing mobility and logistics for development. Rail is also a green mode. Thus, in appropriate markets, railways can deliver the efficient mobility and logistics economies need, with a low carbon footprint. Considering railways when developing the transport network can help countries create green development pathways.

Transport decarbonization is critical for mitigating climate change through near-term actions and long-term transitions. The long-term aim is to achieve zero direct emissions from the transport sector by 2050, in parallel with decarbonization of the energy sector. At the same time, because greenhouse gas (GHG) emissions persist in the atmosphere and contribute to climate change, minimizing the cumulative GHG emissions created on the transition path to zero is critical for keeping to the 1.5 degrees Celsius (°C) target. The challenge for each country is to craft its own whole-economy path toward these goals while meeting its development needs in and beyond the transport sector.

Railways have an important role in reducing transport emissions, while also supporting economic development and increased mobility. Historically, economic development has been strongly correlated with increases in transport demand and transport related GHG emissions. For developing countries to continue to grow in an era of climate crisis, growth in transport emissions must be decoupled from economic development. Any scenario for stabilizing climate change around the target of 1.5°C above preindustrial temperatures requires addressing the anticipated growth in transport emissions in developing countries. Rail, as an energy-efficient mode, can contribute to this effort. This report examines the opportunities and challenges of using rail to decarbonize transport in suburban and intercity passenger as well as intercity freight markets in developing countries.

Structured around the *avoid–shift–improve framework*, this report provides a systematic review of potential contributions that railways can make to development and climate goals. *Avoid* refers to measures that reduce passenger- or freight-kilometers traveled, *shift* refers to measures that change travel from more polluting to less-polluting modes, and *improve* refers to improvement of vehicles, fuels, and/or operational efficiency within a mode.

Because rail is relatively energy efficient, its primary contribution toward mitigating climate change comes from shifting transport from less energy efficient modes, such as road and air, to railways. Rail also supports *avoid* strategies when rail stations serve as the hubs for more compact urban and logistic design—for example, when transit-oriented development encourages densification of urban and suburban areas. Furthermore, a variety of rail technologies, alternative fuels, and operational improvements can *improve* on rail's already low GHG emissions, including through traction electrification coupled with green energy production and through technologies that maximize utilization and reduce inefficient empty equipment movements. For railways, the GHG savings from *shift* are higher than the savings from *improve*, simply because improvements for rail can only chip away at already-low emissions from rail transport.

Shifting traffic from road or air to rail generates significant climate benefits, even when the rail is not yet powered by clean sources of energy or fuels. Although zero net emissions by 2050 represents a key target—requiring complete adoption of noncarbon fuels or energy sources—keeping emissions to a minimum between now and 2050 is also critical because of their cumulative long-term impact. Full transition of railway traction to electrification or other non-carbon fuel will take some years. Even in the interim, moving traffic from air or road to diesel-powered rail will reduce emissions by 70 percent or more per passenger-kilometer (pkm) or ton-kilometer (tkm) and can be an important part of the transition path to zero emissions.

Shifting traffic to rail often requires improvement in physical infrastructure. A reasonable standard of infrastructure is necessary for trains to operate reliably and economically, and improved terminal facilities are needed to provide intermodal access. Improved service is also necessary to induce modal shift. Governments can play an important role by supporting such developments in infrastructure and services.

Modal shift is only possible in rail competitive markets. For passengers, rail competitive markets typically include the following: (1) urban and suburban corridors of approximately 80 kilometers or less (about one hour of travel time); and (2) intercity passenger corridors up to about 500 kilometers for conventional passenger rail and 1,200 kilometers for high-speed rail (about three hours of travel time). For freight, rail competitive markets are determined by the volume of goods movement, the commodity type (bulk or nonbulk), the distance (longer is more rail competitive) and whether the pick-up and delivery are at rail-served points or require transfer to truck for last-mile connectivity.

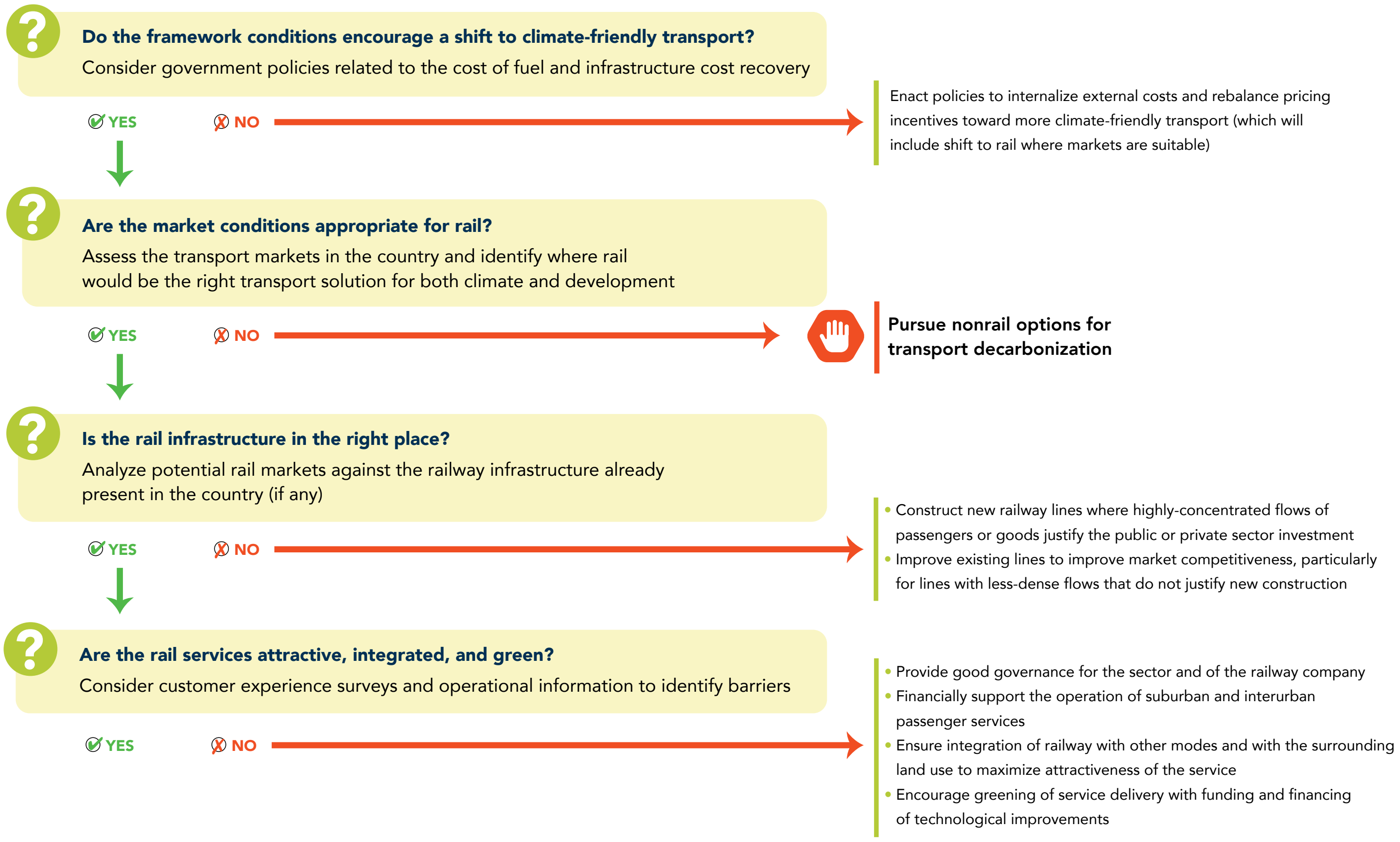
The largest potential improvement in rail's GHG emissions come from electrification of diesel operations, assuming the electricity source is green. However, fixed electric power supply infrastructure needs a minimum traffic density (generally from 5 to 10 million gross tons) for electrification to be commercially viable, because of its capital cost and recurrent maintenance costs. Only a few railways in developing countries carry this level of traffic. The development of battery-electric and hydrogen traction, which are more suited to low density operations, is occurring at a very fast rate for both passenger and freight service. These alternative types of traction are already being tested in-service and should be in widespread use by 2035 or 2040. Many diesel locomotives can also be retrofitted with battery and/or hydrogen fuel cells at mid-life overhaul, thus avoiding a lock-in to diesel energy.

The transition away from diesel traction needs to be managed in coordination with developments in the power sector. Many developing countries face difficulties in generating sufficient power, distributing it reliably, and transitioning away from fossil-fueled power. The benefit of a transition in rail to alternative energy sources (for example, electricity or hydrogen) depends on the alternative energy sources being available, reliable, and green. Thus, the timing of rail's transition to alternative transport energy sources must dovetail with developments in the energy sector. Countries that invest in alternative transport energy sources ahead of the energy sector transition will only realize the full potential of the transition to zero emissions once the clean energy is available.

Railways have other technical opportunities to reduce energy consumption and GHG emissions. A recent innovation has been the development of driver assistance systems, linked to both energy-efficient driving techniques and advising drivers of potential network problems. Other opportunities range from improving the carrying capacity of wagons to using network models to reduce empty backhauls.

The right mix of interventions for maximizing the contribution of rail to transport decarbonization will vary in each country. The process for determining the appropriate mix might follow the series of questions shown in figure E.1. Such interventions will help railways continue to play an important role in social and economic development and the greening of transport.

Figure E.1. Policy Process and Key Questions for Determining Rail's Role in Transport Decarbonization in a Given Country



Do the framework conditions encourage a shift to climate-friendly transport?
Consider government policies related to the cost of fuel and infrastructure cost recovery

Enact policies to internalize external costs and rebalance pricing incentives toward more climate-friendly transport (which will include shift to rail where markets are suitable)

Are the market conditions appropriate for rail?
Assess the transport markets in the country and identify where rail would be the right transport solution for both climate and development

Pursue nonrail options for transport decarbonization

Is the rail infrastructure in the right place?
Analyze potential rail markets against the railway infrastructure already present in the country (if any)

- Construct new railway lines where highly-concentrated flows of passengers or goods justify the public or private sector investment
- Improve existing lines to improve market competitiveness, particularly for lines with less-dense flows that do not justify new construction

Are the rail services attractive, integrated, and green?
Consider customer experience surveys and operational information to identify barriers

- Provide good governance for the sector and of the railway company
- Financially support the operation of suburban and interurban passenger services
- Ensure integration of railway with other modes and with the surrounding land use to maximize attractiveness of the service
- Encourage greening of service delivery with funding and financing of technological improvements

Source: Original figure produced for this publication

Chapter 1: Railways—A Green Transport Mode

Key Messages from Chapter 1

- Rail—whether diesel or electric powered—is more energy efficient and generates lower emissions per passenger or ton of goods moved than almost all road and air modes.

- Therefore, rail's primary role in decarbonizing the transport sector is in serving passenger and goods traffic that would have otherwise traveled by more carbon-intensive modes (*shift*). In typical circumstances, approximately 80 percent of the potentially achievable savings come from mode shift. Attracting a passenger from a two-person car to a mainline diesel train would save about 84 grams CO_2e per kilometer, while shifting one ton-kilometer of freight from heavy truck to diesel bulk rail would save approximately 55 grams CO_2e (see appendix C for calculations).

- While modal shift to rail has the greatest impact on GHG emissions, technical and operational improvements to rail systems themselves can bring additional climate benefits (*improve*). Electrifying the rail movements would save an additional 13 to 19 grams CO_2e per passenger-kilometer or ton-kilometer, assuming an overall emissions factor of the electricity grid of 400 or 200 grams CO_2e per kilowatt-hour respectively.

- Consequently, modal shift should be strongly encouraged in markets where rail can be competitive. By supporting the most energy-efficient mode, countries will reduce GHG emission as well as energy requirements, while continuing to foster economic development and provide high-quality access for people and goods.

Decarbonizing transport is critical for mitigating climate change. The transport sector currently generates 20 percent of global greenhouse gas (GHG) emissions.[1] Transport emissions have grown faster than other sectors over the past 50 years and are predicted to grow by as much as 60 percent by 2050, if action is not taken to mitigate them. While transport GHG emissions in developing countries are lower than in developed countries, they are growing at a much faster rate (ITF 2019). Any scenario for stabilizing climate change around the target of 1.5 degrees Celsius (°C) above preindustrial temperatures requires addressing the anticipated growth in transport emissions in developing countries.

Transport decarbonization needs to satisfy two climate goals. The long-term aim is to achieve zero direct emissions by 2050, in parallel with decarbonization of the energy sector. At the same time, because GHG emissions persist in the atmosphere and contribute to climate change, minimizing the cumulative GHG emissions created on the transition path to zero is critical to keep to the 1.5°C target. The challenge for each country is to craft its own path toward these goals while meetings its development needs.

Railways have an important role in reducing transport emissions, while also supporting economic growth and increased mobility. Historically, economic growth has been strongly correlated with increases in transport demand and in transport related GHG emissions. For developing countries to continue to grow in an era of climate crisis, growth in transport emissions must be decoupled from economic growth. Rail, as an energy-efficient mode, can contribute to this effort. This report examines the opportunities and challenges of using rail to decarbonize transport in suburban and intercity passenger as well as intercity freight markets in developing countries.

The “avoid–shift–improve” framework provides a systematic review of potential contributions from rail. “Avoid” refers to measures that reduce passenger-kilometers or freight ton-kilometers traveled, “shift” refers to measures that change travel from more polluting to less-polluting modes, and “improve” refers to improvement of vehicles, fuels, and/or operational efficiency within a mode.

Because rail is relatively energy efficient, its primary contribution toward mitigating climate change comes from *shifting* transport from less energy efficient modes, such as road and air, to railways. Rail also supports “avoid” strategies when rail stations serve as the hubs for more compact urban and logistic design—for example, when transit-oriented development encourages densification of urban and suburban areas. Furthermore, a variety of rail technologies, alternative fuels, and operational improvements can “improve” on rail’s already low GHG emissions, including through traction electrification coupled with green energy production and through technologies that maximize utilization and reduce inefficient empty equipment movements. For railways, the GHG savings from “shift” are higher than the savings from “improve,” simply because improvements for rail can only chip away at already-low emissions from rail transport.

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[1] GHG emissions include emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (NO_2) and fluorinated (F-) gases, all expressed as CO_2-equivalents. In the transport sector, the vast majority of GHG emission come from CO_2. Proportions are calculated from total global emissions including land use and forestry. The 20 percent includes both domestic and international transport, including fuel use in aviation and shipping (about 3 percent). Historical GHG emissions data from 1990 through 2019 collected online from Climate Watch Data: https://www.climatewatchdata.org/ghg-emissions/?end_year=2019&start_year=1990.

Rail Sector Emissions

Calculations of railway life-cycle emissions (LCE) aim to include all GHG emissions associated with a particular operation, from the materials used in production through to its end use. This includes emissions from:

- Planning and design
- Infrastructure construction
- Rollingstock manufacture
- Operations and maintenance
- Scrapping and disposal

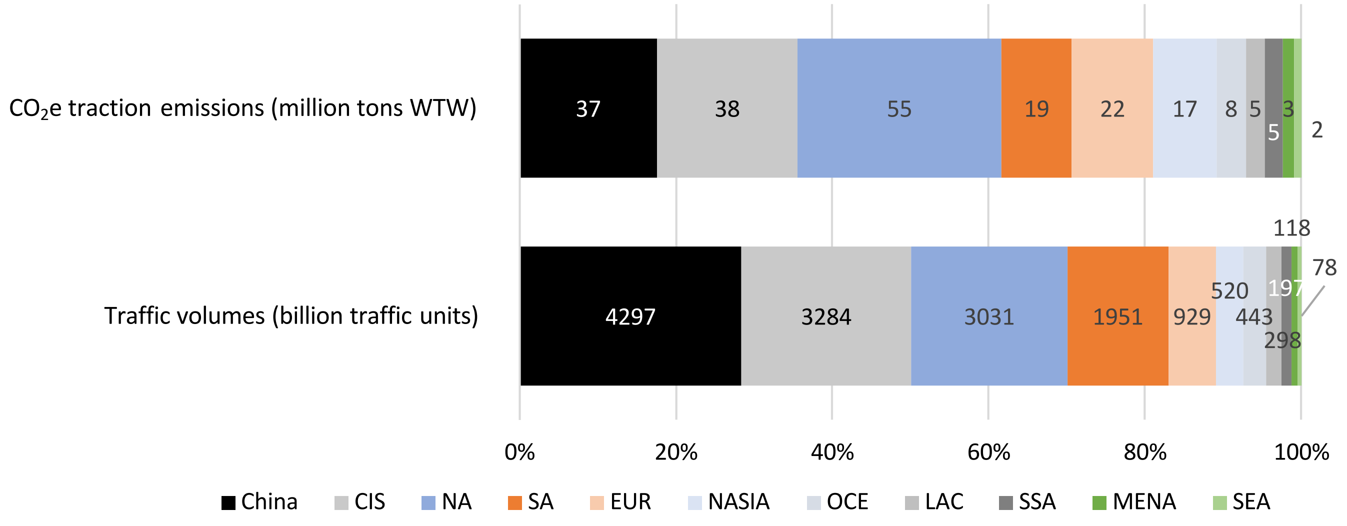
In railways, the largest contributions to total emissions come from infrastructure construction and operations and maintenance. Infrastructure construction emissions are large in magnitude, especially when considering the embedded carbon in materials such as concrete and steel. Conversely, operations and maintenance emissions are much smaller in magnitude, but accrue continuously over the life of the railway for a large cumulative effect. Emissions from planning and design as well as scrapping and disposal of assets are relatively small and generally only occur once during a railway project's long life. Other activities, such as rollingstock manufacturing or infrastructure renewal, happen at periodic intervals. LCE analyses typically amortize the emissions related to capital goods over the life of the asset—for example, rollingstock over lives from 20 to 40 years and infrastructure over lives from 60 to 100 years.

During operations, the rail sector generates GHG emissions from both traction and facilities. About 85 percent of all operational emissions are associated with traction. The remainder are associated with infrastructure operations (for example, signaling, power switches, and switch heating in winter), together with stations and other buildings. See appendix C for more details.

Worldwide GHG emissions from rail traction amount to approximately 210 million tons per year on a well-to-wheel (WTW) basis. North America, the Commonwealth of Independent States (CIS), China, and South Asia are both the largest emitters and the regions of the world with the highest rail traffic volumes. Figure 1.1 shows the GHG emissions from traction and the related traffic units by region.

Traffic mix, traffic density, traction type, and the emissions factor of electricity all influence the level of traction emissions. Freight trains tend to have lower emissions per unit than passenger trains because of slower speeds and less frequent stops compared to suburban or regional services. High density flows are more efficient than low density flows. Electric power supply usually produces fewer GHG emissions than diesel, though the savings depend significantly on whether the electric power supply is clean or not.

Figure 1.1. Rail Traffic Volume, Well-to-Wheel Emissions, and Emissions per Traffic Unit by Global Region, 2018



Source: Original figure produced for this publication.

Note: CO_2e = carbon dioxide equivalent; WTW = well-to-wheel; CIS = Commonwealth of Independent States; EUR = European Union; LAC = Latin America and the Caribbean; MENA = Middle East and North Africa; NA = North America; NASIA = North Asia; OCE = Oceania; SA = South Asia; SEA = Southeast Asia; and SSA = Sub-Saharan Africa. Emissions from consumption of diesel fuel and electricity for traction are measured on a well-to-wheel (WTW) basis. Traffic units are ton-kilometer (tkm) and passenger-kilometer (pkm). For presentational purposes, the world has been divided into eleven regional groups as noted above.

The lowest emissions per traffic unit are in China, CIS, and India—all around 10 grams of carbon dioxide equivalent (g CO_2e) per traffic unit. These railways all have a high level of electrification, substantial freight traffic, and heavily loaded passenger and freight trains. In contrast, North American railways, which carry mostly freight and are primarily diesel operated, have per traffic unit emissions almost double those in China, CIS, and India (19 g CO_2e per traffic unit). Both Oceania (dominated by Australia) and Latin America (dominated by Brazil), whose railways mostly move freight and are diesel powered, have similar per traffic unit emissions to those in North America (17 g CO_2e per traffic unit). Sub-Saharan African railways (dominated by South Africa) have a freight-dominated traffic mix. The South African railways are mostly electrified; however, the electric energy supply depends on coal, which more than negates any emission benefits from electrification (24 g CO_2e per traffic unit). Europe and North Asia (Japan, Korea, and Taiwan) have relatively high emissions (24 and 33 g CO_2e) per traffic unit because their railways mostly provide passenger services, which—although heavily loaded and electrified—have much higher emissions per traffic unit than freight operations. The two remaining groups, MENA (largely Egypt) and Southeast Asia, carry a mix of passenger and freight with limited electrification, resulting in relatively high emissions (23 to 24 g CO_2e) per traffic unit.

Construction emissions can vary significantly between rail projects. The principal influence is the proportion of structures, such as bridges, viaducts, and tunnels. Because of their requirements for concrete and steel, and for electricity in the case of tunnels, constructing these structures generates emissions per kilometer five to ten times greater than for a simple at-grade line. In urban areas, underground stations also contribute significantly. Many high-speed and intercity lines have a significant proportion of structures and thus tend to have higher emissions per route-kilometer during construction. But when converted to emissions per passenger-kilometer or freight ton-kilometer, construction emissions are typically 5 to 10 grams of carbon dioxide equivalent per passenger-kilometer (g CO_2e/pkm), while typical operational emissions range from 12 to 48 g CO_2e/pkm. Further discussion of construction emissions is provided in appendix C.

Construction and operational emissions can be balanced through calcuation of the carbon payback period. This is the period after the investment necessary for operational savings in GHG emissions to offset the additional emissions generated from construction. Olugbenga, Kalyviotis, and Saxe (2019) found that the payback period of rail projects varied widely and concluded that 20 years is a typical payback period without distinction by type of line. Other sources, discussed in appendix C, give a range of values for specific types of line. All estimates are critically dependent on the assumptions regarding mode split and the future emission profile of other modes. Because construction emissions can be significant, construction emissions and payback period should be considered when planning any large infrastructure investments. Where railway lines already exist, the GHG savings from improved rail operations can be realized with modest construction GHG.

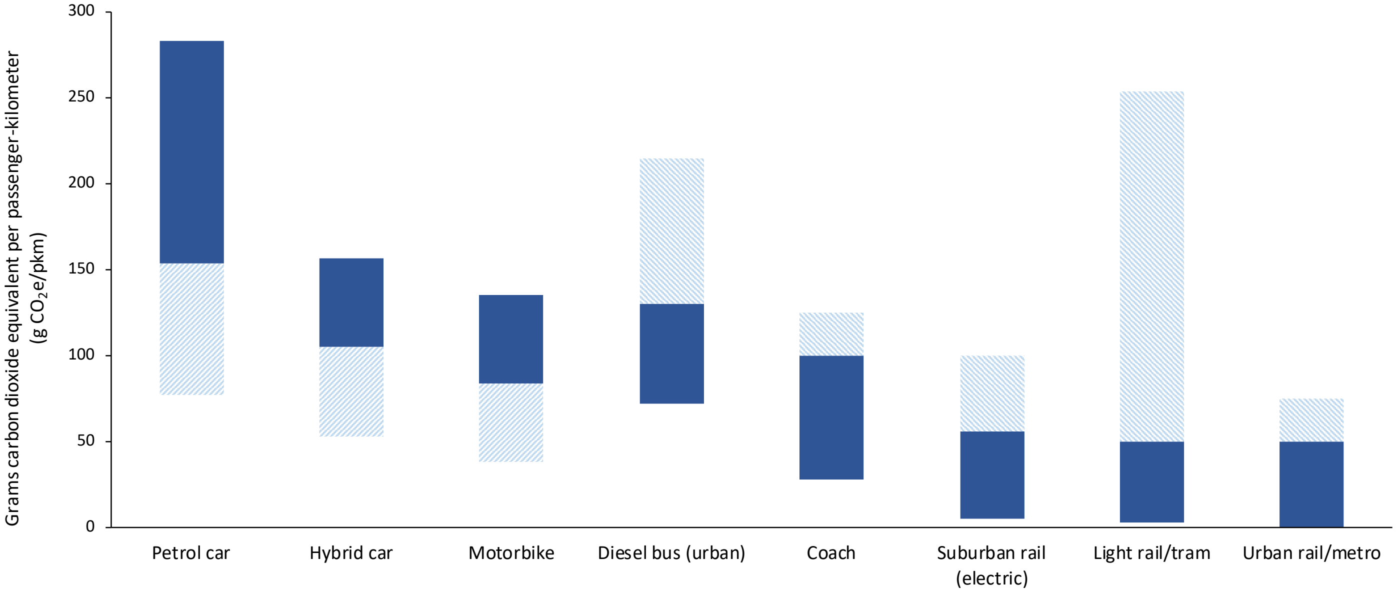
On most railways, operational emissions are much larger than the annual amortized construction emissions. The only exceptions are a few railways that produce very low operational emissions because they are electrified and supplied with low-carbon electricity, such as those in France, Georgia, or Norway.

Rail, Road, and Air Emissions

Rail operations—for suburban, intercity passenger and freight—emit only a fraction of the GHG emissions of most road- and air-based modes of transport, both in aggregate and on a per traffic unit basis. The International Energy Agency (IEA) estimates that, if all passengers and freight now carried by rail were to switch to other modes, carbon emissions from the transport sector would increase by 1.2 gigatons, *five times* the current level of rail emissions (IEA 2019, 15).

Suburban rail typically provides mobility in urban regions at far lower emission levels than competing road modes (typically one-third for traction-related CO_2e/pkm). Figure 1.2 shows typical ranges of emissions by mode for suburban passenger trips. As figure 1.2 shows, public transport is generally less-polluting than private transport. However, as indicated by the shading, the emissions per passenger-kilometer in any particular case are strongly influenced by occupancy of the vehicle.

Figure 1.2. Typical Traction-Related Emissions for Suburban Trips by Mode



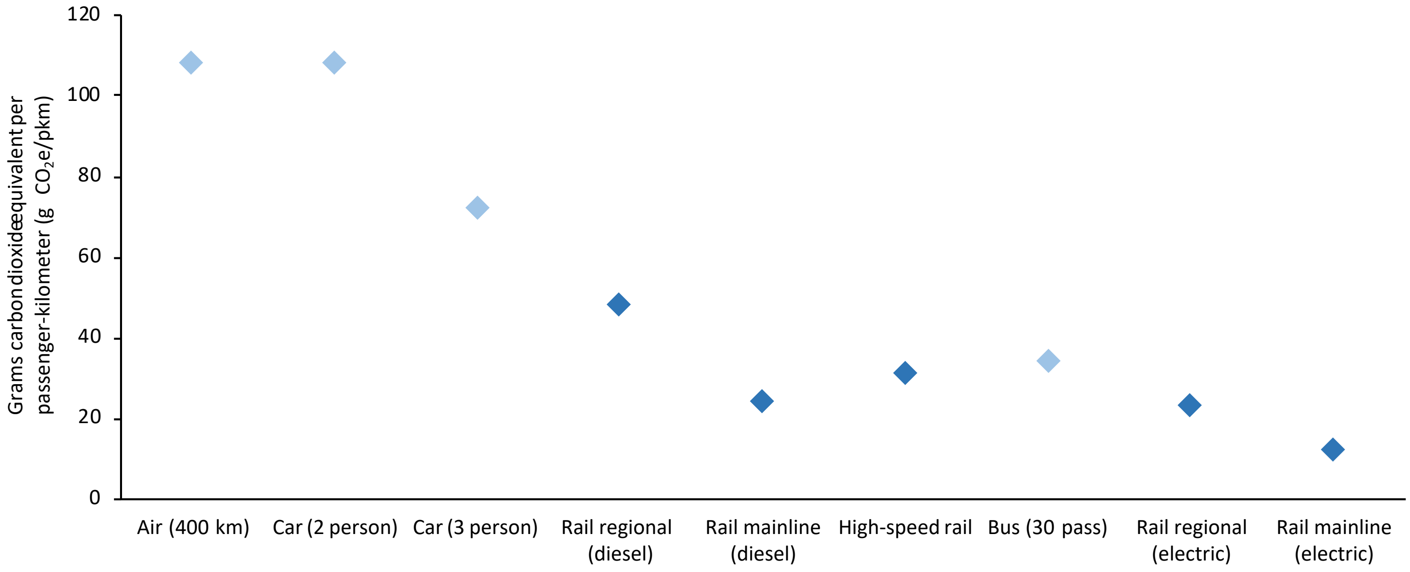
Source: DBEIS 2019; Hill et al. 2018; Gehlhaar 2016; Fabian and Gota 2009; Carbon Independent 2009; and Mizdrak et al. 2020, as compiled by Transport Strategy Centre (Imperial College London). See: https://www.imperial.ac.uk/transport-studies/transport-strategy-centre/applied-research/.

Note: Solid values cover typical operating conditions and are based on average occupancy for public transport. Actual value in any specific city will depend on operating conditions, passenger load for public transport, and–for electric modes–the carbon emission intensity of electricity. Shaded values show the impact of variations in passenger load. For example, the per passenger-kilometer emissions of low occupancy modes, such as cars and motorbikes, decrease if the number of passengers is increased, while the per passenger-kilometer emissions of public modes become greater if occupancy is poor. Shading also accounts for technology (for instance, small vs. average car or scooter vs. motorbike).

The emission produced by intercity passenger rail are likewise much lower than those from alternative road and air transport services. A generalized calculation of the WTW emissions by types of passenger rail service and for competing passenger modes, shows high-speed rail emissions are typically half to one-third the emissions of private automobiles, and one-third of air. Electrified intercity trains generate half the emission of diesel intercity trains (figure 1.3). The assumptions underpinning these estimates, including those shown in figure 1.3 and figure 1.4, are given in detail in appendix B and are typical of the different service types.

Similarly, rail freight generates much lower emissions than road-based modes. A generalized calculation of the WTW emissions by types of freight transport and for competing freight modes shows diesel-powered rail freight generates only a quarter to one-third of the GHG emissions produced by trucks. When electrified, the rail-related emissions would be even less (see figure 1.4). Container ships have lower emission per freight net ton-kilometer. However, where rail and container ships compete, such as in the China–to–Europe trade, the distance for rail is considerably less. As a result, the aggregate GHG emissions per container by ship are only about 20 percent lower than rail. Where available, inland waterway transport has comparably low emissions to rail.

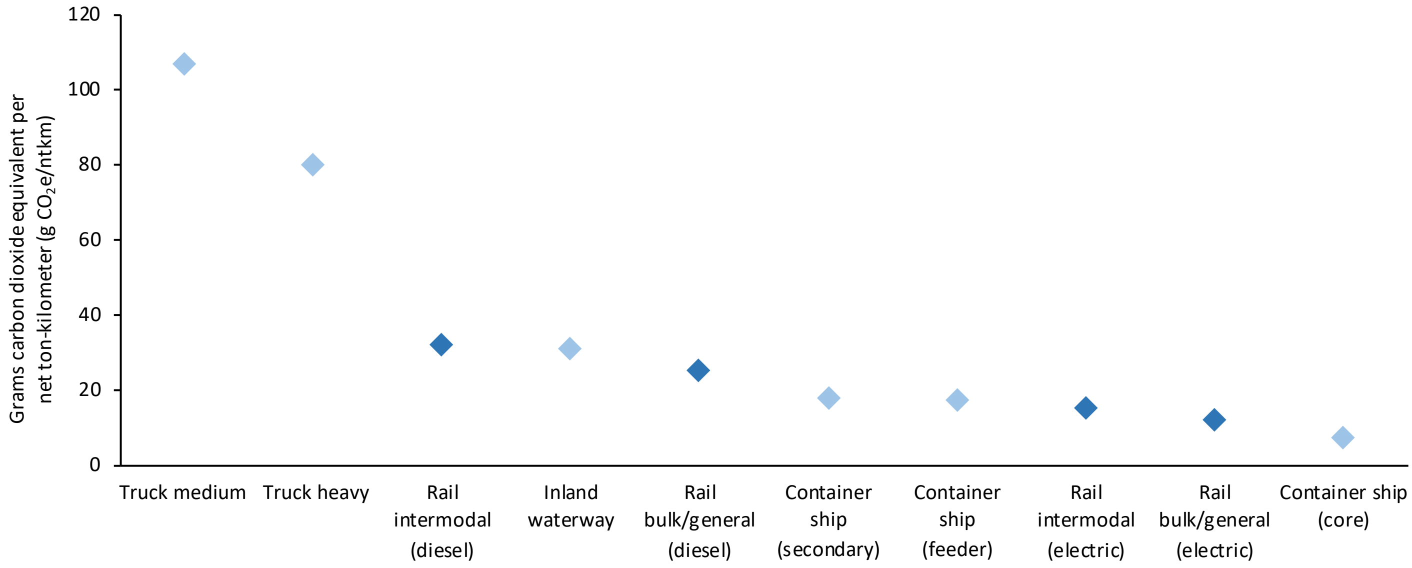
Figure 1.3. Typical Traction-Related Emissions for Intercity Passenger Trips by Mode



Source: Original figure produced for this publication.

Note: See appendix B for methodology. Data assumes carbon emissions of 400 grams per kilowatt-hour for electric modes.

Figure 1.4. Typical Traction-Related Emissions for Intercity Freight, by Mode



Source: Original figure produced for this publication.

Note: See appendix B for methodology. Data assumes carbon emissions of 400 grams per kilowatt-hour for electric modes.

The specific GHG emissions savings in any situation depends on the characteristics of both the rail and nonrail option. Important factors for rail include the following:

- Infrastructure: gradients, track curvatures, and track condition
- Rollingstock age and condition
- Speed of travel
- Directness of route
- Energy source (diesel or electric)
- GHG emissions from the electric energy source, if applicable
- Occupancy (a particularly important factor for suburban and intercity passenger services).

Investment, operational, and policy initiatives that increase occupancy of trains can generate significant savings. As is discussed in chapter 3, improving the quality of passenger trains in Georgia, for example, resulted in substantial increases in patronage, which created significant reductions per passenger kilometer in GHG emissions. Modernizing the wagon fleet to increase the ratio of net weight to gross weight, such as in Ukraine and in India, will also reduce the emissions per net ton-kilometer.

Reference

Carbon Independent. 2009. “Ferry Sources.” Database/calculator, updated January 2009 (accessed May 12, 2022), https://www.carbonindependent.org/sources_ferry.htm.

DBEIS (Department for Business, Energy & Industrial Strategy). 2019. “Greenhouse Gas Reporting: Conversion Factors 2019.” Statistics and other resources for research and analysis, Government of the United Kingdom, London. https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2019.

Fabian, Herbert, and Sudhir Gota. 2009. “CO_2 Emissions from the Land Transport Sector in the Philippines: Estimates and Policy Implications.” Paper presented at the 17th Annual Conference of the Transportation Science Society of the Philippines, Pasay, Philippines, September 4, 2009. http://ncts.upd.edu.ph/tssp/wp-content/uploads/2018/08/Fabian09.pdf.

Gehlhaar, Andreas. 2016. “Report from the Head of Environment of Deutsche Bahn: Facts and Figures on Environmental Protection in 2016.” Deutsche Bahn AG, Berlin. https://www.deutschebahn.com/resource/blob/6925828/f3c7c9bc0d0766230e64d0464f299b56/report_environmental-data.pdf.

Hill, Nikolas, Eugenia Bonifazi, Rebekah Bramwell, Eirini Karagianni, and Billy Harris. 2018. “2018 Government GHG Conversion Factors For Company Reporting: Methodology Paper for Emission Factors.” Final report, Department for Business Energy & Industrial Strategy (BEIS), Government of the United Kingdom. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/726911/2018_methodology_paper_FINAL_v01-00.pdf.

IEA (International Energy Agency). 2019. “The Future of Rail.” Technology report, IEA, Paris. https://www.iea.org/reports/the-future-of-rail.

ITF (International Transport Forum). 2019. *ITF Transport Outlook 2018*. Paris: OECD Publishing. https://doi.org/10.1787/16826a30-en.

Mizdrak, Anja, Linda J. Cobiac, Christine L. Cleghorn, Alistair Woodward, and Tony Blakely. 2020. “Fuelling Walking and Cycling: Human Powered Locomotion Is Associated with Non-Negligible Greenhouse Gas Emissions.” *Scientific Reports* 10 (June): 9196. https://doi.org/10.1038/s41598-020-66170-y.

Olunbenga, Olubanjo, Nikolaos Kalyviotis, and Shoshanna Saxe. 2019. “Embodied Emissions in Rail Infrastructure: A Critical Literature Review.” *Environmental Research Letters* 14(12): 123002. https://doi.org/10.1088/1748-9326/ab442f.

Chapter 2: Avoiding Transport GHG Emissions

Key Messages from Chapter 2

- Rail transport can help avoid transport GHG emissions via:

    1. Maximizing the number of passengers or the freight load carried. For example, changing the seating configuration in a passenger carriage can increase the number of passengers it can carry in suburban service. Reducing the weight of rail rollingstock by using lighter weight materials can increase the rollingstock's carrying capacity for the same weight of equipment plus load.

    2. Managing fleets to minimize empty loading, including through fleet management programs and incentive pricing, to fill empty backhauls or shift passengers to nonpeak hours.

    3. Densifying land use around railway nodes to reduce the number and length of trips and encourage walking and cycling.

- Commercially managed railways will have natural incentives to maximize loading and minimize empty movements, as they increase revenue or reduce costs; however, government has an important role in land-use planning to encourage transit-oriented development around stations and development of multimodal freight villages.

Rail transport offers three opportunities to reduce greenhouse gas (GHG) emissions through avoiding vehicle-kilometers traveled. The first is to carry more passengers or freight for a given weight of rail equipment moved. The second is by avoiding empty movement of rollingstock. The third is by land-use planning, such as encouraging the densification of cities around passenger railway stations.

Maximizing Loading

GHG emissions are primarily driven by gross ton-kilometers (gtkm), the combined weight of the passengers and freight being transported, together with the weight of the locomotive and rollingstock (the tare weight). Emissions can thus be reduced, while still performing the same transport task, through the following two steps:

- Reducing the tare weight of the rollingstock
- Increasing the loading (in terms of passengers or trains) for loaded movements

Lighter-weight materials and relaxed axle load limits allow operation of wagons that carry more goods relative to the tare (empty) weight of the wagons. One project in Ukraine, for example, replaced mineral wagons weighing 22 tons and carrying 58 tons with new ones weighing 24 tons—but carrying 70 tons. This saved at least 5 percent in fuel costs—as well as wagon maintenance costs—compared to the old fleet. Articulated wagons for containers offer another example. They combine better net:gross ratio (ratio between net tons from cargo and gross tons, including locomotives and wagons) with a smoother ride and reduced maintenance costs.

The volumetric capacity of rail freight vehicles is also subject to loading gauge constraints for many traffics. Where such limits apply, the benefits of increasing them should be considered to allow rail access for traffic previously not permitted. Container height limits provide a common example.

Passenger rollingstock also often provides opportunities for improving tare weight per occupant. Much has been achieved by using lightweight materials, subject to crashworthiness considerations. Occupancy can also be increased for a given internal size through the arrangement and type of seating, particularly for suburban services subject to peak loading.

Image 2.1. Empty and Loaded Trains, Vasco de Gama, Goa, India

Source: "Train of 60 Wagons." Photo by Joegoauk Goa (2017), via Flickr. https://www.flickr.com/photos/joegoauk73/38508914764/. License: CC BY-SA 2.0.

Minimizing Empty Movements

Empty wagon movements represent over 30 percent of total movements for many freight operators. The U.S. Class 1 railways consistently have 40 percent of their operations as empty movements (AAR 2015). Even in the former Soviet Union (U.S.S.R.) prior to 1990, when freight movements were effectively controlled by a single operator with a strong production efficiency orientation, 27 percent of wagon movements were empty.[1]

Much of the empty movement is an inevitable consequence of market forces and traffic patterns. Many major freight flows are unbalanced, with volumes much greater in one direction than another. Even if traffic balances out over the year, it is often not balanced over shorter periods. Freight vehicles are often specific to a particular commodity or group of commodities. An obvious example is tank wagons, which are typically used for only one type of liquid (for example, vegetable oil or heavy fuel oil) or cars carrying specific ores or minerals (as in image 2.1). The greater the degree of vehicle specialization (such as ready-mixed cement trucks on road or pneumatic cement rail vehicles) and private ownership, the fewer the opportunities for two-way loading.

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[1] Rail operating statistics for pre-1990 Soviet Union (U.S.S.R.) railways gathered from the Ministry of Railways, Moscow (unpublished).

Nevertheless, some empty running reflects inefficiencies in the overall management of the wagon fleet. For more complicated networks, operations planning can manage the distribution of wagons to reduce empty movements. One example is wagon pooling, which can reduce the number of empty movements caused by interchanged wagons having to be returned empty to their home railway (box 2.1). Railways should be encouraged to seek backloads for otherwise empty movements and remove any regulatory impediments, such as restrictions on reducing rates, to better fill backhauls.

Box 2.1. TTX Wagon Pooling

TTX is a railways wagon pooling company owned by the North American Railways. The TTX fleet makes up about 15 percent of the freight wagons in service in North America. The company rents its wagons to participating railways yet differs from a typical leasing company in that the wagons belong to a pool and not individual railways. Therefore, TTX wagons operate freely on the entire rail network, without wagon return restrictions that often apply to other wagons. This pooling approach improves the efficiency of wagon distribution. TTX reported to the U.S. regulator a 7 percent empty wagon-kilometer, considerably better than wagons owned by other leasing companies.

Source: Lawrence and Ollivier 2015, 59.

Passenger services normally operate with the same number of vehicles in each direction. In such circumstances, railways should try to maximize patronage in the more lightly loaded direction, usually done by relatively simple pricing measures. Fares can be different by direction, by time of day (such as off-peak tickets), or by day of week. Operators should be empowered and encouraged to experiment with differential fares and other measures to both increase patronage and improve aggregate revenue.

Land-Use Planning

Governments can influence land-use development to reduce transport, or at least direct it to lower-emission modes, such as rail. For passenger traffic, this can be summarized as transit-oriented development (TOD), in which commercial and residential development is deliberately encouraged around major transit hubs and along transit corridors.[2] As an example, the Norwegian government's "Policy Guidelines for Coordinated Land Use and Transport Planning" (originally issued in 1993 and revised in 2014) aim to "promote the development of compact cities and settlements, reduce the need for transport and facilitate forms of transport that are climate-friendly and environmentally friendly." The impact on Oslo has been significant, with population densities in the urban area increasing by nearly 37 percent from 1985 to 2016 (Wolday, Cao, and Næss 2018).

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[2] The World Bank has published several guides for implementing TOD, including Salat and Ollivier (2017), Suzuki, Cervero, and Iuchi (2013), and Peterson (2008).

Image 2.2. Intermodal Logistics Terminal in Illinois, United States

Source: "Intermodal." Photo by Sam LaRussa (2017), via Flickr. https://www.flickr.com/photos/blueshift12/48250806881/. License: CC BY 2.0.

Densification of urban land use leads to a reduction in the length and number of car trips. A range of studies[3] have found that denser areas with ready access to rail facilities are statistically associated with reduced automobile travel. Studies such as Huang, et al. (2019) have found that, as might be expected, areas of denser population have a higher frequency of walking and cycling trips. These findings all demonstrate the positive impact of TOD on reducing the use of GHG-intensive travel modes.

The freight equivalent of TOD is "freight villages," in which freight-related activities are clustered around a well-connected logistics terminal. The United States, Germany, and other European countries have many examples (image 2.2). In Australia the national government has recently established a National Intermodal Corporation, responsible for developing major intermodal terminals, including two major ones associated with the Inland Rail case study described in chapter 3. These will replace existing inner-city terminals, which are unsuited to current operations and distant from customers who have migrated from the city centers. Chapter 5 gives more detail of the most advanced of these, at Moorebank in Sydney (see box 5.1 in chapter 5), which is being developed jointly by the government and the private sector.

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[3] An extensive academic literature examines various hypotheses on the interaction between transit usage, car usage and accessibility to suburban rail and metro systems. Two papers give comprehensive reviews and references: Ewing and Cervero (2010) and Boarnet et al. (2020).

Reference

AAR (Association of American Railroads). 2015. "Analysis of Class 1 Railroads." Data packages. https://my.aar.org/Pages/allproducts.aspx

Boarnet, Marlon G., Raphael W. Bostic, Seva Rodnyansky, Evgeny Burinskiy, Andrew Eisenlohr, Huê-Tâm Jamme, and Raúl Santiago-Bartolomei. 2020. "Do High Income Households Reduce Driving More When Living near Rail Transit?" *Transportation Research Part D: Transport and Environment* 80 (March): 102244. https://doi.org/10.1016/j.trd.2020.102244.

Ewing, Reid, and Robert Cervero. 2010. "Travel and the Built Environment." *Journal of the American Planning Association* 76 (3): 265–94. https://doi.org/10.1080/01944361003766766.

Government of Norway. 2014. "Central Government Policy Guidelines for Coordinated Land Use and Transport Planning in 1993." Amended 2014. Ministry of Local Government and Modernization, Oslo.

Huang, Xiaoyan, Xinyu (Jason) Cao, Jiangbin Yin, and Xiaoshu Cao. 2019. "Can Metro Transit Reduce Driving? Evidence from Xi'an, China." *Transport Policy 81* (September): 350–59. https://doi.org/10.1016/j.tranpol.2018.03.006.

Lawrence, Martha, and Gerald Ollivier. 2015. *Attracting Capital for Railway Development in China.* Washington, DC: World Bank. https://openknowledge.worldbank.org/handle/10986/23800.

Peterson, George E. 2008. *Unlocking Land Values to Finance Urban Infrastructure.* Trends and Policy Options; No. 7. Washington, DC: World Bank. http://hdl.handle.net/10986/6552. License: CC BY 3.0 IGO.

Salat, Serge, and Gerald Ollivier. 2017. "Transforming the Urban Space through Transit-Oriented Development: The 3V Approach." Working paper, World Bank, Washington, DC. http://hdl.handle.net/10986/26405. License: CC BY 3.0 IGO.

Suzuki, Hiroaki, Robert Cervero, and Kanako Iuchi. 2013. *Transforming Cities with Transit: Transit and Land-Use Integration for Sustainable Urban Development.* Urban Development Series. Washington, DC: World Bank. http://hdl.handle.net/10986/12233. License: CC BY 3.0 IGO.

Wolday, Fitwi, Jason Cao, and Petter Næss. 2018. "Examining Factors That Keep Residents with High Transit Preference Away from Transit-Rich Zones and Associated Behavior Outcomes." *Journal of Transport Geography* 66 (January): 224–34. https://doi.org/10.1016/j.jtrangeo.2017.12.009.


metrorail
Shosholoza Meyl
metro

Chapter 3: Opportunities for Modal Shift to Rail

Key Messages from Chapter 3

- Rail—whether diesel or electric powered—is more energy efficient and generates lower emissions per passenger or ton of goods moved than almost all road and air modes. Therefore, rail's primary role in decarbonizing the transport sector is in serving passenger and goods traffic that would have otherwise traveled by more carbon-intensive modes ("shift").

- Modal shift to rail is possible in suitable markets and with appropriate government support. Suitable markets include those where traffic flows are dense or expected to become dense (sometimes through intermodal consolidation) and where the cost and service characteristics of rail attract customers. Policies to promote mode shift should target passenger or freight segments where rail is most competitive as well as those with the greatest potential to reduce greenhouse gas emissions. For example, freight rail should be expected to attract nearly 100 percent of large mineral movements, while 15 percent of manufactured goods moving long distance would be considered a good result in a competitive market.

- Significant changes in modal share require the active involvement of government in infrastructure development. Where rail lines already exist, upgrades could be necessary, for example to repurpose freight lines to suburban passenger use, increase intercity passenger lines to higher speeds, or upgrade freight lines to provide a reasonable standard speed (70 to 80 kilometers per hour) and reliable service. Where transport demand has altered substantially, new lines can support green economic development in rail friendly markets.

- Governments can also promote connectivity and intermodal integration through investment, coordination of relevant entities, and regulation. Passenger services need to be coordinated and integrated with feeder modes. For freight, government can support creation of new industry sidings and development of modern (or modernized) consolidation depots with good connections to the road network. Finally, governments can ensure rail operators work with schedules that allow commercial profitability, balancing freight and passenger service needs.

Rail is suited to handling dense traffic flows. One passenger train can carry a thousand or more passengers; one freight train can carry 1,000 to 5,000 tons of freight; and a single track can handle up to 30 pairs of trains a day.

Rail's cost structure, with fixed costs for infrastructure and relatively low variable cost per unit transported, is also suited to dense flows of people or goods. Therefore, "rail friendly" markets that make the most of rail's competitive advantages to offer attractive service and potentially induce shift to rail, include the following:

- Urban and suburban corridors of approximately 80 kilometers or less (about one hour of travel time).
- Intercity passenger corridors up to about 500 kilometers for conventional passenger rail and 1,200 kilometers for high-speed rail (about three hours of travel time).
- High-volume, point-to-point freight flows of any distance.
- Consolidated intermodal freight with distances of approximately 600 kilometers or greater.

However, modal shift is not easy. Shifting traffic to rail calls for improvement in the quality and availability of rail services offered in the market. Such improvements often require investment in rail infrastructure and rollingstock as well as innovative and market-oriented railway management. The supplementary pricing mechanisms include balancing the cost recovery of road and rail, ending subsidies for carbon-based fuel, and introducing carbon taxes. These mechanisms only work effectively if an attractive alternative to road service exists. Especially for passenger services, as countries develop and incomes grow, the demand for mobility will grow and passengers will demand higher quality of service. The examples that follow illustrate the combination of measures taken in suitable markets to yield modal shift.

Suburban Passenger Rail

Despite carrying around 30 billion passengers a year, suburban rail is an often-forgotten mode. While suburban rail is more prominent in developed than developing countries, suburban railways of Mumbai, Kolkata, Chennai, Sao Paulo, Buenos Aires, and Jakarta together carry 6 billion passengers per year. Typically, suburban rail is most effective for connecting the urban center of a major city with the surrounding suburbs and towns in trips of 20 to 80 kilometers. Travel times range from 10 to 15 minutes to the first inner suburban station, 45 minutes to reach the settlements outside the main built-up area, and perhaps up to 1 hour 30 minutes to reach a terminus station at the outer reaches of the metropolitan catchment area. Suburban rail is a potentially fast, high-capacity public transport mode for serving this market, where metro or bus will be slower, and bus will be less reliable. Hence it is often the only public transport mode that can compete with private passenger vehicles for these trips and encourage mode shift.

People living on the periphery of urban areas generate the largest transportation emissions of all urban dwellers, at approximately 1 ton of carbon dioxide equivalent (CO_2e) per person, per year of daily travel (Nicolas and David 2009). Given "the key countermeasure to reduce the high CO_2e emissions is to encourage the emitters to take public transit instead of driving cars" (Wang et al. 2017), suburban rail has significant potential to reduce greenhouse gas (GHG) emissions. GHG savings from suburban rail vary depending on a range of factors, including (1) the mode of transport used before suburban rail and its efficiency; (2) the occupancy rates of the suburban rail and alternative mode; (3) the carbon intensity of the energy used by each mode; and (4) the technology used by the railway. Regardless, the vast majority of suburban railways provide urban mobility at far lower emissions levels than competing road modes (typically, one-third of direct operating CO_2e).

Most suburban rail lines in developed cities were built in the 19th or first half of the 20th century, and travel and land-use patterns conducive to public transport were established before private passenger vehicles became a competitor. The challenge for newer systems is to identify high-demand corridors where suburban rail can attract a large ridership and establish strategic alignments in the face of road-based travel and land use. In some cities, this can be addressed by revitalizing or repurposing existing rail lines with established alignments.

Measures that will make surburban rail emissions particularly low include high occupancy, electric power supply from a green energy source, and regenerative braking. High occupancy and intensive use of the available rail infrastructure are particularly important. Where capacity is available, the marginal GHG of an extra rail trip is usually next to zero. An extra road trip in a private vehicle with an internal combustion engine is not marginal. Better rail solutions can easily lead to emissions of under 25 grams CO_2e per passenger-kilometer and with green energy it is possible to achieve nearly zero emissions.[1]

Suburban rail can shape urban form and contribute to the densification of cities. Changes to land-use patterns are both critical for and dependent on high-capacity public transport. The evolution of activity centers, with communities built around suburban railway stations, will be more efficient than road-led urban sprawl and help to "lock in" a more energy efficient, public transit-based transport future. Cities undergoing rapid urbanization need to make appropriate investments in land and money to facilitate the development of faster modes, such as suburban rail, to avoid high dependency on private vehicles.

Development of suburban rail can be complicated institutionally, politically, and financially. Suburban rail often extends beyond city boundaries, and thus requires multijurisdictional planning and political support. Suburban rail also typically requires considerable financial support for construction. Ongoing subsidy is also often required for rail to remain an affordable mode for poorer citizens. This is particularly critical in low-income countries where price is an important determinant of modal choice. When the suburban rail is part of the national railway, the requirement for funding support often makes the suburban

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[1] For transport, the path to net-zero emissions relies on the concurrent strategies of electrifying consumption and decarbonizing electricity. Electrifying consumption by encouraging uptake of suburban rail is supporting this direction while decarbonizing the mode's electricity is in progress.

rail service an “orphan” within the national railway, neglected for fear it should grow and increase the cross-subsidy needed from other traffic.

Addressing these challenges requires a motivated authority with decision-making powers over the city’s commuter catchment area. This authority takes leadership in urban development and transport planning, considering suburban rail alongside other modes. As connectivity between origin or destination and rail stations is critical for attracting high ridership, the authority would ensure suburban rail is integrated with other modes, both physically through station interchanges as well as through integrated fare systems and service coordination. The authority would also play a role in regional land-use planning so that transit-oriented development at stations and depots can realize land-use objectives, result in efficient city development—which is dense where accessibility is high—and generate customers who improve the project finances.

The examples of suburban rail in Jakarta and Mexico demonstrate these challenges can be overcome so that suburban rail service can operate successfully, shift travelers to rail, and save GHG emissions. In Jakarta, development of a transport master plan at the regional level, along with strong support from the national government and from the Japan International Cooperation Agency (JICA), facilitated the development of the Commuterline suburban service. This service moves approximately 1 million passengers a day and is saving more than 6 percent of Jakarta’s transport GHG emissions. In Mexico, government support enabled the development of a suburban service on a public-private partnership (PPP) basis. The suburban rail services carry over 200,000 passengers daily.

JAKARTA: COMMUTERLINE

Suburban rail provides important public transport services in the Jakarta region. The capital of Indonesia, Jakarta has a population of 10 million in the city and 30 million in the metropolitan region. Increasingly, it has been beset by chronic traffic congestion and pollution that undermines its sustainable development. Jakarta provides a strong example of how the national government has worked effectively with the city government to develop suburban rail effectively integrated with metro, buses, walking, and cycling on a regional basis.

Jakarta benefited from the early development of a regional transport masterplan outlining the roles of various modes of transport. In 1980, JICA supported a regional masterplan and feasibility study, providing loan financing to upgrade and electrify existing rail lines and procure electric multiple units. More than 25 years later, the Commuterline service developed further following this timeline:

- 2007: A new railway law abolishes the previous monopoly of PT Kereta Api Indonesia (PTKAI) and splits responsibility for rail infrastructure and operations.
- 2008: The unit of PTKA previously responsible for the Jakarta suburban services converts to a subsidiary above-rail company PTKAI Commuter Jabotabek (KCJ).
- 2013: All services become air-conditioned.

- 2014: Rail operations simplify, with 8- and 12-car trains, electronic ticketing, and network extensions.

Today, the regional administration is proactively developing its transit system, integrated with the suburban railways and buses, with the national government of Indonesia supporting the development of suburban lines beyond the city boundary (image 3.1).

Jakarta's suburban railway system, Commuterline, operates high-frequency services at modest fares on four major corridors extending 30 to 70 kilometers from Jakarta's central business district. The service is operated by KAI Commuter Jabotabek (KCJ), a subsidiary of the state railway company, over infrastructure belonging to the national government. The 478-kilometer network is narrow gauge (1,067 millimeter) and electrified.

Ridership is about 1 million passengers per day and increasing. Passenger surveys suggest riders are mainly lower- and middle-income commuters and students. Without the suburban rail, half would otherwise use buses, with the remainder using motorcycles and automobiles. Satisfaction with the services is high, with customers reporting Commuterline is generally faster, cheaper, more comfortable, and more convenient than other alternatives.

The Commuterline service has made a substantial impact in terms of reducing GHG emissions, congestion, and air pollution. A 2014 study estimated the rail system (then carrying 500,000 passengers per day) had led to an annual reduction of 540,000 tons of CO_2e, equal to 6 percent of Jakarta's transport GHG emissions. Projections estimated the emissions savings would reach 9 percent of Jakarta's transport emissions by 2019, when passengers per day were expected to reach 1.2 million.

Image 3.1. Commuterline Train at Kramat Station, Jakarta, Indonesia

Source: Photo by Gunawan Kartapranata (2016), via Wikimedia Commons. https://commons.wikimedia.org/wiki/File:Commuterline_at_Kramat_Station_1.JPG.

MEXICO: TREN SUBURBANO

Suburban rail provides important public transport services linking central Mexico City with the municipalities of Tlalnepantla, Tultitlán, and Cuautitlán to the north of the city. Mexico City has a population of around 9 million and a regional population of more than 20 million. Although the metro provides rail transport within the city itself, transport congestion and long journey times to regional centers is an ongoing challenge. The suburban railway line (see image 3.2) was designed to complement the service provided by the metro.

The railway service is provided through a concession to Ferrocarriles Suburbanos S.A. de C.V. The 27-kilometer rail line was built using an existing at-grade alignment on which passenger service had lapsed. Investment of US$706 million was shared between the government (55 percent) and the concessionaire (45 percent). The line was grade separated in key areas and electrified. The concessionaire also supplied electric multiple-unit passenger trains (EMUs) to operate the system.

Before the COVID-19 pandemic, the line carried more than 200,000 people per day. Trains run up to every six minutes in peak periods. With fares about twice those of the metro, the service was operationally profitable and could contribute to its debt service costs with the pre-pandemic patronage.

Image 3.2. Tren Suburbano Arriving at Tlalnepantla, Mexico

Source: "Tren Suburano in Action." Photo by Malcolm K. (2017), via Flickr. https://www.flickr.com/photos/rootsnrails/33923305006/. License CC BY-NC 2.0.

Intercity Passenger Rail

Higher-speed, more frequent, and reliable passenger services enable rail to compete in medium-distance intercity corridors. This section discusses two cases that demonstrate how developing country railways have improved their services and attracted customers from other modes. Georgian Railways improved the quality of its service provided over existing rail infrastructure between the capital city of Tblisi and the Black Sea ports, attracting passengers from road, improving cost recovery, and reducing GHG emissions. In the second case, development of a high-speed rail network in China has generated rapid growth in rail travel. This service has attracted about 35 percent of its traffic from other modes (road and air), while another 15 to 20 percent of traffic was generated. The remaining share transferred from conventional rail services and benefited from expanded access and improved rail service. As electricity continues to decarbonize, the high-speed rail network will create major reductions in transport emissions.

The Chinese example demonstrates the impact of improved frequency as well as speed. Many routes now offer hourly or more frequent service, up from a handful of services daily. In many cases, this was only possible because the high-speed rail (HSR) network provides sufficient capacity. It also demonstrates how replacing locomotive-hauled passenger services with multiple units, running twice as many services—each with half the capacity—is likely to significantly increase the passengers carried without increasing the rollingstock required.

These examples show passengers can be attracted to rail when a high-quality service is provided. In each case, the service improvement made the comfort, frequency, reliability, speed, and availability of the service competitive with road and air options. Such improvements could be made in any rail corridor serving city pairs with large populations and at distances where rail service can be competitive with other options—typically up to 500 kilometers for conventional rail and up to 1,200 kilometers for HSR. Government support is likely to be necessary with the amount depending on the investments required to make the rail corridor competitive and the transport prices prevailing in the market.

GEORGIAN RAILWAY PASSENGER SERVICE

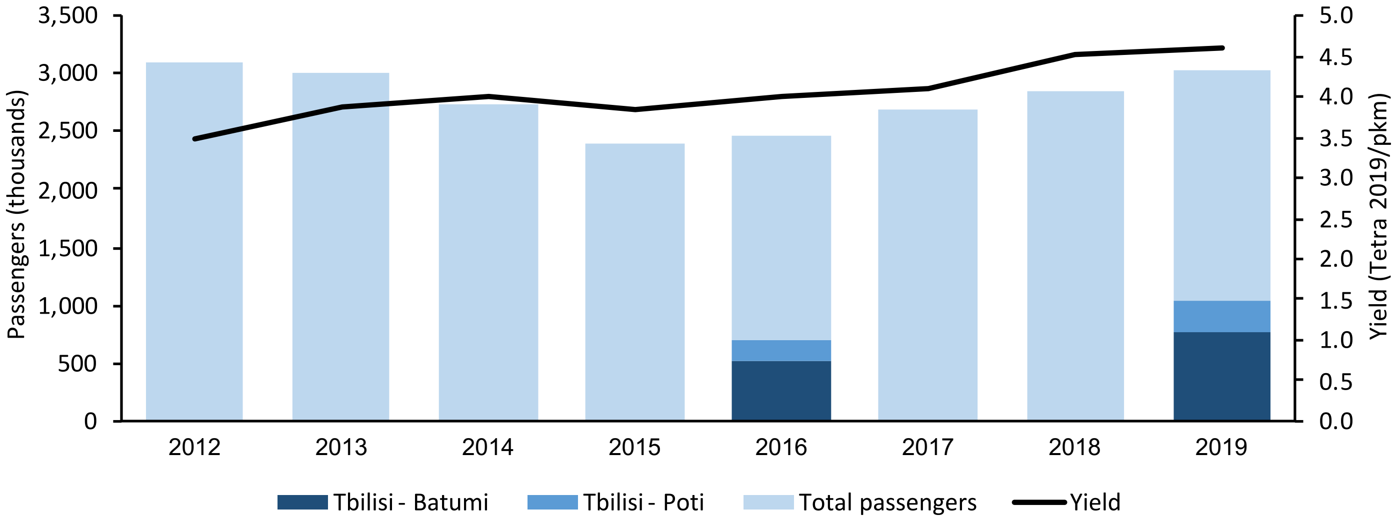
The main business of Georgian Railway (GR) is transit freight, though it also operates a variety of short-distance and longer-distance passenger services. The longest and most popular services operate between Tbilisi and the Black Sea port cities of Poti and Batumi (map 3.1). By 2013, traffic volumes were declining, and the service had become very unprofitable, requiring cross-subsidy from freight.

GR embarked on a new strategy of providing an improved level of service at higher prices while withdrawing from poorly patronized local trains. GR purchased four new, double-deck, EMUs and began operating them on the Black Sea routes from 2016 and 2017. Before the COVID-19 pandemic, GR was operating three return services daily to Batumi and two to Poti. Both services were well patronized, with Batumi averaging 79 percent occupancy and Poti 61 percent occupancy in 2019. This turned around the traffic decline, while improving profitability. Despite several competing bus services, rail now has 60 to 70 percent of the market on both routes, with faster service and competitive prices. Since 2016, GR's overall passenger traffic has increased by 23 percent, with passenger-kilometers increasing by 32 percent and average yield by 15 percent in real terms (figure 3.1).

Map 3.1. Map of Georgian Railway Network

Source: Map produced by the World Bank Cartography Unit (IBRD 46636 | July 2022).

Figure 3.1. Georgian Railways Passenger Traffic



Source: Data provided by Georgian Railway (https://tkt.ge/railway).
Note: pkm = passenger-kilometers.

The improved rail service has generated significant reductions in GHG emissions. Thanks to a low electricity emission factor in Georgia of 0.131 kilogram of CO_2e per kilowatt-hour (see appendix A) and the high occupancy of the trains, a rail trip generates about 0.8 kilograms CO_2e per trip compared to 12 kilograms CO_2e per trip by motor coach.[2] Passengers by rail between Tbilisi and Batumi increased from 515,000 to 765,000 between 2016 and 2019. Assuming these passengers would otherwise have traveled by coach, the savings in GHG emissions from improving the passenger service totals nearly 3,000 tons per year. Had some of these passengers instead traveled by privately operated automobiles, the savings would be even greater.

CHINA: HIGH-SPEED RAIL

Since 2008 China has put into operation more than 38,000 kilometers of dedicated HSR lines. China has many cities with populations greater than 500,000 and generally located at distances (between 200 and 500 kilometers) well suited for HSR. The construction of high-speed lines both improved the speed and comfort of rail travel and increased the capacity to provide passenger services in a capacity-constrained market. The result has been a large growth in rail passenger traffic, with China Railway reporting 2.2 billion passengers in 2020, despite COVID-19 pandemic-related restrictions on travel, of which 1.5 billion occurred on high-speed services (figure 3.2).

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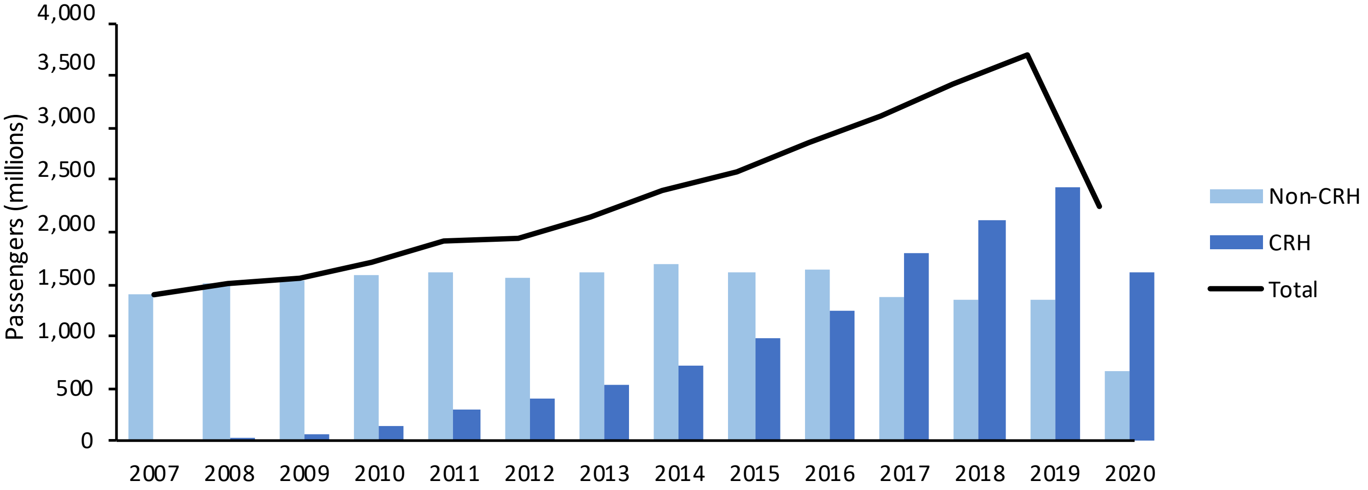
[2] Traveling to Batumi by coach (388 kilometers) will use 0.3 liter per vehicle-kilometer of diesel fuel. Assuming an average load of 30 passengers per coach and using 3.19 kilogram of carbon dioxide equivalent (CO_2e) per liter on a well-to-wheel (WTW) basis gives emissions of about 12 kilograms of CO_2e per trip. Traveling by rail (353 kilometers) will use about 2.1 megawatts per hour (MWh), equivalent to 6 kilowatts per hour (kWh) per passenger and 0.8 kilograms CO_2e.

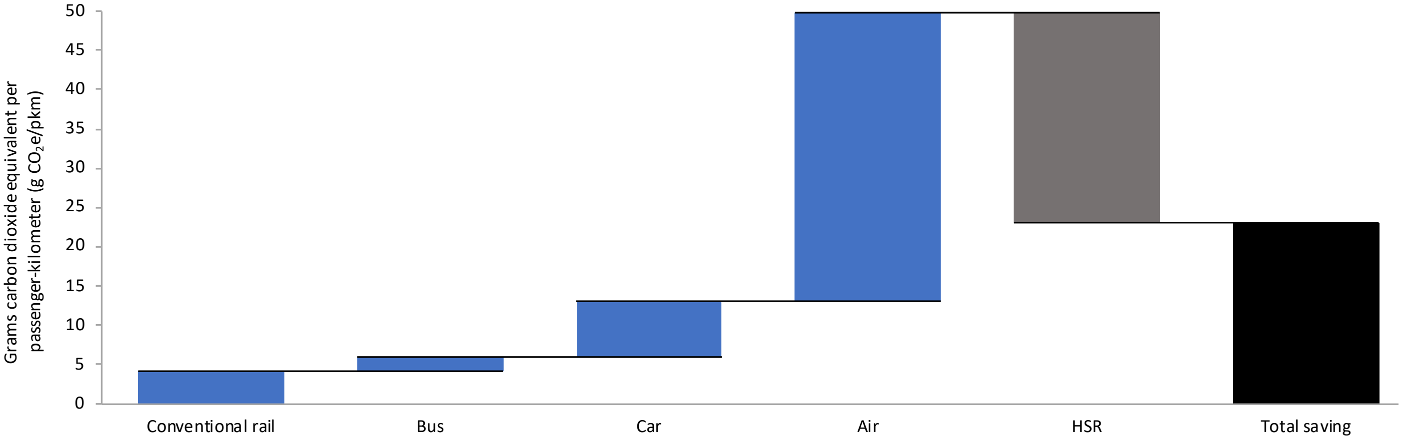
GHG emissions savings total approximately 30 percent compared to a non-HSR scenario, due to diversion from automobiles and air. Surveys suggest HSR passengers are diverted from conventional rail (50 percent), air (20 percent), and bus and automobile (15 percent). The remainder are new trips that were not previously made by any mode. Figure 3.3 shows the net change in operations related to GHG based on these mode shifts, using typical Chinese vehicle occupancies and characteristics. As emissions per kilowatt-hour of electricity reduce and rail travel increasingly replaces trips that would otherwise have been made by air and automobile, the GHG benefit of China's HSR per passenger-kilometer will increase substantially.

Figure 3.2. China High-Speed Rail and Conventional Rail Service Passengers



Source: National Bureau of Statistics of China 2021.
Note: CRH = China Railway High-Speed; 2020 figures affected by COVID-19

Figure 3.3. China: Source of GHG Savings from High-Speed Rail Operation



Source: Original figure produced for this publication.

Image 3.3. High-Speed Train Leaving Shanghai Railway Station, China

Source: "Shanghai Fall 2013." Photo by Remko Tanis (2013), via Flickr. https://www.flickr.com/photos/remkotanis/10724259095/. License: CC BY-NC-ND 2.0.

The GHG savings from HSR will vary substantially from country to country and from service to service, depending on the mix of modes from which trips are diverted and, most importantly, the occupancy of both the HSR and the other modes.[3] HSR is significantly more carbon intensive than conventional rail services with similar load factor as well as well-run intercity bus services. This is because the trains must overcome strong air resistance at high speeds. The GHG impact in any specific country also depends critically on the carbon intensity of electricity in both operations and embedded in the construction materials.

Freight Rail

How much freight traffic shifts from road to rail in any country depends, in substantial part, on how much "rail-competitive" freight the country's economy produces. A key factor is the types of commodities being transported since rail is most competitive for bulk traffic, for which rail's cost advantage is greatest. It is also important because different commodities have different distribution patterns affecting their transport distance and last-mile connectivity. While rail transport provides a lower cost for linehaul movements, shippers consider a range of transport characteristics beyond door-to-door costs when making a mode choice selection. Thus, other important characteristics in determining the "rail competitiveness" of freight include minimum consignment size, freight value, last-mile connectivity, and distance, as discussed below.

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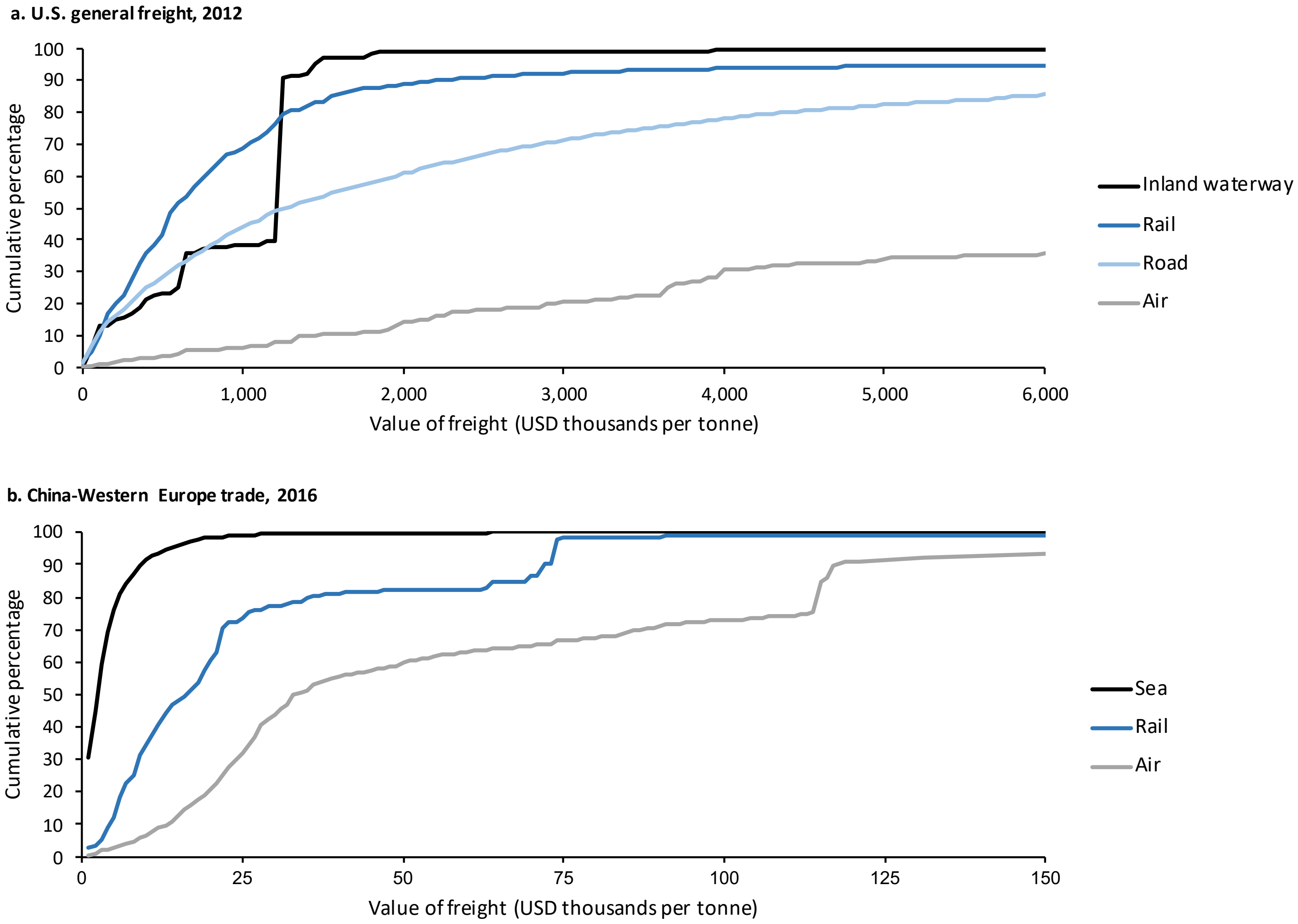
[3] Chinese occupancies are high (80 percent is assumed for high-speed rail (HSR).

Figure 3.4. Value of Freight by Mode in the United States and China–Western Europe Trade



Source: Original figure produced for this publication, based on the following online datasets: United States–U.S. Commodity Flow Survey Datasets (2012), https://www.census.gov/data/datasets/2012/econ/cfs/historical-datasets.html; China–China Customs Statistics Trade Data for Export and Import (2016), http://english.customs.gov.cn/statistics.

- *Minimum consignment size.* A longhaul road truck can typically carry up to 25 tons, while a rail wagon normally holds 40 to 50 tons.[4] This means rail transport is better suited to bulk products (shipped in large consignments) than manufactured products, which tend to be transported in smaller quantities. It is possible to palletize, consolidate, and containerize smaller shipments for rail[5] transport, but this adds handling time, handling cost, and potential unreliability to the transport. Because port traffics are already consolidated and containerized for international shipping, rail can be more competitive for the domestic leg of this traffic.

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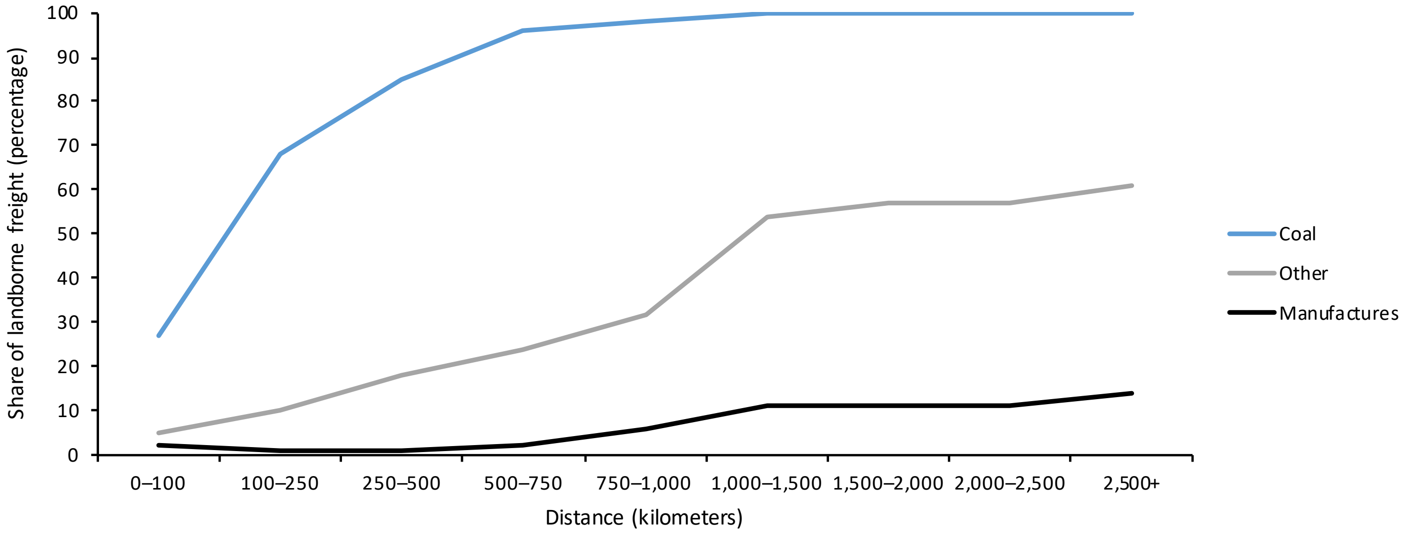
[4] Heavier loads are carried in some countries, for example, in South Africa 34 net tons is possible with two trailers, while in India some rail wagons can carry 80 net tons.

[5] See The Rail Freight Challenge for Emerging Economies: How to Regain Modal Share (Aritua 2019).

Figure 3.5. Rail Share of Freight Traffic in the United States, by Distance Carried, 2012



Source: Original figure produced for this publication, based on the following online dataset: Commodity Flow Survey Datasets (2012), https://www.census.gov/data/datasets/2012/econ/cfs/historical-datasets.html.

- *Freight value.* Shippers of high-value products put a high value on speed, security, and reliability of delivery, causing them to select the mode that can deliver these attributes. This relationship between value of product and mode choice can be seen in figure 3.4, which shows the relationship between the value of shipments for transport by different modes for general freight in the United States in 2012 (panel a), and for all freight between China and Europe in 2016 (panel b). In the United States, the average value of rail freight is considerably lower than road freight, with 70 percent of rail general freight being worth under US$1,000 per ton, compared to about 40 percent for road freight (and under 10 percent for air freight). For the China–Europe trade, nearly all low value goods move by sea, with 90 percent of seaborne freight valued at US$10,000 or less per ton. Rail, with faster transport time than sea as well as good reliability, moved middle-value goods, while air continued to carry the very high-value goods.

- *Last-mile connectivity*. Rail and water are most competitive when they directly serve the origin and/or the destination of the traffic, since consolidating at origin by truck and/or distributed to destination by truck incurs additional handling costs, time, and potential unreliability.

- *Distance*. The longer the shipment distance, the greater the cost advantages of rail relative to truck. This influence is demonstrated in figure 3.5, which shows the cumulative rail share of different commodities by distance in the U.S. market,[6] where both road and rail offer a comparatively high level of service.

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[6] U.S. railways offer a high level of service and carry 33 percent of freight measured by ton-kilometer. Data collected from the Bureau of Transportation Statistics, an online database maintained by the U.S. Department of Transportation (https://www.bts.gov/).

Table 3.1. Commodity Characteristics Affecting Mode Choice

	Consignment size	Value per ton	Direct access to origin and destination	Rail competitiveness
Coal	Large	Low	Mine and consumption point often rail served.	Competitive at any distance if both origin and destination rail served and medium distance if one end not rail served.
Minerals	Large	Low	Mine, processing facility and ports often rail served.	Competitive at any distance if both origin and destination rail served and medium distance if one end not rail served.
Petroleum	Large	Medium	Extraction, processing facilities, and ports often rail served, end-users sometimes rail served.	Competitive at any distance if both origin and destination rail served and medium distance if one end not rail served.
Agricultural products	Large/medium	Low	Product trucked to consolidation points such as grain silos (many rail served). Product then delivered to processing facilities (some rail served) and ports (many rail served).	Competitive for long distances and port movements.
Industrial Products	Medium	Medium	Production facilities and receivers sometimes rail served. Ports often rail served, with traffic consolidated and containerized.	Competitive at medium distances between ports and major production or consumption areas, if service quality is high.
Manufactured Products	Small	High	Production facilities and receivers rarely rail served. Ports often rail/water served, with traffic consolidated and containerized.	Rail competitive at medium distances between ports and major production or consumption areas if service quality is very high.

Source: Original table produced for this publication.

Coal traffic of more than 250 kilometers overwhelmingly moves by rail. At the other extreme, rail's share of manufactured goods is negligible for distances of under 750 kilometers and is still only carrying around 15 percent at distances of 2,500 kilometers. For the other groups of commodities, (agriculture, other minerals, and liquids) rail is beginning to be competitive at 500 kilometers and has over half the traffic by 1,500 kilometers. The characteristics discussed above are different for the various commodities and help explain why some traffic is more susceptible to modal shift than others. Table 3.1 shows typical characteristics by commodity.

In potentially competitive market segments, rail can be expected to only attract a share of the traffic. For example, in the U.S. market for import and export goods from the major California ports to destinations east of the Rocky Mountains (distances of 1,500 kilometers or more) rail carries about 70 percent. Along the east coast of the United States, rail carries 15 to 30 percent of traffic. A few European ports (for example, Hamburg, Koper, and Gothenburg) manage close to 50 percent[7] by rail, though most handle far less. In most

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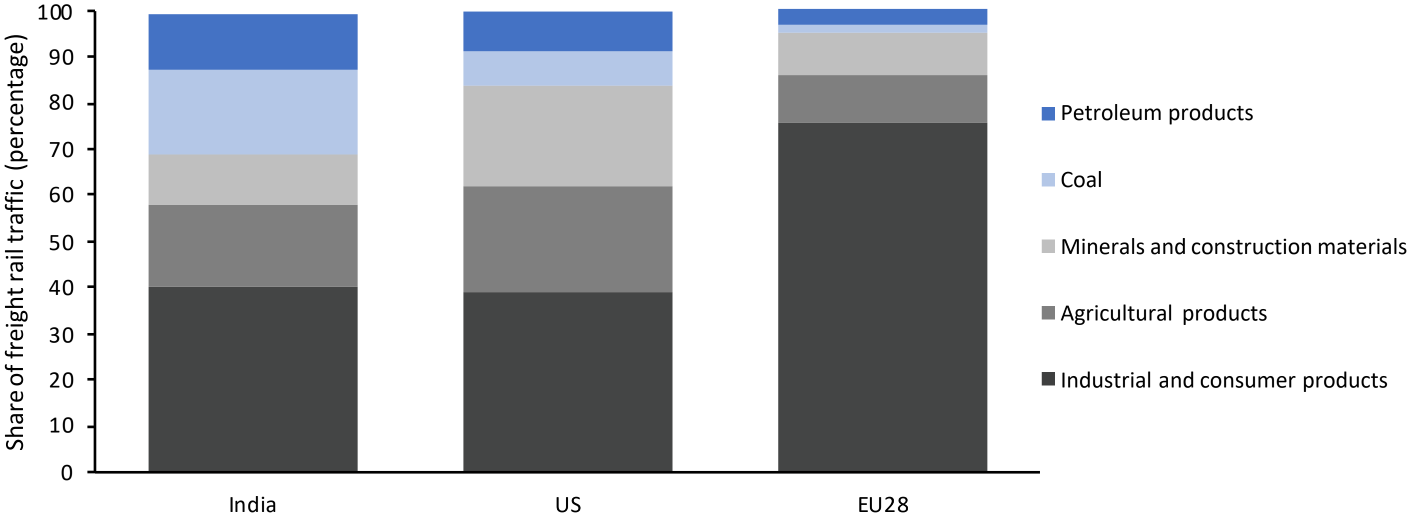
[7] An important factor is that the cubic capacity of a road vehicle is significantly greater than what is contained in an ISO container (standardized to specifications outlined by the International Organization for Standardization) and in many developing countries lower-density traffics are often unstuffed from ISO containers at or near the port before being reloaded into road vehicles with a greater cubic capacity.

countries, whose hinterlands are much closer than in the United States, 30 percent of port traffic moving by rail would be considered a good result.

The types of freight and the distances they need to be transported differ substantially between countries and will determine the potential for shifting traffic to rail and water transport. Figure 3.6 shows the total (road, rail, and inland waterway) freight mix for three economic regions. The European Union transports primarily industrial and manufactured products—the hardest categories to shift to rail—and relatively little coal and minerals, where rail transport dominates. By contrast, the freight mixes in the United States and India have higher proportions of coal and minerals; consequently, the potential for rail movement is greater in those countries.

Figure 3.6. Freight Traffic Mix by Commodity Group, Based on Net Ton-Kilometers

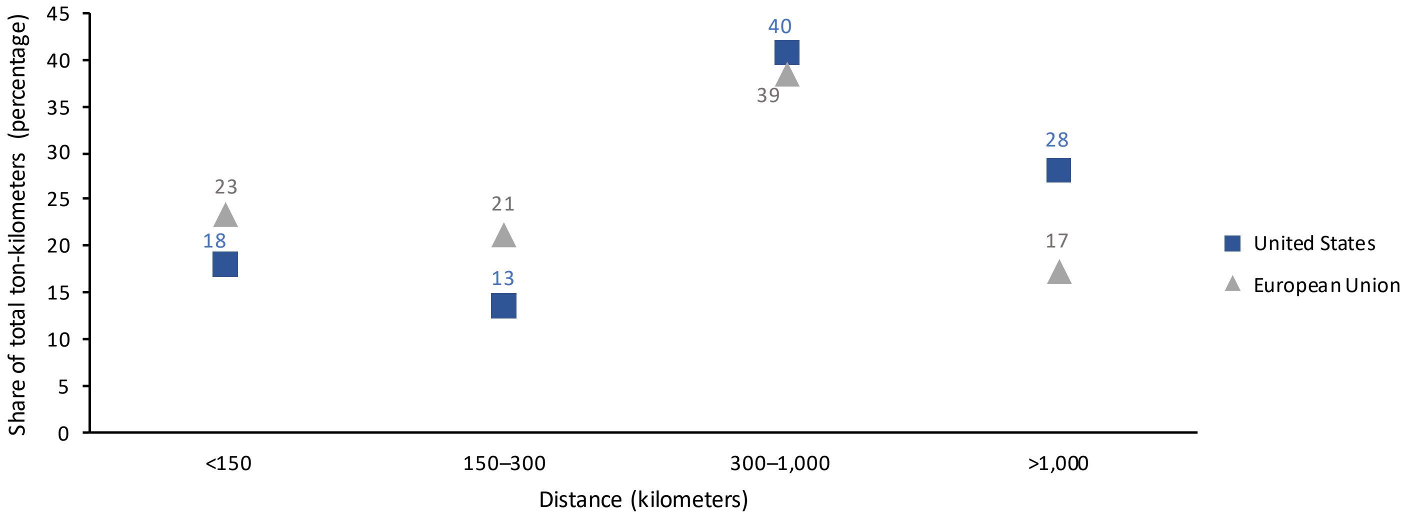


Source: Original figure produced for this publication, based on various published data. India: RITES 2013; United States–U.S. Commodity Flow Survey Datasets (2012): https://www.census.gov/data/datasets/2012/econ/cfs/historical-datasets.html; European Union–Eurostat datasets: "Summary of annual road freight transport by type of operation and type of transport," https://ec.europa.eu/eurostat/web/products-datasets/-/road_go_ta_tott; and "Annual road freight transport by distance class with breakdown by type of goods," https://ec.europa.eu/eurostat/web/products-datasets/-/road_go_ta_dctg.

Note: European Union (number of countries). Graph only includes data for movements >50 kilometers. Shares are measured in net ton-kilometers.

A large share of road traffic moves short distances, where modal shift is unlikely. In the United States and European Union, 30 to 40 percent of net ton-kilometers (ntkm) moves less than 300 kilometers (figure 3.7). With most coal and minerals traffic already moving by rail or water, further modal shift for traffic of under 300 kilometers is unlikely. The traffic moving over 300 kilometers has some potential for mode shift, particularly those with both origin and destination directly connected to rail. The traffic over 500 kilometers with one direct connect to rail mode could also have some potential for modal shift, although this is likely to be limited until much longer distances are reached.

Figure 3.7. Distribution of Road Freight by Distance for the United States and European Union



Source: Original figure produced for this publication, based on various published data. United States–U.S. Commodity Flow Survey Datasets (2012): https://www.census.gov/data/datasets/2012/econ/cfs/historical-datasets.html; European Union–Eurostat datasets: "Summary of annual road freight transport by type of operation and type of transport," https://ec.europa.eu/eurostat/web/products-datasets/-/road_go_ta_tott; and "Annual road freight transport by distance class with breakdown by type of goods," https://ec.europa.eu/eurostat/web/products-datasets/-/road_go_ta_dctg.

Determining a country's potential for modal shift requires analyzing the freight traffic the country generates by commodity, distance, and direct access of rail-to-main origins and destinations. This allows the market to be segmented into rail-dominant traffics, truck-dominant traffics, and competitive traffics. If a railway line is available to serve the rail-dominant traffic, but is not moving it, substantial potential exists for improving the service and shifting the traffic to rail. If a railway line is available to serve the rail-competitive traffic, potential exists to shift a share of the traffic to rail. While each country is different, a shift of 15 to 30 percent of traffic on any given route to alternative modes would be considered a good result in most countries.

If a country's economy produces rail-competitive freight, rail service quality is a key determinant of modal choice. Service includes not only the basic characteristics, such as cost and transit time, but also reliability, flexibility, and information. Surveys of freight customers have repeatedly shown reliability and information are generally more important than transit time. Arrangements need to be made by customers for the receipt and delivery of freight at rail terminals; unreliable delivery will create costs that could deter customers from choosing rail over an alternative mode. Contrary to many views, transit time by itself is rarely a critical factor in most countries—except for the comparatively small express freight segment.

Reliability is critical, particularly when an export container is booked on a specific sailing. Reliable rail service requires infrastructure in sufficiently good condition to allow consistent operation. It also requires an agreed timetable for all operations on the infrastructure, without arbitrary interference from other services that could impede scheduled operation.

Cost is also important. Experience suggests rail-based service can be competitive with a discount on the overall door-to-door cost of as little as 10 to 15 percent. Indeed, in some cases, such as delivering for export, rail can even obtain a premium over road. Such was the case in New Zealand for the export of refrigerated dairy products by rail, which could provide reliable delivery for a specific sailing.

Ensuring smooth interchanges between modes is key for products without a rail-served origin and destination. Efficient rail connections at ports can channel more traffic to rail while reducing truck traffic through port cities. For example, the Alameda Corridor in Southern California channels containers by rail from the ports of Los Angeles and Long Beach to a large multimodal terminal, where local traffic is loaded to truck for delivery and a substantial portion of the long-distance traffic moves by rail. The corridor has saved nearly 900,000 tons of carbon dioxide (CO_2) since its construction.[8] Efficient multimodal terminals are necessary in consumption areas, as they enable goods to reach their final destination by truck.

Where traffic is rail-competitive, appropriate investments and service improvements can influence modal shift. Three cases are described below. In the first case, extension of a line and construction of a high-volume terminal enabled a railway in Brazil to attract grain traffic from road transport. In the second case, development of intermodal terminals and provision of a regular intermodal service enabled rail to attract container traffic between the Port of Karachi and the city of Lahore in Pakistan. A third example, the Inland Rail route in Australia, highlights a new route developed through a mixture of new line construction and reconstruction of existing lines to allow rail to compete more effectively against road for both intercity general freight and rural production carried to ports.

GRAIN EXPORTS FROM MATO GROSSO, BRAZIL

Brazil is a major exporter of corn and soybeans, which need to be transported from production areas in the country's hinterland to its gateway ports for export. Located in the country's midwest, the Mato Grosso (MT) region is the largest Brazilian producer and exporter of both soybeans and corn, with total production in 2019 of about 70 million tons and exports of nearly 40 million (Salin 2021). Mato Grosso is located more than 1,000 kilometers from either the Amazon River or ocean ports.

Ferrovia Norte Brazil railway is a 764-kilometer broad gauge line linking Rondonópolis to Sao Paulo and the port of Santos. The first rail grain terminal in Mato Grosso opened in 1999 in Alto Taquari, a second opened in Alto Araguaia in 2003 (Agência Brasil 2003), and a third opened in 2012 in Itiquira (map 3.2). By this time rail was handling about half of Mato Grosso's expanding soy harvests. To handle rapidly growing traffic, in 2013, the line was extended 124 kilometers to a much larger intermodal grain terminal and complex in Rondonópolis, closer to the southern Mato Grosso farms. By 2019, the railway traffic had grown to 16.2 million tons of grain from Mata Grosso to the port of Santos—9.8

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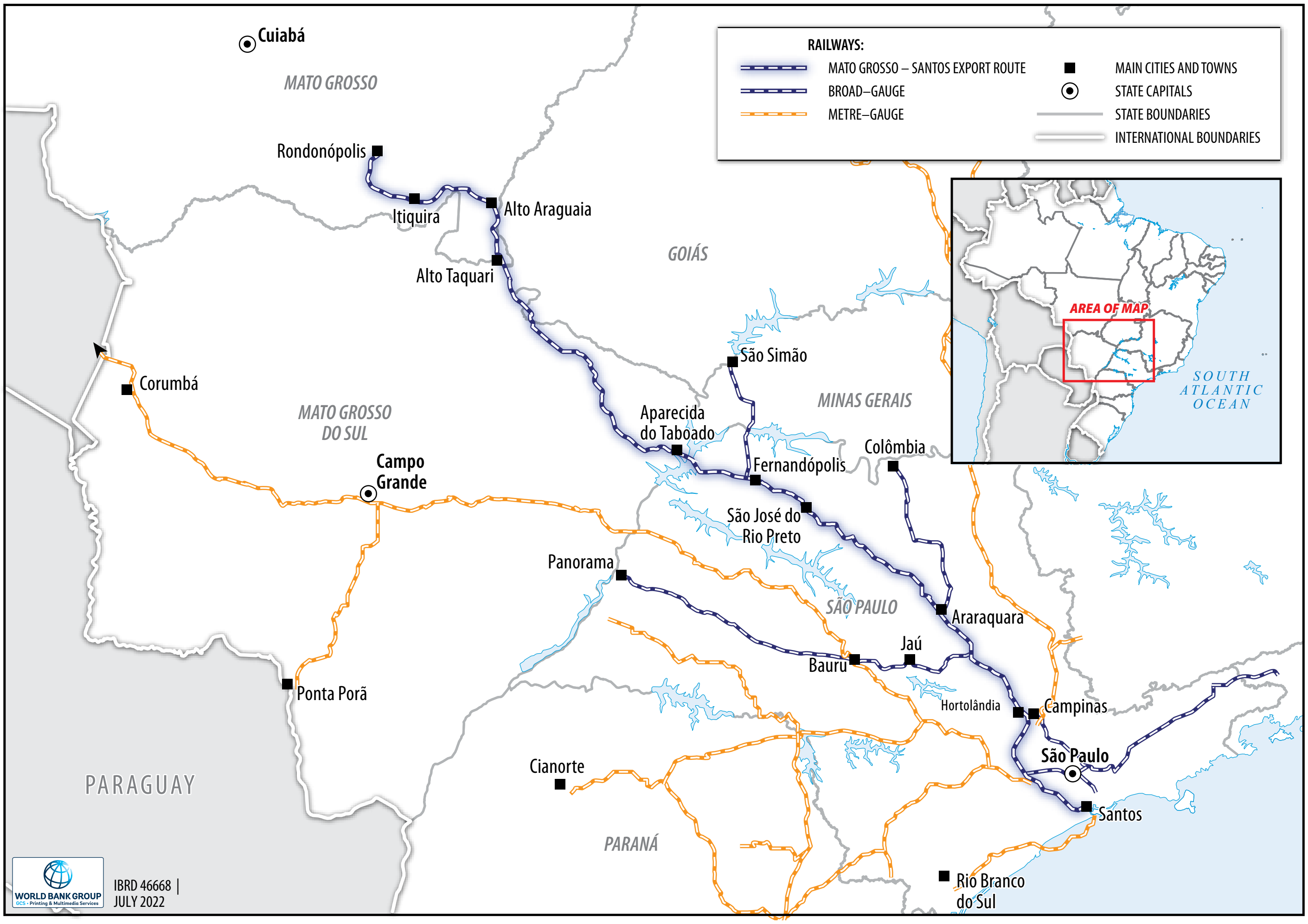
[8] Learn more about how the Alameda Corridor prioritizes public safety on the Alameda Corridor Transportation Authority website: https://www.acta.org/about/what-we-do/public-safety/#:~:text=Alameda%20Corridor's%20efficiency%20in%20moving,eliminated%20vehicle%20idling%20at%20crossings.

Map 3.2. Mato Grosso–Sao Paulo Rail Network



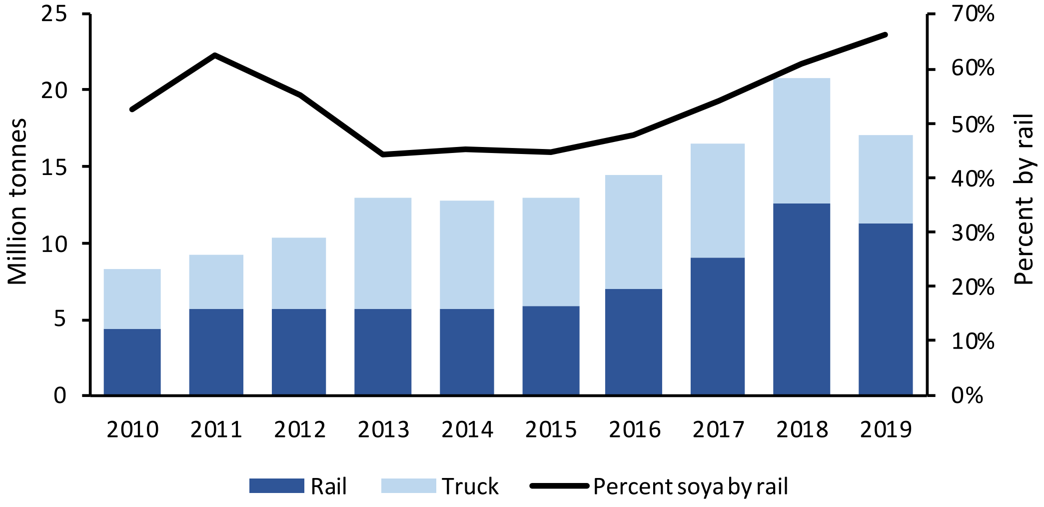
Source: Map produced by the World Bank Cartography Unit (IBRD 46668 | July 2022).

million tons of corn and 6.4 million tons of soybean, 45 percent of the total grain exported through Santos (figure 3.8). The mode share has steadily increased since 2015 and is now well over 60 percent for both soya (panel a) and corn (panel b), both of which have shown steady growth (Salin 2021).

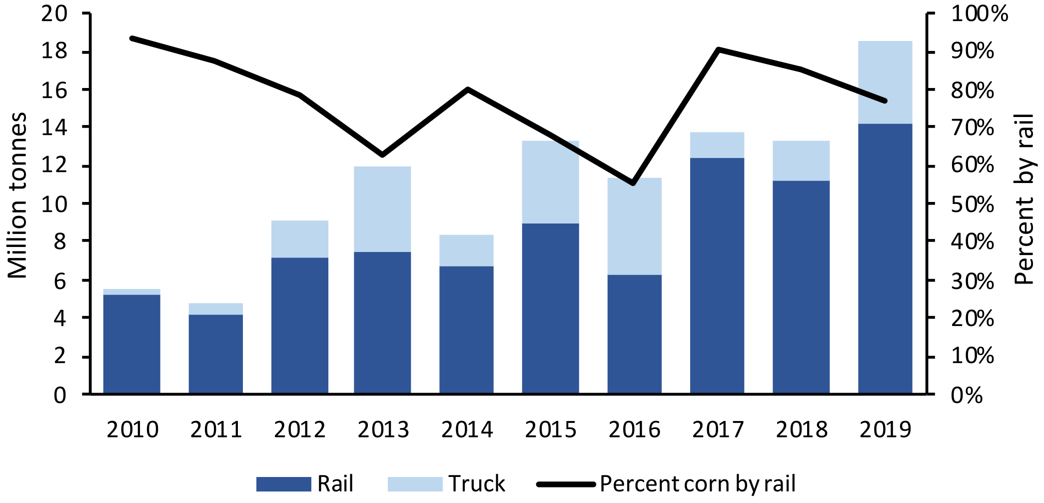
The shifting of this traffic from road to rail, made possible by enhanced capacity and service, has resulted in substantial GHG emissions reductions. World Bank estimates the annual reduction in CO_2e emissions at 200,000 tons, or approximately 25 kilograms CO_2e per ton transported. Against this, the construction of the extension created an estimated 250,000 tons, giving a payback period of just over a year.

Figure 3.8. Traffic and Modal Split for Soya and Corn Exports through Santos Port

a. Soya



b. Corn

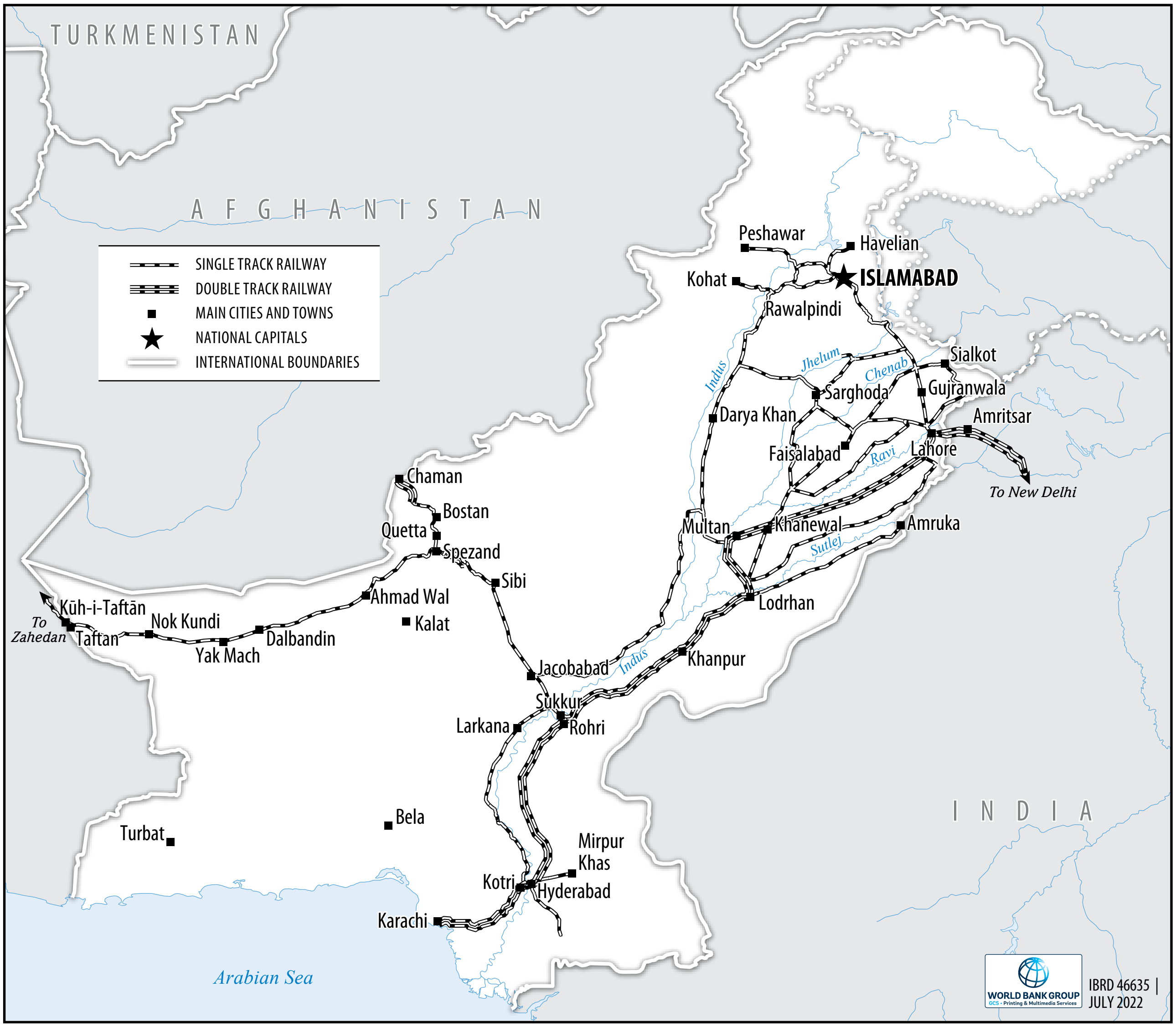


Source: Péra, Filho, and Salin 2021.

PAKISTAN: CONTAINER SERVICE

The Pakistan Railway (PR) system (map 3.3) is traditionally operated and heavily oriented towards passenger services. Over the past decade, its capacity and competitiveness has been hindered by a lack of investment and aging infrastructure. Underinvestment in spare parts and new equipment has led to a decline in locomotives and rollingstock available for service. The condition of many railway lines has deteriorated, trains have slowed, and services have been reduced. As priority was placed on continuing passenger services, PR curtailed freight services and freight carried by the railway declined precipitously for several years. PR's main line from Karachi to Lahore, however, is double track and generally remains in reasonable condition, although its technology—including track, signaling, communications, and road crossings—is outdated.

Map 3.3. Pakistan Rail Network



Source: Map produced by the World Bank Cartography Unit (IBRD 46635| July 2022).

Meanwhile, Pakistan has invested heavily in motorways and upgrading its national highway system. Because of these investment priorities, nearly all import and export traffic to and from Karachi's two main ports[9] moves by road. Railway facilities at the Port of Karachi are designed for a market that no longer exists (single box wagon market) and for much lower volumes of traffic. Container traffic mostly moves from the port to and from local warehouses by road transport because rail facilities on the port are limited and awkward, and the railway is not very sensitive to changing market conditions. This presents several problems for both Pakistan and Karachi, including higher transport costs, greater GHG emissions, more road crashes, and increased traffic congestion, especially in Karachi.

Currently about 3 million twenty-foot equivalent units (TEUs) are handled annually in the Karachi ports, of which around one-third is to and from Karachi itself, a further one-third is unstuffed in Karachi and delivered upcountry by road, and the final one-third is delivered direct by road, principally to Lahore and the Punjab, approximately 1,000 kilometers inland from the port. Until recently, only a very small proportion moved by rail. Poor internal rail connections at the port made it very difficult to operate an efficient trainload-based service.

The potential for reducing GHG emissions through attracting freight from road to rail is clear. To address the problem of the internal port layout, after considerable negotiation a private forwarder is currently operating a daily service from Karachi to Lahore, loading a complete train at a rehabilitated siding just outside the port, which is then hauled by PR to a terminal in Lahore. Plans are in place to increase this to two per day in the short-term. Very recently, PR has begun to operate another block train direct from the purpose-built rail siding of a new container terminal, also to Lahore.

A comparison of the GHG generated by the road and rail alternatives shows a saving of 325 kilograms CO_2e emissions for each TEU carried by road rather than rail. This amount totals about one-third more than the savings per kilometer for soybeans and corn in Brazil, mostly because the absolute levels of fuel consumption for both road and rail are higher in Pakistan then Brazil. In the short run, PR can do little to increase these savings. However, in the longer run, PR should actively pursue, where possible, upgrading infrastructure to allow longer trains—that are more fuel-efficient per TEU carried—or introducing articulated wagons or double-stack—which will both increase the ratio between net tons from cargo and total tons (including locomotives and wagons) (image 3.4).

INLAND RAIL IN AUSTRALIA

The 1,700-kilometer Inland Rail route in Australia combines 642 kilometers of new railway line with upgraded existing lines to create a new "inland" rail route between Melbourne and Brisbane. This route, shown in map 3.4, avoids Sydney, which is currently a severe bottleneck for through long-distance freight (Inland Rail Implementation Group 2015). The route will shorten the distance between Melbourne and Brisbane by about 250 kilometers compared to the existing route and should reduce the transit time, when completed,

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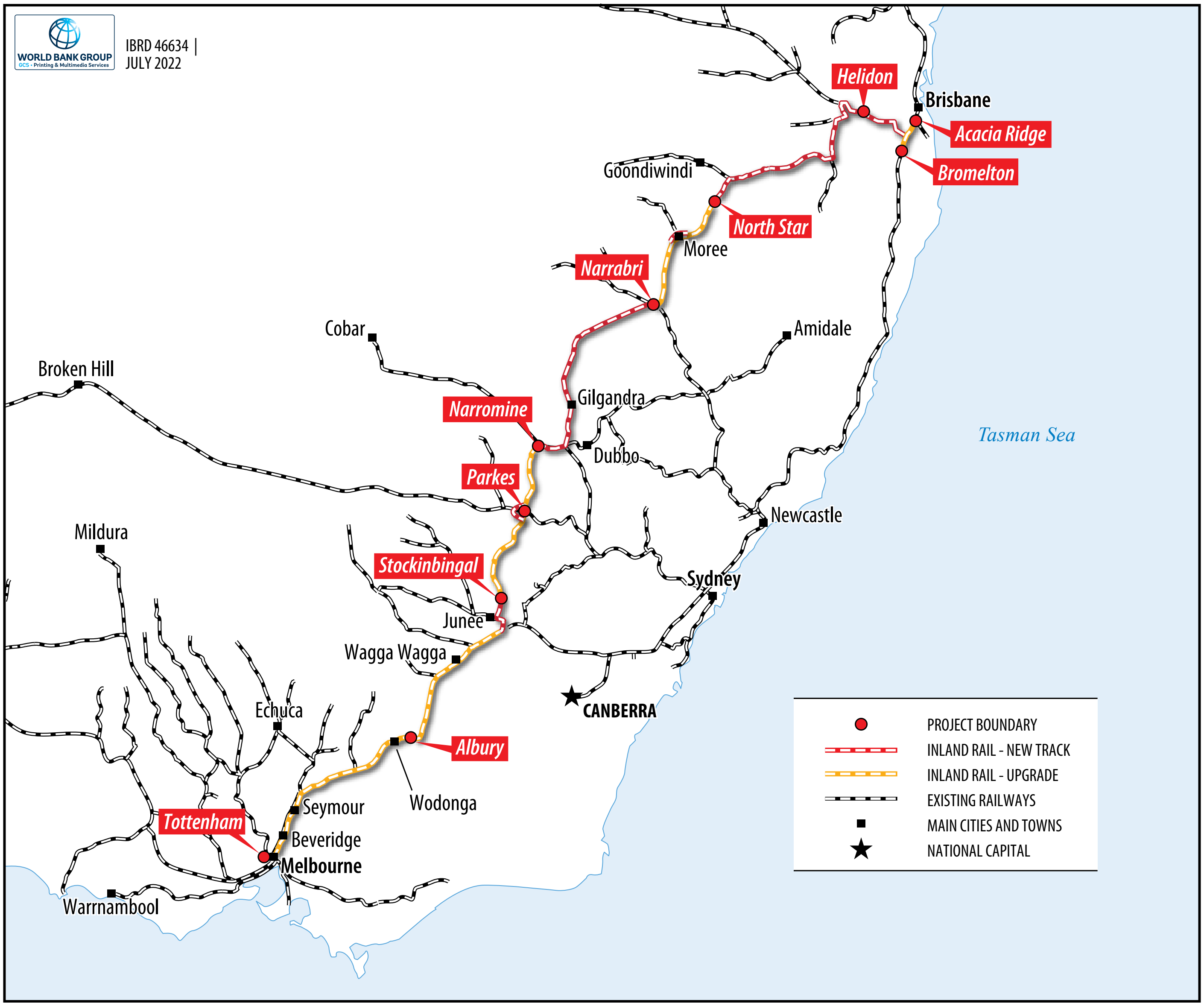
[9] Karachi has two active ports: The Port of Karachi, located in the center of the built-up area, and Port Qasim, about 50 kilometers east of Karachi and surrounded by some heavy industrial facilities and relatively undeveloped land.

from 34 hours to 24 hours. In addition to improving both reliability and availability of rail service, the infrastructure is designed for 25-ton axle loads and with clearances for double-stack operation, which should allow considerable savings in unit operating costs. The new route will considerably improve end-to-end travel and also provide more rail options for industry and agriculture located along the route. The line is constructed as part of the national rail network, managed by the Australian Rail Track Corporation (ARTC), and will be open to all operators. Two new access intermodal terminals/logistics parks will anchor either end of the route.

Map 3.4. Inland Rail Alignment in Australia



Source: Map produced by the World Bank Cartography Unit (IBRD 46634| July 2022).

Image 3.4. Double-Stacked Containers in South Australia

Source: Photo by Michael Coghlan (2021), via Flickr. https://www.flickr.com/photos/mikecogh/51268687280/. License: CC BY-SA 2.0.

Currently, rail claims about 26 percent of the Melbourne–Brisbane freight market, with rates around 85 percent of the road equivalent. Rail costs on the new route should fall from 85 percent to an estimated 60 to 65 percent of the road cost. With improved service time, reliability, and cost compared to road, the rail mode share is forecast to increase from 26 percent to 60 to 65 percent, approaching the share achieved on the Melbourne–Perth route. GHG savings occur from mode shift from road to rail induced by the better cost and quality of service and from the improvement in railway operations (including shorter distance and lower fuel usage for rail traffic transferring from the existing route). These average approximately 38 grams of CO_2e per net ton-kilometer, which should total around 270,000 tons CO_2e for Melbourne–Brisbane freight in 2030.

Reference

Agência Brasil. 2003. “Lula inaugura Terminal Ferroviário da Ferronorte de Alto Araguaia.” *Agência Brasil*, June 3, 2003. http://memoria.ebc.com.br/agenciabrasil/noticia/2003-06-06/lula-inaugura-terminal-ferroviario-da-ferronorte-de-alto-araguaia.

Aritua, Bernard. 2019. *The Rail Freight Challenge for Emerging Economies*: How to Regain Modal Share. International Development in Focus Series. Washington, DC: World Bank. http://hdl.handle.net/10986/31089. License: CC BY 3.0 IGO.

Inland Rail Implementation Group. 2015. “Inland Rail Program Business Case.” Australian Rail Track Corporation Limited (ARTC), Brisbane. https://inlandrail.artc.com.au/inland-rail-program-business-case-2015/.

National Bureau of Statistics of China. 2021. “China Statistical Yearbook.” Beijing: China Statistics Press. http://www.stats.gov.cn/tjsj/ndsj/2021/indexeh.htm.

Nicolas, Jean-Pierre, and Damien David. 2009. “Passenger Transport and CO_2 Emissions.” *Atmospheric Environment* 43 (5): 1015–20. https://doi.org/10.1016/j.atmosenv.2008.10.030.

Péra, Thiago Guilherme, José Vicente Caixeta-Filho, and Delmy L. Salin. 2021. “Brazil Modal Share Analysis for Corn and Soybeans: 2010–19.” Sao Paulo: University of São Paulo, Escola Superior de Agricultura “Luiz de Queiroz,” (ESALQ/USP). https://esalqlog.esalq.usp.br/Brazil_modalshare_USDA-ESALQ2020.pdf.

RITES. 2013. “Chapter 2: India’s Transport Sector System Attributes and Past Performance.” In *Planning Commission Total Transport System Study*. Haryana, India: RITES, Ltd. https://docplayer.net/61045406-Planning-commission-total-transport-system-study-2-1-introduction.html.

Salin, Delmy L. 2021. “Soybean Transportation Guide: Brazil 2020.” U.S. Department of Agriculture (USDA), Agricultural Marketing Service. http://dx.doi.org/10.9752/TS048.08-2021.

Wang, Yuanqing, Liu Yang, Sunsheng Han, Chao Li, and T. V. Ramachandra. 2017. “Urban CO_2 Emissions in Xi’an and Bangalore by Commuters: Implications for Controlling Urban Transportation Carbon Dioxide Emissions in Developing Countries.” *Mitigation and Adaptation Strategies for Global Change* 22 (November): 993–1019. https://doi.org/10.1007/s11027-016-9704-1.

Chapter 4: Reducing Rail GHG Emissions with Technology Interventions

Key Messages from Chapter 4

- While modal shift to rail—even when diesel powered—has the greatest impact on GHG emissions, technical and operational improvements to rail systems themselves can bring additional climate benefits.
- GHG savings in rail operations can be generated by many types of technical interventions, with the greatest potential benefits coming from “greening” traction power. Currently, the technological intervention that yields the greatest potential savings is conversion from diesel power to electrification via fixed infrastructure, when the electricity is sourced from green energy. Battery traction also has large potential savings, with only small losses from storing and discharging the electricity. Currently, fuel cells using hydrogen have lower savings due to the losses during the electrolysis and subsequent fuel cell processing.
- Lower-emission traction technologies are developing at a rapid rate, but are still some years away from being commercially viable; fortunately, retrofitting opportunities exist that make investing in rail now the best opportunity for economic development and climate action. While expensive, fixed infrastructure electric power supply is currently the only established alternative to diesel locomotives, cost-competitive and cleaner technologies could be available in ten to fifteen years. Railways purchasing new diesel locomotives could wish to preserve the option to replace the diesel engine with either batteries or fuel cells when the mid-life overhaul is undertaken. This would avoid locking in the locomotive to diesel fuel for the whole of its operational life.
- Technological interventions beyond power supply have smaller but positive impact. In particular, replacing first- and second-generation diesel locomotives will reduce emissions and result in operational cost savings from fuel savings, reduced maintenance costs, and improved rollingstock utilization.

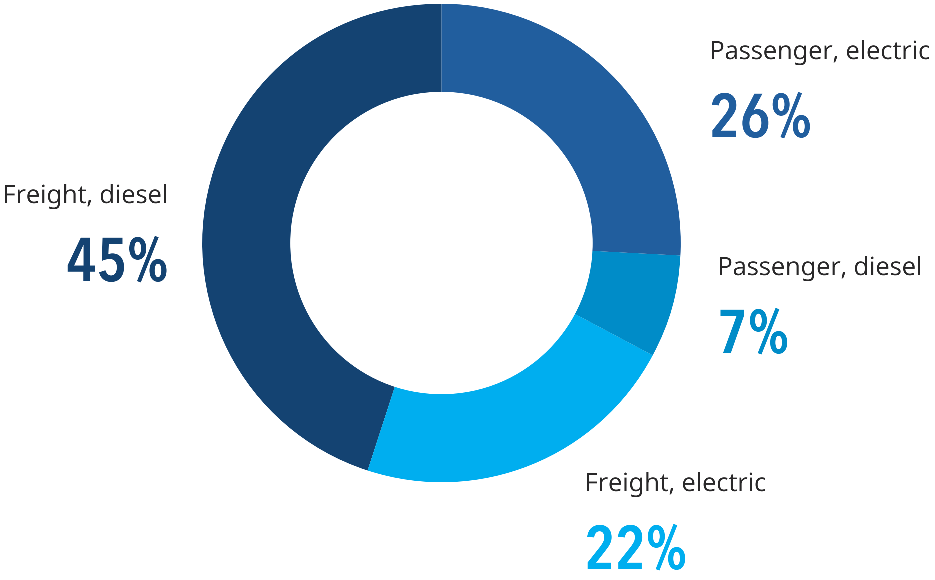
Reducing greenhouse gas (GHG) emissions from rail for a given transport task can take three basic approaches: (1) using fuel/energy with lower GHG emissions; (2) improving the energy efficiency of the conversion of fuel/energy into work; and (3) reducing the work required to perform the transport task. The gains from each approach are discussed below.

Lower GHG Emitting Fuel/Energy

In most countries, the largest potential GHG reduction from improving the rail operation itself will come from conversion of diesel to electric traction. Electric power as an alternative to diesel power can be supplied in three ways: (1) through the rail infrastructure; (2) provided with batteries onboard the train; or (3) generated from hydrogen using a fuel cell onboard the train.

Many railways, especially high-frequency suburban passenger railways, are already powered by electric energy provided through fixed infrastructure, mostly overhead catenary. Figure 4.1 shows that nearly half (50 percent) of the railway energy consumption globally stems from electric power sources.

Figure 4.1. Global Railway Energy Consumption by Segment for 2017



Source: IEA 2019, 110.

The capital cost of electrification with overhead catenary is approximately US$1 million per track-kilometer for straightforward layouts, with ongoing maintenance costs of roughly US$10,000 per track-kilometer per year. These costs will normally be offset by reduced energy costs and reduced locomotive maintenance costs throughout the life of the investment. For certain types of electric trains, the energy dissipated during braking can be partially recovered and either returned to the power supply for use by a subsequent train (a process known as regeneration) or stored either onboard or wayside for subsequent reuse. Electrification is usually financially justified when traffic density exceeds 5 to 10 million gross tons. The practicality and GHG value of converting from diesel to electric traction depend, however, on system reliability and the carbon content of the electricity supplied.

Conversion from diesel to electric power is practical only when electric power supply is available and reliable—a critical issue in many developing countries. Countries where power is unavailable or unreliable need to address power supply challenges before transitioning to electric traction. Otherwise, power outages will affect the railway service—slowing or stranding trains—and reduce its attractiveness and patronage.

Conversion from diesel to electric power reduces GHG emissions only when electric power supply is green (or greening). Electrification will only reduce GHG emissions if the electricity supplied has marginal carbon dioxide equivalent (CO_2e) grid emissions of under 800 grams per kilowatt-hour, after allowing for emissions during the production and transport of the fuel used to generate the emissions, and transmission and distribution losses. For example, at grid emissions of around 600 grams per kilowatt-hour (as in China in 2019), electrification can result in savings of nearly 25 percent compared to conventional diesel traction and at grid emissions of around 400 grams per kilowatt-hour (as in the United States in 2019) savings reach nearly 50 percent.[1] If grid CO_2e emissions are above 800 grams per kilowatt-hour, as is currently the case in, for example, South Africa,[2] electrifying the railway will result in increased overall GHG emissions. It is thus important to understand the power sector transition to green energy when planning to electrify a railway.

Electrification of traction using batteries is promising and more suited than overhead catenary for low-density lines. While battery-operated passenger trains have operated at various times for more than 100 years, interest in batteries has revived because of the potential for charging batteries via clean energy. In contrast to catenaries, batteries do not require a large infrastructure investment and are thus well-suited to railways with low traffic density. Batteries are very energy efficient, with around 90 percent of the energy used to charge the battery subsequently available for use in powering the locomotives or multiple units. The current disadvantages include the size, number, and weight of batteries required for long trips, plus the time required for recharging batteries.

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[1] Based on the diesel well-to-wheel (WTW) emission factor given in table A.1 in appendix A.

[2] See the data on 2019 electricity emission intensities for South Africa and other countries in table A.2 in appendix A.

- A regional passenger train (see table B.2 in appendix B) typically needs about 1,500 kilowatt-hours of energy to cover 300 kilometers per day. The batteries needed to supply this energy would currently weigh about 7 tons—approximately double the weight of a diesel engine and the fuel required for a comparable trip. (Kent, Inwicki, and Houghton 2019b).[3]

- A 1,140-ton intermodal freight train (see table B.6 in appendix B) traveling at 100 kilometers per hour uses about 2,000 kilowatt-hours per 100 kilometers. If the train stopped to recharge or change batteries every 4 hours, the batteries would weigh an extra 40 tons, requiring an additional wagon on most railways. Longer distances would require proportionately larger numbers of batteries or additional changes of batteries.

However, battery costs have reduced substantially and are expected to reduce even further. The capital cost differential between diesel and battery locomotives is dominated by battery costs. In mid-2021, battery costs had fallen to about US$135 per kilowatt-hour[4] (Phadke et al. 2021) when procured at scale, compared to US$300 per kilowatt-hour in the middle of the previous decade. These cost reductions have been largely driven by developments in the road vehicle industry. Costs could continue to reduce in the medium-term as lithium supply expands and possibly reach US$60 to US$80 per kilowatt-hour by 2030, significantly reducing the capital cost differential between diesel locomotives and battery locomotives. At the same time, the ratio of power to weight of batteries is climbing rapidly, thus increasing the interval between refueling stops.

Pure battery technology currently seems to be better suited to small passenger trains with smaller power requirements and opportunities for recharging between trips or to lower-powered locomotives such as shunting locomotives. The Bombardier Talent 3 train introduced in Austria in 2018, for example, claims to have a range of up to 100 kilometers, with batteries rechargeable from overhead lines—when available—or from ground sources, in around ten minutes. Similar trainsets have been developed by other manufacturers for use in other countries, including Japan and elsewhere in Europe. However, many of these are hybrid sets, with batteries complementing either conventional diesel or electric power, which are then recharged when braking.[5]

In at least one case, battery-powered linehaul locomotives are also being developed. Most seem to be designed to operate as one locomotive in a set of three or four, which can provide additional power when required while recharging from braking while the train is going downhill, and their additional power is not required. Pure battery operation of freight trains will require not only robust high-capacity batteries, but also recharging facilities capable of handling heavy loads without disrupting the main electricity distribution network.

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[3] Based on "Options for Traction Energy Decarbonisation in Rail: Options Evaluation" (Kent, Inwicki, and Houghton 2019b), but using 200 watt-hour per kilogram (wh/kg) for battery mass. Battery technology is changing fast and some are available at a claimed 400 wh/kg.

[4] For a freight locomotive wanting to have 18,000 kilowatt-hours (kWh) of storage, this represents a cost of over US$2 million.

[5] For example, in the United Kingdom, one operator has a hybrid train that shuts down its diesel power in a station and, when stationary, uses the batteries for the hotel load.

Image 4.1. Bombardier Talent 3 Battery-Electric Train Arrives in Austria for Testing

Source: ÖBB (Austrian Federal Railways), 2018, via Twitter. https://twitter.com/unsereOEBB/status/1063055035574206466.

The potential of hydrogen as an alternative source of energy is a function of fuel availability. Although direct combustion of hydrogen is technically possible, most research effort is concentrated on the development of hydrogen fuel cells. Importantly, hydrogen is a means for storing energy rather than being an energy source. In most foreseen transport applications, it is produced, distributed to an end-user, and then input to a fuel cell in a vehicle.[6] However, producing hydrogen using electrolysis (which currently generates the least GHG emissions if powered by low carbon electricity) and needs 50 to 55 kilowatt-hours to produce 1 kilogram of hydrogen containing about 40 kilowatt-hours of usable energy, which then outputs about 24 kilowatt-hours[7] from the fuel cell. So, the ratio of input electricity to the emission-free output electricity is at best 2.25 to 1 and once losses due to distribution are included the overall energy efficiency amounts to only 35 percent. Another barrier to the use of hydrogen as a major energy source for railways is the limited supply of green hydrogen; therefore, hydrogen fuel production and distribution infrastructure will need to expand significantly for this alternative energy source to become price competitive and readily available for railway operators.

Additionally, the full GHG emissions of the hydrogen need to be considered. When produced using electricity generated from fossil fuels, the emissions of hydrogen can be as high or higher than the direct combustion of diesel fuel if the grid emission factor is greater than 300 grams per kilowatt-hour. But if hydrogen is produced using green electricity, it generates few GHG emissions in total. The process by which the hydrogen is

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[6] It is also possible to use hydrogen as a fuel for an internal combustion engine, for which it is an ideal fuel with zero carbon dioxide equivalent (CO_2e) emissions, but such applications have not been developed so far in the railway industry.

[7] Thus 60 percent of the energy stored within the hydrogen molecules is converted into electricity. This assumes a proton exchange membrane (PEM) fuel cell, the most common type used in transport.

Image 4.2. Alstom's Coradia iLINT Prototype Hydrogen Train

Source: "World's First Hydrogen Train." Photo by Linus Follert (2018), via Flickr. https://www.flickr.com/photos/airbuxtehude/31289396838. License: CC BY-SA 2.0.

produced is thus critical in establishing its role in decarbonization. Hydrogen also typically requires ten times more storage space than diesel fuel. This can be accommodated in many multiple-unit passenger trains; however, storing hydrogen on a typical freight train would require an extra wagon with a storage tank.

The incremental capital cost of fuel cells is small, but the operating cost of hydrogen as a fuel needs to fall significantly to be competitive (Hydrogen Council 2020). Fuel cells currently cost around US$40 per kilowatt-hour, approximately 30 percent of the cost of lithium batteries. However, green hydrogen[8] is currently relatively costly at between US$3 to US$6 per kilogram produced (European Commission 2020). Although this cost will probably reduce once hydrogen fuel is produced at scale, costs will still be considerably more than conventional fossil fuels, such as oil. Fuel cells produce around 24 kilowatt-hours per kilogram of hydrogen and so would need a cost at the filling point of US$2.40 per kilogram to compete with a typical industrial electricity cost of US$0.10 (10 cents) per kilowatt-hour for battery power. If production of hydrogen expands and the price of renewable electricity drops sufficiently, such a cost for hydrogen appears achievable. While this is likely to be some years away, prototype rollingstock is already under development, for example, with a hydrogen-powered passenger multiple-unit (the two-car Coradia iLINT) already operating—mainly in Europe—with a claimed range of over 600 kilometers and a mainline freight locomotive under development in Canada.

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[8] Hydrogen produced using renewable resources. There are other types of hydrogen, but all generate greenhouse gas (GHG) during the manufacturing process.

Table 4.1. Alternative Fuels: Well-to-Wheel Emissions per Kilowatt-Hour

Technology	GHG emissions (kg CO_2e/kWh)
Diesel	0.83
Hydrogen in a combustion engine (steam methane reformation of natural gas)	0.80
Brown hydrogen (fuel cell)–formed by electrolysis using brown electricity	0.80
Liquified petroleum gas (LPG) in a combustion engine	0.70
Natural gas (compressed or liquified) in a combustion engine	0.60
Overhead electrification	0.33
Biodiesel[a]	Near zero
Green hydrogen (fuel cell)–formed by electrolysis using green electricity	Near zero

Source: "Options for Traction Energy Decarbonisation in Rail: Final Report" (Kent, Inwicki, and Houghton 2019a). Grid emission assumed as 280 grams per kilowatt-hour where applicable (330 grams per kilowatt-hour on a WTW basis).

Note: GHG = greenhouse gas; kg CO_2e/kWh = kilograms of carbon dioxide equivalent per kilowatt-hour.

[a] The assumed zero emissions for biodiesel clearly depend on the volume of biofuel that is used as feedstock. If crops are grown specifically for this purpose, the well-to-wheel (WTW) emission will be significantly greater than zero. In addition, such biofuels risk conflicting with food security.

Other alternative fuels could reduce GHG emissions during the energy transition. A variety of energy sources have been developed in recent years and have prototype vehicles already in operation. Table 4.1 summarizes the unit emissions per kilowatt-hour.

Some alternative fuels (for example, a blend of diesel and biofuels) could be valuable during a country's transition to green electricity. However, a significant risk exists for the lock-in and creation of stranded assets if countries invest heavily in the production and distribution of transition fuels likely to have only a very time-limited role in the low-carbon transition.

Railways can also green their stations and other facilities, through a variety of technologies ranging from installation of energy-efficient lighting to rooftop solar. India Railways, for example, aims to install rooftop solar in nearly 7,000 stations across India. The 1,000+ stations already equipped with solar power are generating over 120 megawatts of power (Thakur 2022).

Improving Energy-to-Work Efficiency

Over time, manufactures have improved the fuel efficiency of their locomotives, electric multiple-unit passenger train (EMUs), and diesel multiple-unit passenger train (DMUs). Innovations such as AC (alternating current) traction motors and wheel slip control technology have enabled newer locomotives to be more fuel efficient than older ones. For example, “third generation” diesel locomotives, first manufactured in the 1990s, are approximately 20 percent more fuel efficient than their predecessors. Manufacturers continue to improve the fuel efficiency of their products, although step changes in efficiency are not currently foreseen. Locomotives on most railways have economic lives of 30 to 40 years, so railways with aging fleets can expect to only realize gradual fuel savings and improved efficiency as they replace old locomotives with more modern ones, which represents a significant capital investment in most cases. Similarly, EMUs and DMUs have long lives, so the overall improvement from replacing older models with newer is likely to be gradual.

Reducing the Work per Transport Task

Numerous other measures can contribute to reducing the work required to deliver a transport task. In addition to reducing the ratio between gross ton-kilometer (the primary driver of energy usage) and the transport task (as measured by net ton-kilometer and passenger-kilometer), these measures include the following:

- Train drivers using driver-assistance tools to minimize acceleration and deceleration, thereby reducing fuel consumption; experience has demonstrated improvements of at least 5 percent.

- Review the use and need for traditional shunting locomotives and introduce rail tractors where practical.

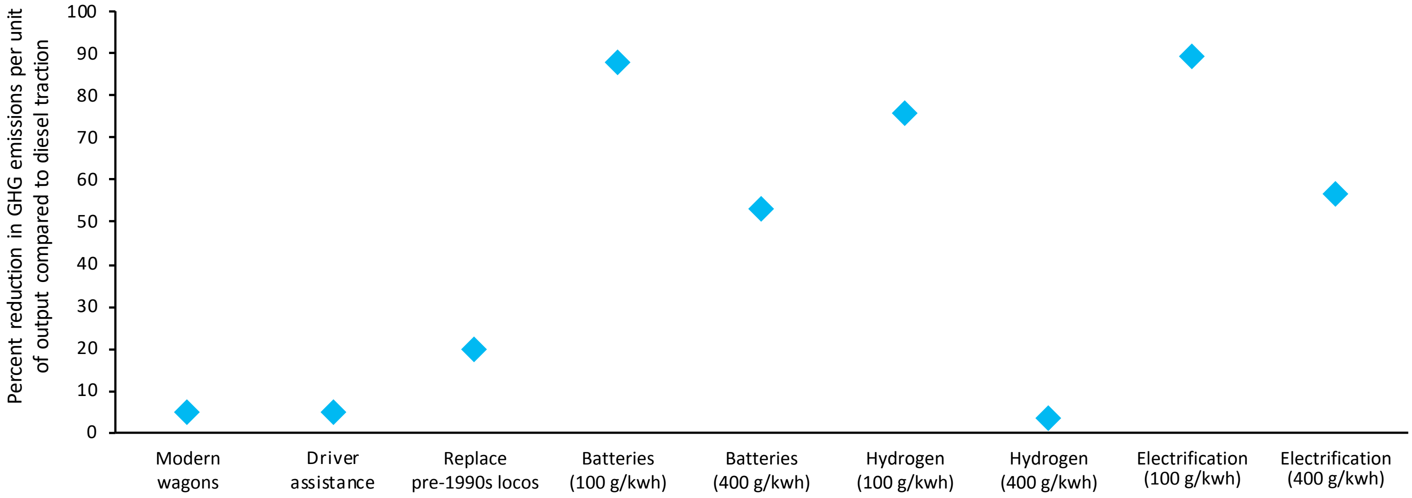
- Replace jointed track, where it remains, with continuously welded rail to help reduce fuel consumption by 5 to 10 percent (Kerkápoly 1965).

- Lubricate curves to reduce friction between vehicle wheels and the track.

Comparison of Interventions

GHG savings in rail operations can be generated by many types of technical interventions. As shown in figure 4.2, the technological intervention that yields the greatest potential savings is electrification via fixed infrastructure, when the electricity is sourced from green energy. Battery traction also has large potential savings, with only small losses from storing and discharging the electricity. Currently, fuel cells using hydrogen have lower savings due to the losses during the electrolysis and subsequent fuel cell processing. If the electricity source has an emission factor greater than 400 grams per kilowatt-hour, hydrogen fuel cells worsen GHG emissions, once transmission losses and fuel production and transport emissions are considered. Although not of the same magnitude as electrification, other interventions are also beneficial, particularly replacing first and second-generation diesel locomotives where these remain. These upgrades will also result in operational cost savings from fuel savings, reduced maintenance costs, and improved rollingstock utilization.

Figure 4.2. Emissions Reduction from Technological Interventions Compared to Diesel Traction



Source: Original figure produced for this publication.

Note: GHG = greenhouse gas; g/kwh = grams per kilowatt-hour.

Each technological option for reducing railway GHG emissions comes with costs, advantages, and disadvantages, as summarized in table 4.2.

Table 4.2. Summary of Technological Options

Intervention	Potential GHG reduction (percent)	Approximate cost	Advantages	Disadvantages
Electrification	60–90	US$1 million/kilometer ± 50%. Maintenance cost US$10,000/km, per annum	Permanent solution, requires reliable and low-carbon electricity.	Requires electric multiple-units (EMUs) and locomotives
Hydrogen	5–75	Cost of fuel cells/kilowatt is reducing, but also needs cheaper hydrogen	Fast refueling and longer range than batteries	Requires reliable supply of cheap renewable hydrogen (~US$2/kilogram)
Batteries	55–85	Cost of batteries per kilowatt-hour has reduced very fast	Already in service for small multiple-unit passenger services and shunting locomotives	Batteries are a significant weight for larger trains and recharging is relatively slow
Modern diesel locomotives	Up to 20	US$2–3 million per locomotive	Easy to implement. Lower maintenance cost, higher reliability, increased tractive effort	Commits to diesel for 30 years, but there will be opportunities for mid-life conversion
Driver assistance	5-8	Very small	Easy and quick to implement. Better driver information should reduce overall operating costs	
Modern wagons	5	US$100,000 per wagon	Lower maintenance costs and more efficient loading will improve rail's competitiveness	

Source: Original table produced for this publication.

Railway assets have long lives, while developments in lower-emission technology are moving at a rapid rate. During the next few years, the sector must ensure any investment does not lock-in a railway to a technology that becomes inferior in the medium/long term. Currently, the only established alternative to a mainline diesel locomotive is electric power supply through expensive fixed infrastructure. However, in ten or fifteen years, there could be cost-competitive and cleaner technologies available. Railways purchasing new diesel locomotives, might wish to ensure that the option exists to replace the diesel engine with either batteries or fuel cells when the mid-life overhaul is undertaken. This would avoid locking in the locomotive to diesel fuel for the whole of its operational life.

Reference

European Commission. 2020. “Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: A Hydrogen Strategy for a Climate-Neutral Europe.” COM(2020) 301 final, European Commission, Brussels. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0301.

Hydrogen Council. 2020. “Path to Hydrogen Competitiveness: A Cost Perspective.” Policy Paper, Institution of Gas Engineers and Managers (IGEM), Derby, United Kingdom. https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf.

IEA (International Energy Agency). 2019. “The Future of Rail.” Technology report, IEA, Paris. https://www.iea.org/reports/the-future-of-rail.

Kent, Stephen, Simon Inwicki, and T. Houghton. 2019a. “Options for Traction Energy Decarbonisation in Rail: Final Report.” RSSB Research Report T1145, Rail Safety and Standards Board, London. https://www.sparkrail.org/Lists/Records/DispForm.aspx?ID=26141.

Kent, Stephen, Simon Inwicki, and T. Houghton. 2019b. “Options for Traction Energy Decarbonisation in Rail: Options Evaluation.” RSSB Research Report T1145, Rail Safety and Standards Board, London. https://www.sparkrail.org/Lists/Records/DispForm.aspx?ID=25995.

Kerkápoly, Endre. 1965. “Der lückenlos geschweisste Oberbau aus der Sicht des Eisenbahnbetriebs.” [“The seamlessly welded superstructure from the point of view of railway operations.”] *Eisenbahntechnische Rundschau (ETR) [Railway Technical Review* (RTR)] 14 (12): 16–24.

Phadke, Amol, Aditya Khandekar, Nikit Abhyankar, David Wooley, and Deepak Rajagopal. 2021. “Why Regional and Long-Haul Trucks are Primed for Electrification Now.” Report, Lawrence Berkeley National Laboratory, Berkeley, California. https://eta-publications.lbl.gov/publications/why-regional-and-long-haul-trucks-are.

Thakur, Rajesh Kumar. 2022. “Indian Railways Pushes Rooftop Solar to Meet Its Energy Needs.” New Indian Express, January 17, 2022. https://www.newindianexpress.com/nation/2022/jan/17/indian-railways-pushes-rooftop-solar-to-meet-its-energy-needs-2407883.html.

Chapter 5: Policy Options to Encourage Greening of Transport with Rail

Key Messages from Chapter 5

- Governments have a range of tools to encourage shift to rail and adoption of GHG efficient technologies, including: (1) pricing and taxing measures; (2) planning and land-use measures; (3) financial measures (investments and operating support); and (4) governance of the railway enterprise and the railway sector.
- These measures are most effective when used together. While pricing and taxing measures can create economic incentives toward reducing GHG emissions, a competitive rail alternative is necessary before modal shift will happen. This could require government interventions in planning and land use, financial support, and good governance to achieve.
- The appropriate mix of interventions for maximizing the contribution of rail to transport decarbonization will vary in each country. The report suggests a structured process for identifying the needed interventions.

Governments have a range of tools to encourage shift to rail and adoption of technologies that are more energy efficient. Pricing and taxing measures can provide appropriate economic signals to encourage reducing GHG emissions. Planning and land-use measures can encourage concentrated development around rail nodes and intermodal connections with other modes. Financial measures (investments and operating support); and good governance of the railway enterprise and the railway sector are needed to deliver good rail service. This chapter summarizes the range of interventions available to policy makers to encourage shift to rail and adoption of GHG efficient technologies and suggests an approach for selecting the appropriate set of policies for individual countries.

Pricing and Taxing Measures

Governments have significant influence on the transport prices customers face, and the relative prices of different modes. Pricing mechanisms are generally viewed as efficient measures used to support strategies to reduce emissions. This is primarily due to their broad coverage, extensive duration, and potential level of ambition achieved by one policy (Tvinnereim 2014). Over time, properly calibrating these pricing measures will send the correct economic signals and provide incentives for a broad range of actions to reduce GHG emissions, including shifting to less GHG-emitting modes and adopting green technologies.

The most basic pricing/taxing measure is to eliminate subsidies and other supports that encourage use of carbon-based fuels. For example, in 2015, Indonesia substantially reduced its subsidies for diesel and gasoline in one step by 80 percent, resulting in approximately US$20 billion becoming available for other programs. Phasing out subsidies for carbon-based fuels normally needs to be coupled with programs to offset the impact on poor citizens and done gradually to avoid “shocking” the economy.

Carbon pricing mechanisms can provide additional incentives to reduce GHG emissions. Carbon pricing mechanisms have two main variants: emissions trading systems and carbon taxes. The emissions trading systems approach sets a baseline or a cap on emissions and creates a market for trading emissions credits. Carbon taxes are charged for GHG emissions and are often levied on the sale of fossil fuels, including fuel for transport. More than 60 countries and regions have implemented a carbon pricing mechanism to discourage GHG emissions, with around half of those mechanisms being emissions trading systems and the other half being carbon taxes. Approximately one-third of these mechanisms apply to transport.

Carbon prices must be set at a meaningful level to be impactful. Prices range from less than US$1 to US$120 per ton carbon dioxide equivalent (tCO_2e). Prices in developing country hover on the lower end. For example, Argentina charges US$5 per tCO_2e, or US$0.02 (2 cents) per liter.[1] This represents less than 1 percent of the total fuel price in Argentina (Climate Transparency 2020) and was designed to have minimal immediate

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[1] See the World Bank’s Carbon Price Dashboard: https://carbonpricingdashboard.worldbank.org/map_data.

impact on the price of fuel, as it replaces a gasoline tax.[2] Such a price is unlikely to change transport behavior or have a significant impact on transport GHG emissions.

Balancing cost recovery of infrastructure can encourage modal shift to rail. In some countries, rail users (usually freight users) are charged all or a substantial portion of the cost of providing rail infrastructure, while government-provided support for building roads and highways and cost recovery through fuel taxes and tolls is modest. Rebalancing the cost recovery (as is done now in many European countries) would "level the playing field" for rail.

Similarly, internalizing external costs can encourage modal shift to rail. Each form of transport generates external costs—GHG emissions, noise, congestion, and crashes—borne by others. These can be measured, costed, and taxed to the entities generating them. However, these steps are often politically difficult and various countries have instead introduced policies that—rather than penalizing road modes—offer financial support based on the externalities avoided if traffic moves by rail or water rather than by road. The United Kingdom's Mode-Shift Revenue Support (MSRS) is such a program (box 5.1). It has helped increase rail's mode share from the main container ports, which has now reached 50 percent in some of the main corridors.

Box 5.1. United Kingdom: Mode-Shift Revenue Support

The Mode-Shift Revenue Support (MSRS) Program in the United Kingdom assists "companies with the operating costs associated with running rail or inland water freight transport instead of road . . . to facilitate and support modal shift" (Arup & Partners 2020, 8). Over the past five years, nearly £100 million British pounds of funding has been awarded to 10 different companies, enabling the realization of significant externality benefits in terms of environmental benefits, road traffic congestion, accidents, and noise pollution. Different versions of the scheme apply for intermodal container, for bulk freight, and inland waterways.

In operation since 2010, the MSRS program divides the United Kingdom into 18 zones with a maximum grant for each container moved between two specific zones, whether empty or full and no matter the size. One set of rates applies to port movements, with one road leg, and another for purely domestic movements, with two road legs. The maximum rates are set to equal the difference between road and rail for a particular journey; actual grants are generally considerably less than the maximum. The bulk freight scheme follows similar principles.

In fiscal year 2018/19, MSRS grants supported the movement by rail of around 900,000 intermodal containers at a cost of about £16 million, or £18 per container.

Scotland and Wales also offer freight facilities grants (FFGs), which help offset the capital cost of providing rail and water freight handling facilities.

Source: Lawrence and Ollivier 2015, 59.

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[2] See the "Argentina Country Profile" for 2018, published on the Green Fiscal Policy Network website: https://greenfiscalpolicy.org/policy_briefs/argentina-country-profile/.

Financial Support for Rail

Public sector financial support will be key to shifting traffic from road and air to rail. Most plans for rail to attract customers from higher-emitting modes start with investment to build or improve the railway infrastructure so that the railway services can be competitive with alternatives. Such interventions could range from upgrading an existing freight line (US$500,000 to US$1 million per track-kilometer); to increasing speeds on conventional intercity passenger lines (US$1 million to US$3 million per track-kilometer); to building a new high-speed railway line (US$10 million to US$30 million per route-kilometer), depending on the market. In lower-density markets, government will also need to provide support for maintenance of infrastructure (as it does for roads). Government will also need to support the operations of many suburban and interurban rail services, so they can provide competitive quality services and affordable prices.

For example, the government of India supports the Dedicated Freight Corridor Corporation of India, Ltd. in building new, high-capacity dedicated freight corridors (DFCs) parallel to existing mixed-use and heavily congested lines. The construction of these DFCs is part of India's nationally determined contributions under the Paris Climate Agreement[3] and are intended to provide high-quality rail freight transport that will attract freight traffic from road to rail. Lines under construction will connect Mumbai and New Delhi (western corridor) and Ludhiana and Deen Dayal Upadhyay (eastern corridor), with some sections of each corridor already operating. The initiation of a truck-on-train service between Panlapur and New Rewari on the western corridor illustrates an early success in the DFCs shifting trucks from road to rail (box 5.2).

Box 5.2. Truck on Train Service in India

The truck-on-train service puts trucks onto flat wagons for transport by rail. The service, which can handle 300 trucks per day, delivers the trucks in 10 hours, compared to 24 to 36 hours by road. In the first 11 months of operation, the service transported nearly 5,000 trucks, saving an estimated 1.1 million liters of diesel fuel and over 3,000 tons of GHG emissions.

Source: Information provided by the Dedicated Freight Corridor Corporation of India, Ltd.

Governments can also support railways in shifting to green technology. While most railways will naturally favor GHG-reducing technology because of energy cost savings, railways might not be able to afford the investment involved. Governments could accelerate these investments by funding them or supporting the railway to obtain low-cost financing for them.

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[3] As quoted in India's nationally determined contribution report, submitted to the UNFCCC in 2016: "Dedicated Freight Corridors (DFCs) have been introduced across the country. In the first phase, two corridors viz. 1,520 kilometer Mumbai–Delhi (Western Dedicated Freight Corridor) and 1,856 kilometer Ludhiana–Dankuni (Eastern Dedicated Freight Corridor) are being constructed. The project is expected to reduce emissions by about 457 million tons carbon dioxide (CO_2) over a 30 year period" (Government of India 2016, 14).

Planning and Land Use

Governments play a key role in the planning and coordination of transport and can leverage that role to meet transport needs while greening transport. Key efforts include the following:

- Support railway development in rail-appropriate markets. When considering how to meet transport needs, governments should support rail investment in markets where rail can offer competitive service and lower cost.
- Integrate rail with other modes. Connect rail physically to other modes, with common passenger stations, intermodal logistics facilities and efficient rail infrastructure at ports. Governments should support integrated ticketing for suburban rail and provision of multimodal services for intercity transport.
- Land use. Include land-use planning in the development of transport plans, so that cities can benefit from densification around passenger stations and railways can benefit from the concentration of passenger flows and improved access and egress provided by transit-oriented development. Governments should encourage or even require logistics facilities to build rail as well as road access.

An example that combines elements of all three efforts is the Moorebank Logistics Park, currently under development in Sydney, Australia (box 5.3). This will be a key facility for long-distance freight to and from Sydney for which rail is becoming increasingly competitive. Moorebank Logistics Park offers a direct link to a major container port and has already become the national distribution center for a major Australian retailer.

Box 5.3. Moorebank Logistics Park

Moorebank Logistics Park (MLP), under development in western Sydney, links the main Sydney container port by rail direct to terminals and warehousing on a 243-hectare site. The precinct has the capacity to handle up to 1.05 million twenty-foot equivalent units (TEUs) of import–export (IMEX) freight and 0.5 million TEUs of interstate freight per year. It will have 850,000 square meters of high-quality warehousing as well as auxiliary facilities. Direct rail connections to the existing rail network and two major arterial roads are being constructed. Australia has had an open-access rail policy for over 30 years and both the IMEX and interstate rail terminals will operate as open-access terminals, accessible to all operators and with standard charges.

The project is overseen by a land trust, owned jointly by a government company and a private investor, which acts as the landlord. Much of the site was previously an Army base and the government is the majority shareholder in the trust. The overall development of the logistics park itself, including the leasing of warehousing space and the development and operation of the rail terminals is being undertaken by a subsidiary of the land trust investor. Individual tenants can then develop their own warehouses subject to a masterplan.

Source: Moorebank Logistics Park website (LOGOS Property, Australia): https://logosmlp.com.au/.

Governance

Railways will only deliver competitive service and shift traffic from higher emitting modes if the railway is incentivized and empowered to provide competitive services. At the national level, governments can encourage rail-competitiveness by addressing the following (World Bank 2017):

- Sector structure. Setting the sector structure to encourage efficiency and market orientation, including through encouraging fair competition and providing for private sector participation in the sector.
- Sector governance. Adapting the economic regulation of the sector to be objective and fair and encourage innovation and customer service. Requiring railway entities to report on GHG emissions and measures to reduce them.
- Corporate governance. Where the railway is a state-owned enterprise, establishing arm's length oversight that allows railway management to make commercial decisions within the framework of the government's objectives related to safety, traffic, financial sustainability, and care of assets. Paying for loss-generating services provided by the railway, so that they railway can maintain financial viability.

Developing a Decarbonization Policy

Policy measures are most effective when used together. Pricing and taxing measures are relatively ineffective at shifting traffic from road to rail unless an adequate rail service alternative is available. In the absence of a reliable and accessible alternative mode, increases in road freight transport costs, for example, will manifest as additional charges that burden road freight users and the economy. Creating an attractive alternative often requires both investment in infrastructure and rollingstock as well as customer-oriented management of the railway enterprise. Smart investment requires coordinated planning and land use so that railway lines connect with other modes for first- and last-mile connectivity and easy transfer.

The European Union (EU) was a leader in developing a policy with both pricing/taxing measures with financial measures to shift freight from road to rail. In 1992, the EU issued a Combined Transport (CT) Directive (92/16/EEC) to promote multimodal transport. The directive aimed to eliminate regulatory and quantitative restrictions on CT operations and allowed financial support for CT (box 5.4). The CT directive is supported by the Weights and Dimensions Directive 2015/719, which enabled countries to allow heavier load limits for the feeder legs of CT movements.

The EU is currently reviewing the CT directive to increase its scope and impact. By 2015, direct grants were implemented by five countries and five other countries made attempts, but then discontinued them. Seven countries had relaxed vehicle weight and dimension limits for the feeder legs of CT. Contributions to intermodal terminal capital costs were provided by 10 countries, ranging from support for rail connections to improvements in internal layouts. Such support can be particularly effective in helping terminal operators negotiate the interface with the rail infrastructure authority. An independent review determined that direct funding for intermodal-related infrastructure and the intermodal services themselves were the two most effective approaches to internalizing the externalities of road transport and encourage a shift to CT (KombiConsult 2015).

Box 5.4. Policies Implemented under the European Union Combined Transport Directive

As of 2017, policies related to combine transport (CT) formed five main groups (the number of countries implementing them is given in brackets):

- Exemption from all or part of road taxes for intermodal road feeder legs (17 countries);
- Exemption from other charges and restrictions for the feeder legs (12);
- Reduced rail network access charges (4);
- Aid (direct grants) for intermodal operations (6); and
- Aid (direct grants) for investments in intermodal terminal infrastructure (10).

Source: KombiConsult 2015.

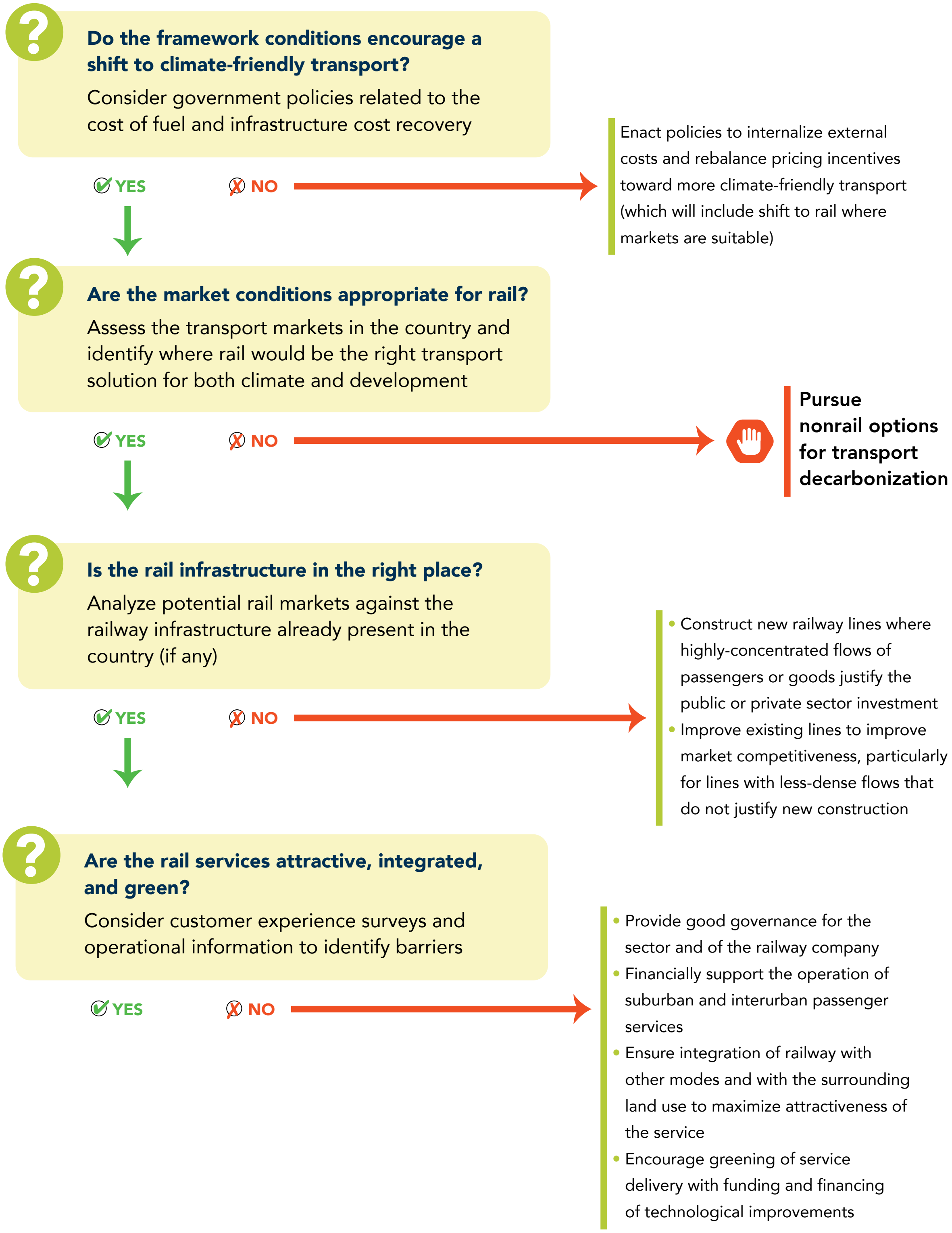
Outside the EU, Switzerland's program to shift transit road freight to rail combines financial support with pricing relief from road tolls. The program targets intermodal freight that could transit Switzerland by rail, including the following:

- Grants for trans-Alpine CT road/rail services;
- Support for investments in CT terminals and equipment; and
- Reimbursement of road tolls for pre- and post-rail movement.

Switzerland reports this program has reduced transit freight volume by approximately one-third.

The right mix of interventions for maximizing the contribution of rail to transport decarbonization will vary in each country. The process for determining the appropriate mix might follow the series of questions shown in figure 5.1. Such interventions will help railways continue to play an important role in social and economic development and the greening of transport.

Figure 5.1. Policy Process and Key Questions for Determining Rail’s Role in Transport Decarbonization in a Given Country



Do the framework conditions encourage a shift to climate-friendly transport?

Consider government policies related to the cost of fuel and infrastructure cost recovery

✓ YES ✗ NO

Enact policies to internalize external costs and rebalance pricing incentives toward more climate-friendly transport (which will include shift to rail where markets are suitable)

Are the market conditions appropriate for rail?

Assess the transport markets in the country and identify where rail would be the right transport solution for both climate and development

✓ YES ✗ NO

Pursue nonrail options for transport decarbonization

Is the rail infrastructure in the right place?

Analyze potential rail markets against the railway infrastructure already present in the country (if any)

✓ YES ✗ NO

- Construct new railway lines where highly-concentrated flows of passengers or goods justify the public or private sector investment
- Improve existing lines to improve market competitiveness, particularly for lines with less-dense flows that do not justify new construction

Are the rail services attractive, integrated, and green?

Consider customer experience surveys and operational information to identify barriers

✓ YES ✗ NO

- Provide good governance for the sector and of the railway company
- Financially support the operation of suburban and interurban passenger services
- Ensure integration of railway with other modes and with the surrounding land use to maximize attractiveness of the service
- Encourage greening of service delivery with funding and financing of technological improvements

Source: Original figure produced for this publication

Reference

Arup & Partners. 2020. "Review of Revenue Support Freight Grant Schemes: Final Report." Prepared for the Department for Transport, Ove Arup & Partners, Ltd., London. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/864460/review-revenue-support-freight-grant-schemes.pdf.

Climate Transparency. 2020. "Argentina Country Profile 2020." Profile extracted from the "Climate Transparency Report 2020." Climate Transparency, Berlin. https://www.climate-transparency.org/media/argentina-country-profile-2020.

Government of India. 2016. "India's Intended Nationally Determined Contribution: Working Towards Climate Justice." Report submitted to the United Nations Framework Convention on Climate Change (UNFCCC). https://unfccc.int/sites/default/files/NDC/2022-06/INDIA%20INDC%20TO%20UNFCCC.pdf.

KombiConsult. 2015. "Analysis of the EU Combined Transport: Final Report." Study prepared for European Commission, Directorate-General for Mobility and Transport, Publications Office of the European Union, Luxembourg. https://transport.ec.europa.eu/system/files/2016-09/2015-01-freight-logistics-lot2-combined-transport.pdf.

Tvinnereim, Endre. 2014. "The Bears Are Right: Why Cap-and-Trade Yields Greater Emissions Reductions than Expected, and What that Means for Climate Policy." *Climatic Change* 127 (November): 447–61. https://doi.org/10.1007/s10584-014-1282-1.

World Bank. 2017. "Railway Reform: A Toolkit for Improving Rail Sector Performance." 2nd ed. Toolkit (online and print), Transport and ICT Global Practice and the Public-Private Infrastructure Advisory Facility (PPIAF), World Bank, Washington, DC. https://ppiaf.org/sites/ppiaf.org/files/documents/toolkits/railways_toolkit/index.html.

Appendix A: Emission Factors

The fossil-fuel emission factors used in this paper include well-to-wheel (WTW) emissions. In this report, WTW emissions include (1) emissions generated during the actual operation of the vehicle, commonly known as tank-to-wheel (TTW) emissions; (2) emissions associated with electricity generation; and (3) emissions associated with getting the fuel to the vehicle that uses it, sometimes referred to as well-to-tank (WTT) emissions. Emission factors (given in table A.1) have been taken from the standards adopted for emissions reporting in the European Union (EU), which include both WTW (all) and TTW (operation only) estimates.

Table A.1. Petroleum Fuels Emission Intensitie

Fuel type	Density (kg/liter)	Kg CO_2e/liter		Kg CO_2/liter	
		TTW	WTW	TTW	WTW
Gasoline	0.745	2.42	2.88	2.36	2.82
Ethanol	0.794	0.06	1.24	0.00	0.60
Diesel	0.832	2.67	3.24	2.63	3.19
Biodiesel	0.890	0.07	1.92	0.00	0.55
Liquified petroleum gas (LPG)	0.550	1.71	1.90	1.66	1.85
Aviation gasoline (AvGas)	0.800	2.50	3.01	2.48	2.99
Jet gasoline (Jet B)	0.800	2.50	3.01	2.48	2.99
Jet kerosene (Jet A1 and Jet A)	0.800	2.54	3.10	2.52	3.08
Heavy fuel oil (HFO)	0.970	3.06	3.31	3.02	3.28
Marine diesel oil (MDO)	0.900	2.92	3.53	2.89	3.50
Marine gas oil (MGO)	0.890	2.88	3.49	2.86	3.46

Source: CEN 2012.
Note: Kg CO_2e/liter = kilograms of carbon dioxide equivalent per liter; kg CO_2/liter = kilograms of carbon dioxide per liter; kg/L = kilogram per liter; TTW = tank-to-wheel; WTW = well-to-wheel.

Electricity-related emissions are given for a selected group of countries quoted in the examples in the paper (table A.2). Emissions are based on grid averages based on the electricity dispatched to third parties. These are in turn based on International Energy Agency (IEA) data—publicly available online for some countries to 2019 and for others to 2017—which has been adjusted by 2 percent to convert from carbon dioxide (CO_2) to carbon dioxide equivalent (CO_2e), combined with individual country data, where available (United Kingdom and France). For Scope 3 emissions, 15 percent has been added in all cases. Transmission and distribution losses have been taken as 4 percent for high-voltage lines to, for example, railway networks, with a further 6 percent for distribution to low-voltage recharging outlets.

Table A.2. Electricity Emission Intensities, 2019

Grams of carbon dioxide equivalent per kilowatt-hour (g CO_2e/kWh)

	2019 grid	Upstream	High-voltage distribution	Low-voltage distribution
United States	391	59	465	489
Russia	374	56	445	468
China	610	92	726	763
South Africa	937	94	1,068	1,124
Brazil	112	17	133	140
Germany	357	54	425	446
France	51	8	61	64
India	735	110	875	919
Georgia	110	17	131	138
United Kingdom	198	30	236	248

Source: World Bank estimates based on the International Energy Agency (IEA) dataset: "Emissions per kWh of Electricity and Heat Output (Edition 2018)," IEA CO_2 Emissions from Fuel Combustion Statistics: Greenhouse Gas Emissions from Energy (database), Paris, IEA (accessed August 30, 2022), https://doi.org/10.1787/5f382d97-en.

Classification of Emissions

The Greenhouse Gas Protocol, developed in the 1990s, provides a comprehensive, global, standardized framework for measuring and managing emissions. It classifies greenhouse gas (GHG) emissions into three groups: Scope 1, Scope 2, and Scope 3.

- **Scope 1** emissions are produced directly from railway-owned and controlled resources. They arise from both stationary combustion (for example, diesel or coal boilers to heat buildings) and mobile combustion, such as diesel rail traction, infrastructure maintenance equipment, or terminal plant. Where railways generate all or part of their electricity the associated emissions are also Scope 1.

- **Scope 2** emissions are produced indirectly from the consumption of purchased energy, such as electricity or district heating. For railways this is overwhelmingly electricity, which is used for traction as well as providing power for track equipment (signals, points), stations, offices, depots, and workshops.

- **Scope 3** includes all other indirect emissions—not included in Scope 2—generated in the provision of inputs to the railway (such as the production of ballast, sleepers and rail) or in the disposal of by-products (for example, scrapping of vehicles). The GHG Protocol[1] separates these into 15 categories, almost all of which could be applicable to railways.

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[1] For more details on the GHG Protocol guidance for the Scope 3 technical calculation, see: https://ghgprotocol.org/scope-3-technical-calculation-guidance. To read the full GHG Protocol, go to: https://ghgprotocol.org.

While several railways nowadays routinely report Scope 1 and Scope 2 emissions, Scope 3 emissions are much more difficult to estimate and, in most cases, depend on factors outside the control of railways.[2] One specific example is the emissions involved in extracting, processing, and transporting fuel and energy before its use by the railway.[3] These will vary from situation to situation, but a reasonable working figure is 15 percent above the "tank-to-wheel" (TTW) emission factors; when included, the total emissions are given the generic title of "well-to-wheel" (WTW). The TTW emissions are thus equivalent to Scope 1 (for diesel) and Scope 2 (for electricity) while the difference between the WTW and TTW figures is Scope 3. The emissions incurred during the production and supply of material, spare parts and other inputs is also Scope 3. Few detailed estimates are available of the breakup between these three groups of emissions although individual railways are increasingly providing detailed analyses on an annual basis.[4]

Most reporting covers emissions occurring in the normal course of operations. However, emissions are also created during the construction of infrastructure and the manufacturing and disposal of rollingstock and other assets. These emissions, which occur at irregular intervals, are typically converted to an annual average and then combined with operational emissions to produce life-cycle emissions. Another way to incorporate construction emissions into consideration is to calculate an emissions payback period.

Reference

Canadian National Railway. 2020. "2020 Sustainability Report: Delivering Responsibly." Canadian National Railway, Montreal. https://www.delivering-responsibly.cn.ca/.

CEN (European Committee for Standardization). 2012. "Methodology for Calculation and Declaration of Energy Consumption and GHG Emissions of Transport Services (Freight and Passengers)." CSN EN 16258. CEN, Brussels. https://www.en-standard.eu/csn-en-16258-methodology-for-calculation-and-declaration-of-energy-consumption-and-ghg-emissions-of-transport-services-freight-and-passengers/.

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[2] Where they have been calculated, they have been quite large; however, most in this case were associated with the extraction, refining, and transport of its diesel fuel.

[3] For electricity this includes processing the fuel used for generation and transmission losses between the generation plant and the railway substations. Losses between the substation and the locomotive are normally included in Scope 2 but sometimes in Scope 3.

[4] See, for example, the sustainability report published by Canadian National Railway (2020).

Appendix B: Calculation of Operational Emissions by Mode

Overview

Table B.1 summarizes various calculations comparing the greenhouse gas (GHG) emissions from rail with emissions from other modes.

Broad statements on the relative “carbon footprint” of the different modes can be made with some confidence. However, the wide variation in the passenger estimates—reflecting differing assumptions on vehicle occupancy and average load, the distance traveled (in the case of aircraft), the terrain (in the case of road and especially rail) and the average speed of travel—means that such factors need to be considered when drawing conclusions in individual situations. Similar uncertainties exist for freight, as highway freight can be carried in vehicles of widely differing sizes, with specific consumption steadily decreasing as the size increases. Where modes are powered by electricity, grid emission factors—in kilograms of carbon dioxide equivalent per kilowatt-hour (kg CO_2e/kWh)—vary sharply between countries as well as over time. Intermodal comparisons, therefore, must be done with care to ensure comparability. Finally, the application of these estimates, for any given origin and destination, should also consider the distance between them will vary by mode, with air generally being the most direct.

This appendix provides normalized estimates of unit energy consumption for each mode under a range of assumptions. These have been converted into emission estimates using the emission factors given previously in appendix A.

Table B.1. Examples of GHG Emissions Comparisons by Mode

Source	Year	Passenger (g CO_2e/pkm)				Freight (g CO_2e/ntkm)		
		Rail	Bus[a]	Car	Air	Rail	Truck	IW
Japan/East Japan Railway Co.	2019	19	56	137	96	–	–	–
Germany/TREMOD	2016	12/63[c]	32	142	211	22	101	31
France/ADEME[b]	2018	3–24	147	133	141	10	92	30
Taiwan/HSR	2019	34	68	102	272	–	–	–
IEA	2020	6–101	37–124	70–220[d]	93–133	–	–	–
United Kingdom/DEFRA	2020	37	27	58–174[d]	82–129[e]	26	85	–

Source: Japan East: East Japan Railway Company 2021; Germany/TREMOD: Transport Emissions Model: https://www.ifeu.de/en/methods-tools/models/tremod/; France ADEME: ADEME website: https://bilans-ges.ademe.fr, 2019; Taiwan HSR: THSRC 2020; IEA: IEA 2021; UK DEFRA: DBEIS 2020.

Note: g CO_2e/pkm = grams of carbon dioxide equivalent per passenger-kilometer; g CO_2e/ntkm = grams of carbon dioxide equivalent per net ton-kilometer; IW = inland waterway; TREMOD = Transport Emission Model; ADEME = ADEME = Agence de l’environnement et de la maîtrise de l’énergie; HSR = high-speed rail; IEA = International Energy Agency; DEFRA = U.K. Department for Environment, Food and Rural Affairs.

a. The higher bus emissions levels appear to be from urban buses; the lower levels appear to be from long-distance coaches.

b. Estimates for France assume 1.6 passengers per car.

c. In Germany, high speed rail (HSR) = 12, and conventional service = 63.

d. Estimates for passenger car emissions by the IEA assume one passenger in car (213 and 174), and three passengers in car (71 and 58).

e. The estimates for air passenger emissions in the United Kingdom would nearly double if radiative forcing is allowed for (see box B.1). This appears to have been assumed in both the German and Taiwan estimates.

Passenger Rail

Intercity passenger services fall into three broad groups:

- High-speed services, typically traveling at 200 kilometers per hour (kph) and above
- Conventional mainline services, typically trains with up to 10 carriages, but often larger in countries such as China, India, Russia, and Pakistan
- Regional services, which typically call at almost all stations, rarely reach even 80 kph and range in size from eight-car multiple-unit services in the Commonwealth of Independent States (CIS) to two or three carriages hauled by locomotives in others

Table B.2 gives typical train characteristics, which have been assumed to prepare normalized energy consumption estimates.

Table B.2. Typical Passenger Train Characteristics[a]

Train type	Traction	Carriages	Gross weight	Commercial speed (kph)[b]	Technical speed (kph)[c]	Stops per 100 km	Capacity (Passengers per train)	Load factor (%)
HST	MU	8	345	200	250	1	460	75
Mainline	Loco	12	640	75	90	2	960	75
Regional	MU	4	140	40	60	10	240	30

Source: World Bank analysis.

Note: HST = high-speed train; MU = multiple-unit passenger train; kph = kilometers per hour; km = kilometer.

a. All services are assumed to be operating over moderately flat terrain (3 meter per kilometer rise and fall), with good track for HST and moderate track for mainline and regional.

b. Average speed including en-route stops.

c. Average speed excluding en-route stops.

Energy is initially required to accelerate from rest, and subsequently if the train is slowed or makes intermediate stops. Traction energy is also consumed in various ways by trains to overcome resistances to motion, summarized as follows:

- *Rolling resistance*, representing the resistance on a flat section of track from friction between the wheels and the rail as well as friction from the axle bearings of the vehicles. Rolling resistance is broadly constant with train speed.
- *Air resistance*, often included within rolling resistance. Air resistance is largely (but not completely) independent of the size of the train, but varies at about the square of the speed, and becomes the dominant form of resistance for high-speed trains.
- *Grade resistance*, a direct function of the increase in altitude covered by the train, whether completed in one long climb or a series of short undulations. In theory, grade resistance could be balanced to some extent by the gain in energy when descending, though this often seems to be relatively small by comparison.
- Curve resistance, which reflects the resistance between the rail and wheels when negotiating a curve. This is very small in most cases and can be neglected.

Table B.3. Components of Energy Consumption by Passenger Train Type

Megajoules per thousand gross ton-kilometers (MJ/'000 gtkm)

Train type	Traction type	Rolling resistance	Grade resistance	Air resistance	Stops	"Hotel" power	Total
HST	MU	6	20	167	35	11	239
Mainline	Loco	9	30	17	6	38	100
Regional	MU	9	30	31	14	7	91

Source: World Bank analysis.
Note: HST = high-speed train; MU = multiple-unit passenger train.

Table B.4. Unit Fuel Consumptions and Emissions from Operations by Passenger Train Type

Train type	Fuel/seat-km		Fuel/pkm		WTW emissions/seat-km (g CO_2e)		WTW emissions/pkm (g CO_2e)	
	Diesel (L)	Electric (kWh)	Diesel (L)	Electric (kWh)	Diesel	Electric	Diesel	Electric
HST		0.058		0.077		23		31
Mainline	0.006	0.022	0.008	0.029	18	9	24	12
Regional	0.005	0.017	0.015	0.057	14	7	48	23

Source: World Bank analysis.
Note: Seat-km = seats per kilometers; pkm = passenger-kilometer; WTW = well-to-wheel; g CO_2e = grams carbon dioxide equivalent; HST = high-speed train; L = liter; kWh = kilowatt-hour. Conversion from seat-km to pkm based on load factor, Table B-2.

Trains, especially passenger trains, also need to provide power for on-train services, such as lighting, wi-fi and climate control (for example, heating and air-conditioning) in passenger cars. Known as the "hotel load," this power use varies significantly between train types and services.

The various types of resistance have been studied intensively over many years and modified as technology has developed.[1] Formulae have been developed to estimate resistance in terms of train size, axle load, speed, and grade, of which the best known are the Davis formulae, developed in the United States. Similar formulae have been developed in other countries,[2] especially for high-speed passenger trains. These have been used in table B.3 to estimate the components of energy consumption for the three train types given earlier, in table B.2 (Lukaszewicz 2001).

The energy consumption is the same whether the service is fueled by either diesel or electricity[3] and thus can be readily converted into specific fuel consumption given factors for the efficiency of the tractive unit[4] (table B.4). The table also gives emissions per seat-

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[1] For example, the rolling resistance term covering vehicle bearing resistance was reduced as roller bearings replaced what were known as journal bearings.

[2] For example, the "von Borries Formel," "Leitzmann Formel," and "function de Barbier."

[3] Or, indeed, hydrogen or battery electric.

[4] The conversions assume 1 liter of diesel fuel can provide 11.8 megajoules (MJ) at the rim in a modern diesel locomotive, while a modern electric locomotive should be able to apply 3.1 kilowatt-hour (kWh) at the rim. The theoretical ratio of kWh:liters to perform the same amount of work is thus 3.8:1, though this varies in particular cases depending on the actual rim efficiencies and experience has shown a ratio of 3.4:1 is more commonly observed in practice.

kilometer and per passenger-kilometer, using the well-to-wheel (WTW) emission factors of appendix A.

On a straight level track, and when running at a constant speed, energy consumption is a function of the mass and average speed of train. At 200 kph around 70 percent of the energy consumed is required to overcome wind resistance; this resistance increases at approximately the speed to the power of 1.6 and at 350 kph around 90 percent of the energy consumed is required for this task.

Although wide variations exist between the different train types, the influence of track characteristics is relatively small for most passenger trains. An average rise of 5 meters per 100 kilometers, equivalent to hilly terrain, would only increase the total resistance, and hence fuel consumption, by 10 to 20 percent. The most significant influences are speed and onboard facilities. A mainline train on very flat ground running at a speed of, say, 75 kph and with minimal onboard facilities (such as basic lighting and overhead fans) would only use about 45 megajoules per thousand gross ton-kilometers (MJ/'000 gtkm), equivalent to about 4 liters per thousand gross ton-kilometers (L/'000 gtkm).

Table B.5 provides a selection of reported fuel consumption for different passenger services. Most of these figures are systemwide estimates that average across different routes with varying terrain and stop distances, for example. Therefore, consumption on any given service within these systems could vary by a range of –20 percent to +50 percent. As examples, both the Indian and Ukrainian electric services primarily operate on relatively flat terrain at fairly low speeds, while the Taiwanese conventional services operate over relatively hilly terrain at a rather faster speed. The Ukrainian diesel services, by contrast, mostly operate in a much hillier region of Ukraine.

Table B.5. Reported Fuel Consumption by Type of Passenger Service

Country	Year	Train type	Passengers/train	Commercial speed (kph)	Liter/'000 gtkm	KWh/'000 gtkm
Ukraine	2018	Interurban	380	58	9	15
Ukraine	2018	Regional	105	36	10	23
India	2018	Nonsuburban	1,452	44	4	20
China	2015	Conventional	640	82	6	25
China	2015	HSR	960	200	–	38
Spain	2015	Conventional	77	80	9	40
Spain	2015	HSR[a]	248	132	–	38
Japan	2014	HSR	–	–	–	60
Japan	2014	Conventional	–	–	–	53
Taiwan	2019	HSR	673	162	–	89
Taiwan	2017	Conventional	251	74	–	70

Source: World Bank analysis, based on unpublished data for Ukraine and China. For India and Spain, the analysis was based on data provided in Government of India 2019 and Spanish Railways Foundation 2020. For Taiwan, data on high-speed rail services came from THSRC 2020 and data for conventional services from the Taiwan Railways Annual Report 2017: http:/www.railway.gov.tw/tw/.

Note: kph = kilometers per hour; '000 gtkm = thousand gross ton-kilometers; HSR = high-speed rail.

a. The HSR in Spain (Alta Velocidad Española, AVE) = 70 percent; other long-distance networks = 30 percent.

Freight Rail

Freight services can be classified into three broad groups:

- Bulk freight, typically traveling loaded in one direction and empty in the reverse
- Intermodal services, typically loaded at least partially in the reverse direction
- General freight services, operating with a mixture of empty and loaded wagons in both directions

The normalized estimates of fuel consumption are based on the train characteristics given in table B.6. As the train characteristics of the first two types are quite different in the two directions, these have been distinguished in the analysis.

Table B.7 summarizes the components of energy consumption, in the same format as presented for passenger services.

Table B.6. Freight Train Characteristics Assumed for Normalized Energy Consumption Estimates

Train type	Direction	Wagons	Gross weight (kilograms)	Net weight (kilograms)	Technical speed	Stops per 100 km
Bulk	Loaded	50	3,500	2,500	60	1
	Empty	50	1,000	0	80	1
Intermodal	Loaded	30	1,440	900	90	1
	Return	30	840	300	90	1
General	Both	20	1,000	600	70	2

Source: World Bank analysis.
Note: All services are assumed to be operating over moderately flat terrain (3 meters per kilometer rise and fall), with moderate track.

Table B.7. Components of Energy Consumption by Freight Train Type

Megajoules per thousand gross ton-kilometer (MJ/'000 gtkm)

Train type	Direction	Rolling resistance	Grade resistance	Air resistance	Stops	Total
Bulk	Loaded	11	30	5	1	47
	Empty	20	30	14	2	67
Intermodal	Loaded	10	30	14	3	57
	Return	20	30	20	3	71
General	Both	10	30	12	4	55

Source: World Bank analysis.

The energy consumption is the same whether the service is powered by either diesel or electricity and thus can be converted into specific fuel consumption as discussed earlier. Table B.8 also gives emissions per gross ton-kilometer (gtkm) and per net ton-kilometer (ntkm), using the WTW emission factors provided in appendix A.

Table B.8. Unit Fuel Consumptions and Emissions from Operations by Freight Train Type

Train type	Direction	Fuel/'000 gtkm		WTW emissions/gtkm (g CO_2e)		WTW emissions/ntkm (g CO_2e)	
		Diesel (L)	Electric (kWh)	Diesel	Electric	Diesel	Electric
Bulk	Loaded	4.0	15.2	12.7	6.1	25.1	12.0
	Empty	5.7	21.6	18.1	8.6		
Intermodal	Loaded	4.8	18.4	15.4	7.3	32.4	15.4
	Return	6.2	23.7	19.8	9.5		
General	Both	4.7	17.9	15.0	7.1	24.9	11.9

Source: World Bank analysis.
Note: '000 gtkm = thousand gross ton-kilometers; WTW = well-to-wheel; g CO_2e = grams carbon dioxide equivalent; ntkm = net ton-kilometers; L = liter; kWh = kilowatt-hour.

In contrast to passenger trains, the main influence on freight train fuel consumption in practice is terrain. Most freight trains travel at speeds for which air resistance is not a major factor. Almost flat terrain, as in India, will see fuel consumption reduce to about 2.6 liter per thousand gtkm. Conversely, very hilly terrain, with an average rise of 7 meters per kilometer, will see fuel consumption increase to around 7 to 8 liters per thousand gtkm. However, a container train traveling at 140 kph will have over double the air resistance in table B.7 and its fuel consumption will increase by about 30 percent. Table B.9 gives a selection of reported fuel and energy consumption (mostly systemwide) for a range of operators.

Table B.9. Reported Fuel Consumption for Freight

Country	Year	Gross tons/train	Technical speed	Liter/'000 gtkm	KWh/'000 gtkm
Ukraine	2018	3,269	43	4.6	11.0
India	2018	3,191	44	2.3	5.4
China	2013	3,548	49	3.2	10.1
Spain	2019	905	53	7.6	32.0

Source: World Bank analysis.
Note: Liter/'000 gtkm = liter per gross ton-kilometer; kWh/'000 gtkm = kilowatt-hour per thousand gross ton-kilometer.

Road Transport

Estimates of road transport emissions have been generated based on specific assumptions on vehicle characteristics and loading (table B.10). The estimates focus on nonurban operations and specifically those likely to compete or substitute for rail transport.

Table B.10. Road Transport Characteristics Assumed for Normalized Energy Consumption Estimates

Type	Fuel	Average speed (kph)	Occupancy (%)	Capacity (passenger or tons)	Emissions/pkm, ntkm (g CO_2e)
Car	Gasoline	70	50	4	108
Minibus	Gasoline	70	65	12	51
Coach (basic)	Diesel	60	75	50	17
Coach (standard)	Diesel	75	70	40	34
Medium truck	Diesel	60	60	10	107
Heavy truck	Diesel	50	60	20	80

Source: World Bank analysis.
Note: kph = kilometers per hour; pkm = passenger-kilometer; ntkm = net ton-kilometer; g CO_2e = grams carbon dioxide equivalent.

As with rail, all services are assumed to be operating over moderately flat terrain—with a 3 meter per kilometer rise and fall—and over sealed roads in reasonable condition, with an international roughness index (IRI) of 3 to 4.

Table B.10 gives the fuel consumption assumed for each vehicle type. Several sources provide estimates of fuel consumption by vehicle type for developed countries. Examples include the following:

- Estimates published annually by the Federal Highways Administration (FHWA), specific to U.S. vehicle types and operating conditions.
- Estimates updated annually by the U.K. Department for Environment, Food and Rural Affairs (DEFRA).
- Estimates included in the “Handbook on the External Costs of Transport” (European Commission 2020), revised at irregular intervals.
- The estimates based on the COPERT[5] model, developed by the European Commission.

All consistently show average nonurban fuel consumptions for cars of 6 to 7 liters per 100 kilometers—though these will be for better-quality roads than are often found in developing countries. Therefore, 8 liters per 100 kilometers has been assumed in this report. Another source for coach fuel consumption is from industry surveys; consumption for a range of Volvo buses operating across Europe in 2012 and averaging 60 kph was

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[5] Developed by the European Commission to assist in estimating national emission inventories on a consistent basis, the COPERT methodology, a computer software-based tool, calculates emissions from road transport.

around 25 liters per 100 kilometers, which could increase to around 30 liters per 100 kilometers for interurban operation.

Several specialist studies have been conducted in Europe based on analysis of individual trucks under varying operating conditions, such as congestion, grade, emission standards (Euro V, Euro VI, etc.) (Ziyadi et al. 2018; Notter, Keller, and Cox 2019). These are essentially microsimulation models, but in the United States some detailed studies have also been done using specially instrumented heavy vehicles during commercial operations.

Broadbased estimates for developing countries are difficult to find. One of the most comprehensive is the operating statistics published annually in India on the performance of the publicly owned bus operators (Government of India 2020). This covers 56 operators, but many operate either wholly or partially provide urban services that have been excluded; only those with an average passenger trip length of over 75 kilometers (12 operators) have been considered. These operated buses report an average capacity of 50 passengers, an average load factor of 75 percent, and an average fuel consumption of 19.5 liter per 100 kilometers. This fuel consumption is much lower than for European operators, but these buses will typically have very limited ancillary demands, such as air conditioning, phone chargers, onboard toilets and wi-fi. However, other operators in India, and in many other developing countries, operate long-distance buses similar to European standards.

A toll-road study in China (ADB 2008) surveyed the estimated fuel consumption of 1,200 road users at a variety of sites. Average consumptions totaled 10 liters per 100 kilometers for car; 16 liters per 100 kilometers for minibus; and 20 liters per 100 kilometers and 30 liters per 100 kilometers for medium and heavy trucks respectively.

Water Transport

Inland waterways compete with railways in few locations in developing countries, other than the Yangtze in China and the Amazon basin in Brazil, both of which are largely served by ocean-going vessels. The earlier estimate in table B.1 is based on TREMOD, the official Transport Emission Model used by the German government; it will be specific to the Rhine and the associated waterways, and no independent estimate has been developed for this report.

The main circumstances in which railways and ocean shipping compete is for container transport between China as well as various locations in Eurasia and Europe. The shipping route is invariably much longer; however, the scale of the large container vessels is such that total GHG emissions are comparable under current operating conditions. Table B.11 considers three sizes of container ship: one operating on the China–Europe route, one operating to secondary ports such as Karachi, and a feeder vessel operating between a hub port such as Dubai and a regional port such as Umm Qasr in Iraq. The analysis assumes the same pattern of demand as the container train in table B.6: fully loaded in one direction, but with two-thirds of the containers empty on the return leg. Fuel density (heavy fuel oil, or HFO) is taken as 1,176 liters per ton with a well-to-propeller emission factor as given in appendix A.

Table B.11. Container Vessel Characteristics Assumed for Normalized Energy Consumption Estimates

Ship type	Capacity (TEU)	Deadweight tonnage (DWT)	Net tons (average)[a]	Speed (knots)	Fuel (HFO) (tons/day)	Emissions (g CO_2e/ntk)
Core service	20,000	220,000	146,000	24	260	7
Secondary	4,500	46,000	32,850	24	144	18
Feeder	1,000	11,000	7,300	24	31	17

Source: World Bank analysis.

Note: TEU = twenty-foot equivalent unit; HFO = heavy fuel oil; g CO_2e/ntk = grams carbon dioxide equivalent per net ton-kilometer.

a. Based on 10 tons per twenty-foot equivalent unit (TEU), loaded, and 2 tons/TEU, empty.

The characteristics include an average speed of 24 knots, which historically was the speed most containerships were designed to sail. Nowadays, “slow steaming” is a much more widespread practice, and this reduces daily consumption by one-third, although this reduction could require some modifications to the vessel. After allowing for the longer voyage at the lower speed, fuel consumption and emissions could be 25 percent lower than those shown in the table.

Air Transport

Passenger railways and airlines compete for travel in the 300 to 1,200 kilometer range; airlines offer few shorter flights—and even in China, with the fastest high-speed rail (HSR) in the world, rail finds it difficult to compete with air at longer distances. These sectors are normally flown using jet aircraft with capacities of 150 to 250 passengers. Table B.12 gives the fuel consumptions assumed for this report, together with emissions per seat-kilometer (seat-km), per passenger-kilometer (pkm), and per net ton-kilometer (ntkm), using the WTW emission factors in appendix A.

Box B.1. Radiative Forcing

Aviation has impacts on climate change both through its direct carbon dioxide equivalent (CO_2e) emissions as well as non-CO_2e effects from nitrogen oxides (NOx), aerosols, water vapor, contrails, and what was once described as “induced cirrus cloudiness.” A radiative forcing index (RFI) was introduced in 1999 to measure the relative strength of the CO_2e and non-CO_2e impacts, but this has been the subject of considerable research and reassessment over the intervening period. Current thinking is that little impact exists below 9,000 meters, though fuel emissions above that height should be factored (Cox and Althaus 2019).[a]

However, few flights of under 650 kilometers reach 9,000 meters and even at 1,200 kilometers the proportion of fuel spent during the cruise phase is relatively small. For the purposes of this paper the impact of the non-CO_2e effects has therefore been excluded.

Source: Cox and Althaus 2019.

Note: a. Cox and Althaus (2019) recommend a factor of 2 although the Atmosfair emissions calculator uses a factor of 3.

Such aircraft typically use substantial amounts of fuel when taking off, then use much lower volumes when cruising and then landing. These can be estimated using flight simulation packages and then converted into fuel and emissions generated per seat-km and pkm for flights of various lengths.

Estimation of the impact of aviation on global warming is complicated by the existence of substantial non-CO_2e impacts (box B.1), whose effects are only partially known. These have not been included in the calculations in this section. Table B.12 gives the estimated fuel consumption for these flights. In practice, fuel consumption can easily vary by 10 percent or more, depending on the airline operating strategy as well as weather and other events. In table B.13, these estimates have been converted into specific fuel and emissions per seat-km and pkm using the WTW emission factors in appendix A.

No emissions have been estimated for air freight; precise measurement is difficult as most air freight moves in the belly of passenger services and the emissions thus need to be apportioned between passenger and freight. Two main methods are used for this; both give emissions per ntkm 30 to 40 times greater than emissions for rail.

Table B.12. Aircraft Characteristics Assumed for Normalized Energy Consumption Estimates

Aircraft type	Fuel	Distance (km)	Cruise speed (kph)	Occupancy (%)	Seats
ATR 72-600	Avtur	400	510	75	70
Airbus 319	Avgas	700	829	75	134
Boeing 737-800	Avgas	1,000	842	75	189

Source: World Bank analysis.
Note: km = kilometers; kph = kilometers per hour; % = percent.

Table B.13. Unit Aviation Consumptions and Emissions

Aircraft	Fuel (liters)	Consumption (liters)		Emissions (g CO_2e)	
		Seat-km	Pkm	Seat-km	Pkm
ATR 72-600	740	.026	.035	80	108
Airbus 319	2,727	.029	.039	89	120
Boeing 737-800	4,157	.022	.029	68	89

Source: World Bank analysis.
Note: g CO_2e = grams carbon dioxide equivalent; seat-km = seat-kilometer; pkm = passenger-kilometer.

Reference

ADB (Asian Development Bank). 2008. “TA 4369 Expressway Tolls and Diversion Study.” Unpublished report.

Cox, Brian, and Hans-Jörg Althaus. 2019. “How to Include Non-CO_2 Climate Change Contributions of Air Travel at ETH Zurich.” ETH Zurich Research Collection. Report prepared on behalf of the Mobility Platform of ETH Zurich. INFRAS, Bern. https://doi.org/10.3929/ethz-b-000409314.

DBEIS (Department for Business, Energy & Industrial Strategy). 2020. “Greenhouse Gas Reporting: Conversion Factors 2020.” Statistics and other resources for research and analysis, Government of the United Kingdom, London. https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2020.

European Commission, Directorate-General for Mobility and Transport. 2020. “Handbook on the External Costs of Transport.” Version 2019–1.1, European Commission Publications Office, Luxembourg. https://data.europa.eu/doi/10.2832/51388.

Government of India. 2019. “Indian Railways Annual Statistical Statements 2018-19.” Report, Directorate of Statistics and Economics, Ministry of Railways (Railway Board), New Delhi. https://indianrailways.gov.in/railwayboard/uploads/directorate/stat_econ/2018-19/Stat_Annual_Statement_2018-19.pdf.

Government of India. 2020. “Review of the Performance of State Road Transport Undertakings for April, 2016 – March, 2017.” Transportation Research Wing, Ministry of Road Transport and Highways, New Delhi. https://morth.nic.in/sites/default/files/srtucopy_compressed.pdf.

IEA (International Energy Agency). 2021. “Rail.” Tracking report, IEA, Paris. https://www.iea.org/reports/rail.

East Japan Railway Company. 2021. “JR East Group Integrated Report 2021.” East Japan Railway Company, Tokyo. https://www.jreast.co.jp/e/environment/pdf_2021/all.pdf.

Lukaszewicz, Piotr. 2001. “Energy Consumption and Running Time for Trains: Modelling of Running Resistance and Driver Behaviour Based on Full Scale Testing.” Doctoral dissertation, Department of Vehicle Engineering, Royal Institute of Technology, Stockholm. https://www.diva-portal.org/smash/get/diva2:8954/FULLTEXT01.pdf.

Notter, Benedikt, Mario Keller, and Brian Cox. 2019. “HBEFA—Handbook of Emission Factors for Road Transport 4.1: Quick Reference.” INFRAS, Bern. https://www.hbefa.net/e/help/HBEFA41_help_en.pdf.

Spanish Railways Foundation (Fundación de los Ferrocarriles Españoles). 2020. “Observatorio del Ferrocarril en España: Informe 2019.” Report, Ministerio de Transportes, Movilidad y Agenda Urbana, Goberno de España, Madrid. https://cdn.mitma.gob.es/portal-web-drupal/ferroviario/observatorio/ofe_2019_mar2021.pdf.

THSRC (Taiwan High-Speed Rail Corporation). 2020. “2019 Annual Report.” THSRC, Taipei. https://www.thsrc.com.tw/event/InvestorRelations/ShareholdersMeeting/2019_anual_report_EN.pdf.

Ziyadi, Mojtaba, Hasan Ozer, Seunggu Kang, and Imad L. Al-Qadi. 2018. “Vehicle Energy Consumption and an Environmental Impact Calculation Model for the Transportation Infrastructure Systems.” *Journal of Cleaner Production* 174 (January): 424–36. https://doi.org/10.1016/j.jclepro.2017.10.292.

Appendix C: Non-Traction Emissions

Operational Non-Traction Emissions

Approximately 85 percent of the total emissions by railways are related to the energy required to operate trains, known as "traction" (UIC 2012). The traction proportion is generally higher for freight-only networks because they have no passenger stations, few other buildings, and simpler track layouts and signaling systems. Take as an example Aurizon and Canadian National with more than 90 percent of their energy usage for traction. Table C.1 shows the energy shares for a variety of railways.

A significant 15 percent of mixed railways operational emissions can thus be traced to "non-traction" emissions. An analysis of non-traction energy for infrastructure managers finds they typically use 50 to 60 percent for infrastructure operations (for example, signaling, power switches, and switch heating in winter) and the remainder for stations and other buildings. Train operators typically use almost all non-traction energy for stations and freight terminals, maintenance depots, and other buildings.

Although small compared to traction emissions, reducing non-traction emission represents a quick and relatively inexpensive way to start reducing GHG emissions in the sector. Specific interventions include the use of LED lights wherever possible, improved insulation in buildings, better temperature control, and more extensive installation of solar panels for local power supply.

Table C.1. Railway Energy Use

	Percent (%) traction
Ukraine	85
Aurizon	94
Canadian National	91
Indian Railways; diesel only	97
Poland (PKPE); electricity only	85

Source: Various, including Aurizon 2020 and Canadian National Railway 2020.
Note: PKPE = Polskie Koleje Państwowe Energetyka, an energy subsidiary of Polish Railways.

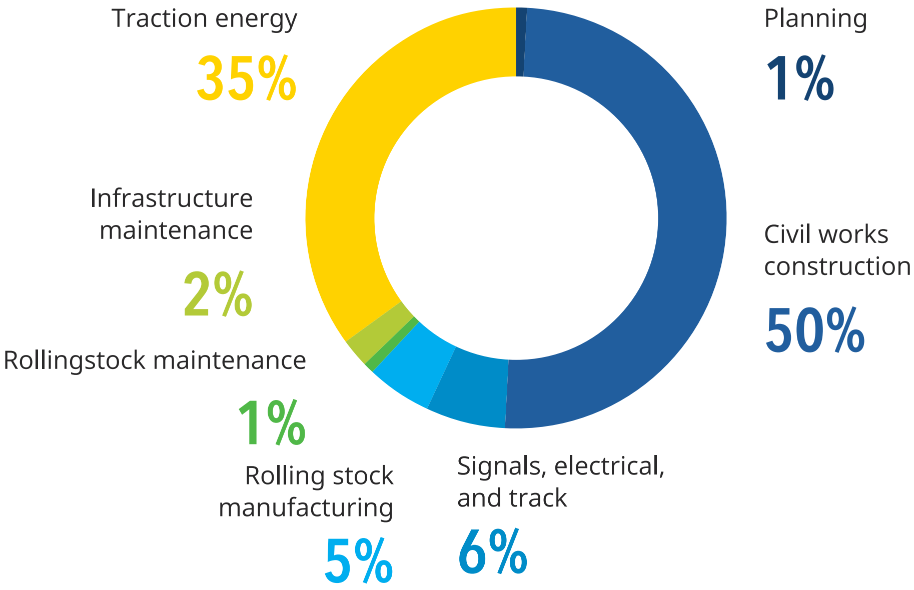
Construction Emissions

An alternative classification of emissions follows the life-cycle emissions (LCEs) approach as to include all emissions associated with a particular operation "from cradle to grave." LCEs could therefore include the following:

- Planning and design
- Infrastructure construction
- Rollingstock manufacture
- Operations
- Scrapping and disposal

Construction emissions tend to represent a significant share of LCE. Together with operational emissions, they dominate LCEs. As illustrated in figure C.1, a feasibility study analysis of the Rhine–Rhone high-speed rail (HSR) line, "ligne à grande vitesse," or LGV (ADEME, RFF, and SNCF 2009) showed construction emissions dwarf planning and rollingstock manufacture emissions. Scrapping and disposal emissions were not calculated, but would be minimal—with much of the rollingstock, track, and signaling/ electrical equipment typically recycled. But the traction emissions are unusually low in this example, as the line is powered by very low-carbon electricity generated largely from nuclear and hydroelectricity. In a more typical example, the traction-related emissions would be five or more times larger and would total more than 70 percent of the LCEs, with construction then making up a further 23 percent.

Figure C.1. Life-Cycle Emissions for Rhine–Rhone LGV



Source: Adapted from ADEME, RFF, and SNCF 2009.

Construction emissions have three main components—transporting materials to the site, the installation of the materials and the emissions created during the extraction or manufacture of the materials.[1] The first two of these are straightforward to measure, normally existing as direct functions of the energy consumed. The extraction/manufacturing emissions are based on estimates of the physical quantities of materials involved in construction with parameters giving the embedded emissions per unit of input.[2]

Construction emissions estimates used a range of methodologies for many years, with correspondingly wide-ranging results. In 2016 the International Union of Railways (UIC) compared 10 alternative methodologies for estimating LCEs (UIC 2016); five of them were each applied to three typical corridors (high-speed, a hilly freight line, and a short suburban line). The construction emissions for the three lines, converted into tons of carbon dioxide equivalent (CO_2e) at the time of construction, ranged from highest to lowest by 3:1. This was due to variations in the level of detail assumed in the different methodologies (such as the type and number of bridges or type of track structure) and also to the embedded emissions assumed for the various components, especially for the three main contributors: concrete, steel, and electricity. A separate literature review of LCEs generated from 57 rail projects of all types (Olugbenga, Kalyviotis, and Saxe 2021) concluded the estimation approaches had only limited comparability, and often generated location-specific results with limited transferability.

LCEs are often expressed in terms of emissions per annum or per traffic unit. This requires an estimate of the duration of the life cycle, which is typically taken to be the life of the longest-lasting component—usually the civil construction. This life cycle is normally taken to be 60 years (but sometimes 100 or 120 years) and some capital components will thus be replaced one or more times during the cycle.[3] The total emissions over the project life can then be converted into an equivalent annual figure and, using the traffic forecast for the project, into an equivalent amount per passenger-kilometers (pkm) or net ton-kilometers (ntkm), as shown in table C.2. As construction emissions are essentially independent of the use that will be made of the infrastructure, all construction emissions per pkm or ntkm are inversely proportional to the assumed forecast.

Standard methodologies[4] are now increasingly being adopted. Table C.2 provides three estimates of emissions for a single-track mixed-use line, prepared independently in India, Germany, and Sweden. The estimates are reasonably consistent, giving 1,300–2,100 tons CO_2e per route-kilometer, depending on the assumptions for earthworks, the embedded emissions from materials, and the average distance construction material is transported to the site. For double track, the emissions would be a little less than double, with some economies of scale for the earthworks. For any particular line, however, the estimates are going to depend on the proportion of the line that is on structure or in tunnel.

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[1] Some methodologies also now include the impact of land-use changes as a result of the project; these have not been considered in this report.

[2] These are generally obtained from economy-wide databases, such as Ecoinvent: https://ecoinvent.org/the-ecoinvent-database/.

[3] The same approach is normally employed for rollingstock, with lives from 20 to 40 years, depending on the type of service.

[4] Both the German and Swedish studies in table C.2 largely followed the "Product Category Rules (PCR) for preparing an Environmental Product Declaration (EPD) for Interurban railway transport services of passengers, a methodological framework created for how the construction and operation of the rail infrastructure and the manufacture of the rail vehicles should be taken into account in an environmental assessment. Another standard approach is (PAS 2080)" (BSI Group 2016).

Table C.2. Construction Emission Estimates for Single-Track Mixed-Use Railway Lines

Item	Unit	India[a]	Germany[b]	Sweden[c]
Subgrade	Route-km	-	195	830
Track	Route-km	-	432	393
Signals	Route-km	-	57	-
Subtotal	Route-km	1,294	684	1,223
Electrification	Electric route-km	-	25	86
Bridges	Bridge-km	-	9000	7,736
Tunnels	Tunnel-km	-	10,000–16,000	2,970
Stations	Station	-	600–10,000	16,000
Total		1,294	1,398	2,082
Type		Secondary	Network	Mainline
Traffic density (millions)		4	3.1	4.5
Greenhouse gas (g/pkm)[d]		5.4	7.5	7.7

Source: Various, including TERI 2012; Schmied and Mottschall 2013; Stripple and Uppenberg 2010.

Note:

a. See the "Life Cycle Analysis of Transport Modes (Volume 1)" (TERI 2012). Unelectrified line with only small bridges and no tunnels.

b. See Schmied and Mottschall 2013. Tunnel estimates are for driven (10,000) and cut-and-cover (16,000) tunnels separately.

c. See Stripple and Uppenberg 2010. Table figures exclude emissions from deforestation along railway. Tunnel estimates are for rock (that is, unlined) tunnels. Passenger density is combined passenger and freight.

d. Grams carbon dioxide equivalent (CO_2e) per passenger-kilometer. Assumes a 60-year life.

The German study quoted in table C.2 also analyzes the relationship of construction emissions to total LCE. This is done for different types of service, giving estimates of 12 to 18 percent for freight, long-distance passenger, and suburban passenger. Train operation averages about 70 percent with the remainder being largely infrastructure operation and maintenance.

Among intercity rail lines, high-speed lines typically have higher consumptions of concrete and steel—the two components generating most of the embedded emissions—with correspondingly higher construction emissions (see table C.3). However, this is balanced in the examples by the much higher passenger density.

The results for the various HSR lines reflect the different carbon intensities of energy generation, topography, and the impact of other environmental considerations, which can result in more tunneling (as in the case of HS2). Similarly, high speed lines in China are often elevated to minimize land-take, involving heavy use of concrete. Table B.4 estimated typical traction emissions for a HST at 30 to 40 grams CO_2e/pkm and the construction emissions calculated in table C.3 would thus be 15 to 20 percent of total emissions, similar to the conventional lines in table C.2. This ratio is, however, critically dependent on such lines achieving their planned traffic volumes. Lines that carry only 5 million passengers per annum are likely to have more than 50 percent of their total emissions resulting from construction.

Table C.3. Construction Emission Estimates for Double-Track High-Speed Rail

Item	UK HS2[a] Phase 2A	Beijing–Shenyang[b]	LGV Med[c]	LGV SEA[c]	Taiwan[c]	Beijing-Tianjin[c]
Distance	58	692	250	302	345	117
Percent of line in tunnel	5	32	5	–	14	–
Percent of line on viaduct	11	47	6	3	73	85
Earthworks (million cubic meters)	40	–	71	76	–	–
Number of stations	0	19	3	0	8	4
GHG emissions from construction per route-kilometer (tons CO_2e/rkm)	17,100	25,830	6,800	5,800	17,600	13,900
Average annual ridership (millions)	20 (est)	25	16	15	20	23
GHG emissions from construction per passenger-kilometer (g CO_2e/pkm)[d]	8.5	10.3	4.3	3.7	8.9	6.0

Source: Various, including unpublished World Bank data; Government of the UK 2017; and Baron et al. 2011.
Note: HS2 = The U.K.'s high-speed line; LGV Med = lignes à grande vitesse Méditerranée (high-speed rail line in France); LGV SEA = lignes à grande vitesse Sud Europe Atlantique (high speed rail line in France); GHG = greenhouse gas; kg CO_2e/rkm = kilograms carbon dioxide equivalent (CO_2e) per route-kilometer; g CO_2e/pkm = grams CO_2e per passenger-kilometer.

a. See Government of the UK 2017.
b. Estimates for Beijing–Shenyang line construction emissions based on unpublished World Bank data.
c. See Baron et al. 2011.
d. Data assumes 100-year life due to dominance of structures.

The same is true for inner-urban and suburban lines involving a lot of tunneling or viaducts and, in many cases, large below-ground stations. The construction emissions per route-kilometer for Crossrail, a major suburban rail project under construction across the center of London, with considerable new tunneling, are expected to be about 17,000 tons.[5] In Melbourne, the 9-kilometer Metro Tunnel, with five underground stations, has estimated construction emissions of 62,000 tons per route-kilometer, of which around 75 percent is associated with the stations. Another major suburban rail project in Melbourne, also planned to be largely underground, has estimated construction emissions for 26 kilometers of tunnels and 6 stations at 1.85 million tons, equivalent to 70,000 tons per route-kilometer.[6]

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[5] 1.7 million tons for the 100-kilometer route length. See the Crossrail webpage on "Energy Efficiency and Carbon" for more information on the project's expected construction emissions: https://learninglegacy.crossrail.co.uk/learning-legacy-themes/environment/energy-efficiency-and-carbon/.

[6] Nearly 40 percent of the emissions are for electricity used during construction, which in Victoria emits around 0.8kg/kilowatt-hour.

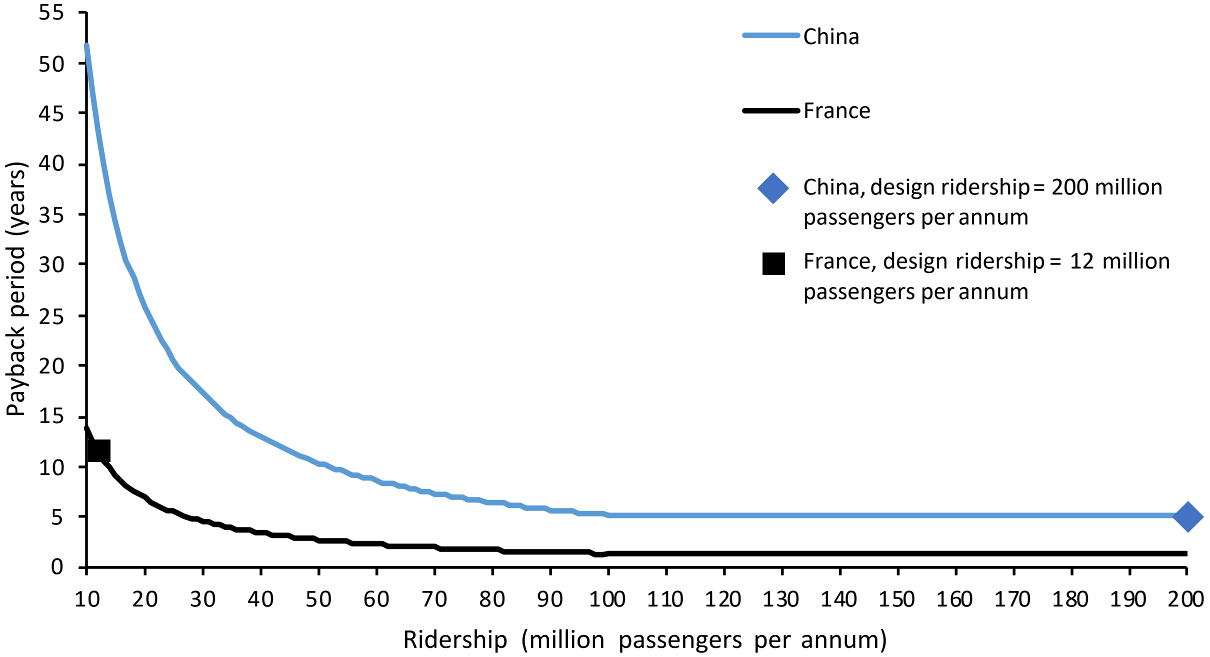
Comparisons of construction emissions between different rail projects, or between different modes, should be done with care. The variations between countries in the embedded emissions for individual materials can be significant, as can the variations in the emissions from electricity, as shown in the Melbourne examples above. Applying amortized construction emissions to completed infrastructure is also problematic, as the infrastructure construction emissions and, to a lesser extent, the vehicle construction emissions do not occur every year, but—in most cases—are long gone. Comparisons of modal construction emissions are probably best suited to the analysis of new construction when comparing between alternative modes, say between an intercity expressway and a parallel railway.

Emissions Payback Period

It is common to consider the carbon impact of a new project by calculating the carbon payback period. This is the time after project completion required for the carbon emissions saved from operating an investment to offset the emissions generated during construction. The payback period of rail projects is sensitive to assumptions about the diversion of traffic to rail from more carbon-intensive modes, load factors, and the source of energy for traction as well as the emissions from construction. The literature gives examples of the emission payback period of rail projects ranging from 5 to 70 years, with 20 years being a typical payback period (Olugbenga, Kalyviotis, and Saxe 2021).

The estimated payback period for high-speed passenger rail projects can range from 5 to 30 years, depending on the share of track underground or elevated, and the amount and source of diverted traffic. Figure C.2 shows the number of years required for two examples (in China and France), under a range of traffic volumes. The Chinese line, which had construction emissions of over 40,000 tons per kilometer, forecast an annual average passenger volume of 200 million, and should recover its emissions well within 10 years. The French line had much lower construction emissions (8,000 tons per kilometer), but it also had a much lower annual traffic forecast at 12 million, and so will take more than 10 years to recover the emissions. However, a line constructed to Chinese standards and with the Chinese level of emissions, but with a more typical demand in Europe of 10 to 15 million passengers annually, would take around 40 years to cover the construction emissions. As an extreme example, the HS2 in the United Kingdom is expected to take 60 years to become carbon neutral, given the significant embedded emissions in its tunneled infrastructure (Cornet, Dudley, and Banister 2018).

Figure C.2. Construction Emission Payback Period



Source: Original figure produced for this publication.

For suburban passenger services, the UIC estimate a typical payback period of 15 years, similar to an estimate for the Crossrail project in London of between 9 to 13 years, depending on service operating patterns and the type of rollingstock.[7] For freight rail projects, UIC estimates a typical payback period of 12 years (UIC 2016). However, the dedicated freight corridors in India are expected to have a carbon payback period of only 8 years.

When estimating payback periods, reduced emissions in the alternative modes also need to be considered. All road vehicles could eventually be electric, which will reduce the carbon savings from operations resulting from rail investment and thereby lengthen payback periods, although the transition to electric vehicles could be quite lengthy in developing countries, especially for trucks. It is therefore important to shorten the carbon payback period of rail lines, both by reducing emissions during construction and by increasing the savings in operations.

Many construction designs and processes can be re-engineered to reduce emissions and hence shorten payback periods. Some of these are related to the design of components, such as the composite viaduct span used for HSR in the United Kingdom and France, which halves the carbon content, or to the use of lower-carbon materials, such as the plastic sleepers currently under investigation.[8] Others are more comprehensive—the new HS2

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[7] See the Crossrail webpage on "Energy Efficiency and Carbon" for more information on the project's estimated payback period: https://learninglegacy.crossrail.co.uk/learning-legacy-themes/environment/energy-efficiency-and-carbon/.

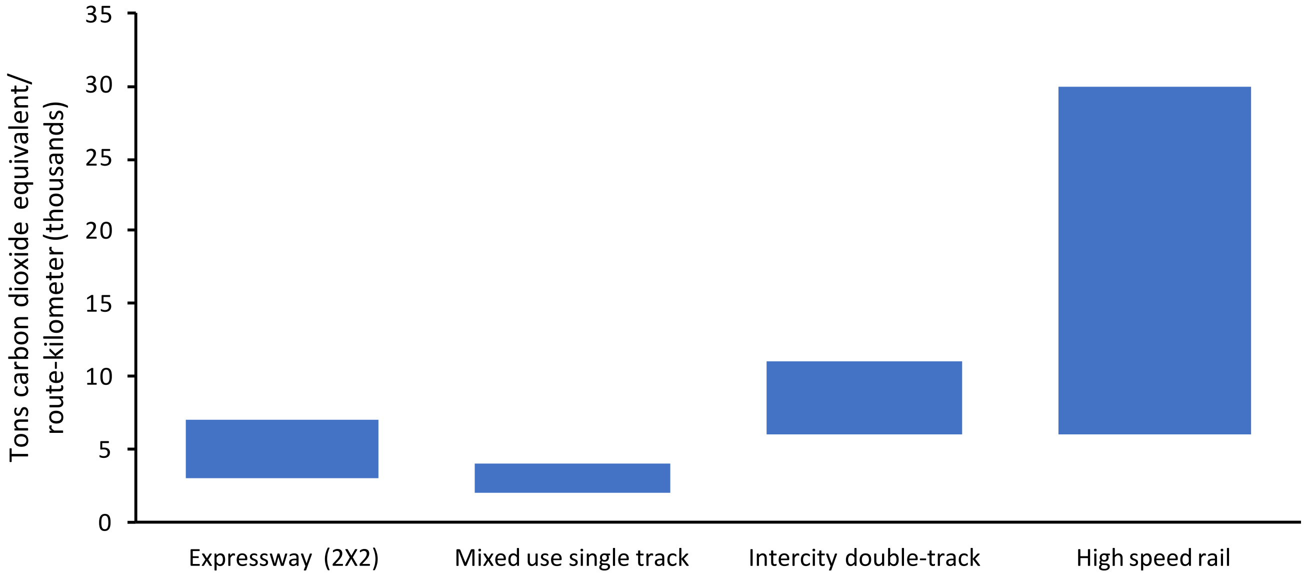
[8] A study by Quik, Dekker, and Montforts (2020) investigated the safety and sustainability of six alternatives to the standard cement-concrete sleeper. Of these, one made of recycled ethylene had under half the emissions of the concrete sleeper, as well as providing the opportunity for further recycling.

Curzon Street station in Birmingham aims to achieve net-zero carbon emissions from the energy consumed to operate building systems, such as heating, cooling, and lighting—for example, by using LED lighting—and from generating low-carbon energy through solar panels on the platform canopies and ground source heat pumps.

Rail projects should not be viewed in isolation from the rest of the transport system and construction emissions should be viewed against alternative options for meeting the transport demand. The appropriate comparator to a railway would be a four-lane expressway. Construction emissions are not routinely calculated for highways, so data are limited. However, the World Bank published a report summarizing construction emissions for expressways (World Bank 2011), which estimated the construction emissions for an at-grade four-lane expressway at 3,300 tons CO_2e per route-kilometer (route-km). Structures generated much larger emissions, at about 75,000 tons CO_2e/route-km. An independent Indian study estimated 3,450 tons CO_2e/route-km for a similar at-grade expressway. The total for any given expressway will depend on the proportion of structures along the route. Allowing 1 percent of route length for structures gives an average of 4,000 tons CO_2e/route-km for a four-lane expressway; allowing 5 percent would give an average of 7,000 ton; construction involving long tunnels will generate much larger volumes; a 26-kilometer, six-lane expressway in Melbourne will generate 2.02 million tons, or 78,000 tons CO_2e/route-km.

Figure C.3 shows how the available expressway construction emission figures compare to the construction emissions for various types of railways. The expressway emissions are on the same order of magnitude as the single track and double track lines. The expressway would be substantially less than the HSR construction, but the expressway would also have a passenger capacity of about 40 to 50 million passengers per annum, far below the 100 to 150 million passenger capacity of an HSR.

Figure C.3. Range Estimates of Greenhouse Gas Emissions from Construction of Railways and Expressways



Sources: World Bank 2011 and tables C.2 and C.3, shown above in appendix C.

Reference

ADEME, RFF, and SNCF (Agence de l'environnement et de la maîtrise de l'énergie, Réseau ferré de France, and Société nationale des chemins de fer français). 2009. "1er Bilan Carbone ferroviaire global : La Ligne à Grande Vitesse Rhin–Rhône au service d'une Europe durable." SNCF, Paris. https://www.banquedesterritoires.fr/sites/default/files/ra/Le bilan carbone de la LGV Rhin-Rhône.pdf.

Aurizon (Aurizon Holdings, Ltd.). 2020. "2020 Sustainability Report: Delivering for a Sustainable Future." Aurizon Holdings, Ltd., Fortitude Valley, Queensland, Australia. https://www.aurizon.com.au/-/media/Aurizon%20Media%20Library/Sustainability/Overview/Sustainability%20Report%202020/Sustainability%20Report%202020.

Baron, T., M. Tuchschmid, G. Martinetti, and D. Pépion. 2011. "Carbon Footprint of High Speed Rail." UIC report, International Union of Railways (UIC), Paris. https://railroads.dot.gov/sites/fra.dot.gov/files/fra_net/15009/Carbon%20Footprint%20of%20High-Speed%20Rail%20UIC%202011.pdf.

BSI (British Standards Institution) Group. 2016. "PAS 2080: Requirements of Carbon Management in Infrastructure." BSI Group, London. https://knowledge.bsigroup.com/products/carbon-management-in-infrastructure/standard.

Canadian National Railway. 2020. "2020 Sustainability Report." Canadian National Railway, Montreal. https://www.cn.ca/-/media/Files/Delivering-Responsibly/Delivering-Resp-2020-en.pdf?la=en.

Cornet, Yannick, Geoffrey Dudley, and David Banister. 2018. "High Speed Rail: Implications for Carbon Emissions and Biodiversity." *Case Studies on Transport Policy* 6 (3): 376–390. https://doi.org/10.1016/j.cstp.2017.08.007.

Government of the United Kingdom. 2017. "High Speed Rail Phase 2a (West Midlands–Crewe) Environmental Statement, Volume 5: Route-Wide Environmental Reports and Maps." High-Speed Rail Two (HS2), Ltd., London. https://www.gov.uk/government/collections/hs2-phase-2a-environmental-statement#volume-5:-route-wide-environmental-reports-and-maps.

Olugbenga, Olubanjo, Nikolaos Kalyviotis, and Shoshanna Saxe. 2021. "Embodied Emissions in Rail Infrastructure: a Critical Literature Review." *Environmental Research Letter* 14 (12): 123002. https://doi.org/10.1088/1748-9326/ab442f.

Quik, J. T. K., E. Dekker, and M. H. M. M. Montforts. 2020. "Safety and Sustainability Analysis of Railway Sleeper Alternatives: Application of a Novel Method for Material Loops." RIVM report 2020-0181, National Institute for Public Health and the Environment (RIVM), Ministry of Health, Welfare and Sport, the Netherlands. https://www.rivm.nl/bibliotheek/rapporten/2020-0181.pdf.

Schmied, Martin, and Moritz Mottschall. 2013. "Treibhausgasemissionen durch die Schieneninfrastruktur und Schienenfahrzeuge in Deutschland." (German) ["Greenhouse Gas Emissions by the Rail Infrastructure and Rail Vehicles in Germany."] Öko Institut, Büro Berlin. https://www.oeko.de/oekodoc/1852/2013-520-de.pdf.

Stripple, Håkan, and Stefan Uppenberg. 2010. "Life Cycle Assessment of Railways and Rail Transports—Application in Environmental Product Declarations (EPDs) for the Bothnia Line." Report B1943. IVL (Swedish Environmental Research Institute), Stockholm. https://www.ivl.se/english/ivl/publications/publications/life-cycle-assessment-of-railways-and-rail-transports---application-in-environmental-product-declarations-epds-for-the-bothnia-line.html.

TERI (The Energy and Resources Institute). 2012. "Final Report: Life Cycle Analysis of Transport Modes (Volume I)." Prepared for National Transport Development Policy Committee (NTDPC), Project code 2011UD02, New Delhi, TERI. https://niti.gov.in/planningcommission.gov.in/docs/sectors/NTDPC/Study%20Reports/TERI/Study_Life%20Cycle%20Analysis%20of%20Transport%20Modes_Submitted%20to%20the%20Govt%20on%20Jan%204,%202013/LCA_Final%20Report%20Vol%20I.pdf.

UIC (International Railway Union). 2012. “Study on Non-Traction Energy Consumption and Related CO_2 Emissions from the European Railway Sector.” Final report of a UIC Study prepared by IZT and Macroplan, UIC, Paris.https://uic.org/IMG/pdf/uic_non-traction_energy_study_final_report_june_2012.pdf.

UIC (International Railway Union). 2016. “Carbon Footprint of Rail Infrastructure.” UIC report, UIC, Paris. https://uic.org/IMG/pdf/carbon_footprint_of_railway_infrastructure.pdf.

World Bank. 2011. “Transport Greenhouse Gas Emissions Mitigation in Road Construction and Rehabilitation: A Toolkit for Developing Countries.” Working paper/toolkit, World Bank, Washington, DC. https://documents.worldbank.org/en/publication/documents-reports/documentdetail/660861468234281955.

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