



# NDC ASPECTS

## Transport Sectoral Modelling - 'Avoid-Shift-Improve' measures (Deliverable 3.1 - T.2 Report)

Annex 4 of Deliverable 3.1

October 2023

Isheeka Dasgupta, Gabriel Möring Martinez, Johannes Pagenkopf, Murat Senzeybek, Stephan Schmid

DLR

Version: 1



October 2023

[www.ndc-aspects.eu](http://www.ndc-aspects.eu)

### Executive Summary

Transport has a major contribution to global emissions and accounted for 21% of global anthropogenic CO<sub>2</sub> emissions in 2015, which continues to grow due to increasing personal and freight travel demand. Of the global CO<sub>2</sub> emissions in the transport sector in 2018, 45% were from road-based passenger transport and 30% from road-based freight transport.

The following report quantifies and examines measures that can be taken in the transport sector in representative countries to aid discussions of increasing the ambitiousness of transport sector in the Nationally Determined Contributions to reach the Paris agreements. The measures are aligned in the 'Avoid, Shift and Improve' framework and their opportunities relating to GHG emission reduction potential and constraints to achieving them are discussed. This report is part of the Deliverable D3.1: Report and academic article manuscripts on opportunities and constraints in Industry, Transport, Buildings and AFOLU of the NDC ASPECTS project and covers the work conducted in Task 3.3 "Sectoral Modelling for Transport".

In the NDC's submitted by countries, avoiding or reducing travel demand and shifting to more sustainable modes appear less than electrification and other technology improvement measures for the transport sector. Possible emission reduction by reducing work-related travel trips is quantified in the report given the relative ease of implementation of this measure and wide global applicability. This report examines the potential of teleworking and avoiding work trips in selected regions and the barriers to increasing it. Constraints such as occupational structures, IT infrastructure, building space and gender are quantified and compared among regions, and the rebound effects related to them are discussed.

Global trends of 'SUVisation' occurring, with 45% of global sales in 2021 as SUVs and 40% electric passenger cars as e-SUVs, need to be combatted. Given the foreseeable increase in travel demand, urbanization, and strain on critical battery materials, alternative solutions must be sought. We explore the potential of lighter and smaller vehicles to replace passenger trips in different regions and the resulting GHG emissions that could be saved in 2030. This includes vehicles ranging from e-scooters, e-bikes, and e-mopeds to e-microcars in our analysis. The maximum potential of emission reduction of passenger road transport emissions is found to range from 35-50% for selected major countries in 2030 if all suitable trips are replaced with LEVs. To achieve maximum potential, barriers and current experiences related to cost, safety, charging infrastructure and gender are examined in selected regions to highlight differences and possible synergies. Shifting towards lighter vehicles must be discussed and pushed for in international and national policy.

Shifting from road to rail for freight transport is a globally accepted measure commonly included in NDC's given the high energy efficiency of rail. However, given the large time and planning scales, geographic and infrastructural challenges to increasing rail's share in rail suitable tonne kilometres, it lags in its commitment targets globally despite comprehensive plans to increase rail modal shares. The report thus deep dives into current plans and the hurdles that are being faced by individual countries.

In 2023, the electrification of passenger cars emerges as the most economically viable solution for decarbonizing the passenger car sector. Notably, 55% of countries worldwide have established non-binding targets for achieving 100% electric or electrified vehicle sales between 2025 and 2050. However, the widespread adoption of electric vehicle (EV) technology poses challenges, given its non-mature status and limited mass adoption. To address this, the report qualitatively examines the constraints facing customers both in the EU and globally and proposes possible solutions based on existing

studies and the literature. Additionally, the work quantitatively models passenger car sector emissions in the EU up to 2060. Furthermore, recognizing the dearth of studies on stock fleet turnover and its impact on CO<sub>2</sub> emission mitigation, we conduct a quantitative analysis of the effects of implementing circulation bans in the EU. Such bans can be helpful in moving closer to the EU's 2050 target and aligning with the Paris Agreement.

## Contents

|          |                                                                                 |           |
|----------|---------------------------------------------------------------------------------|-----------|
| <b>1</b> | <b>Introduction to Sector.....</b>                                              | <b>7</b>  |
| <b>2</b> | <b>Avoid: Teleworking as a mitigation option .....</b>                          | <b>10</b> |
| 2.1      | Introduction, Overview .....                                                    | 10        |
| 2.2      | Methodology .....                                                               | 11        |
| 2.2.1    | Chosen approach.....                                                            | 11        |
| 2.2.2    | Modelling.....                                                                  | 11        |
| 2.3      | Data .....                                                                      | 12        |
| 2.3.1    | Teleworking jobs .....                                                          | 12        |
| 2.3.2    | Commute distances.....                                                          | 13        |
| 2.3.3    | Modal split for commute.....                                                    | 13        |
| 2.3.4    | Emission factors .....                                                          | 14        |
| 2.4      | Relevance of the regional perspective .....                                     | 15        |
| 2.5      | Pathway.....                                                                    | 16        |
| 2.6      | Link to the Sectoral Conversions regarding MOs .....                            | 16        |
| 2.7      | Key opportunities and constraints (O&C) .....                                   | 16        |
| 2.7.1    | Digital connectivity and internet access .....                                  | 17        |
| 2.7.2    | Power grid .....                                                                | 18        |
| 2.7.3    | Residential space and energy consumption .....                                  | 19        |
| 2.8      | Mitigation option results.....                                                  | 20        |
| 2.9      | Gender differences.....                                                         | 22        |
| 2.10     | Conclusions.....                                                                | 22        |
| <b>3</b> | <b>Shift: Light Electric Vehicles as a mitigation Option .....</b>              | <b>24</b> |
| <b>4</b> | <b>Electrification of passenger cars as mitigation option .....</b>             | <b>26</b> |
| 4.1      | Introduction.....                                                               | 26        |
| 4.2      | Methodology .....                                                               | 27        |
| 4.2.1    | Chosen approach and scientific concept .....                                    | 27        |
| 4.2.2    | Data .....                                                                      | 28        |
| 4.2.3    | Econometric model .....                                                         | 28        |
| 4.2.4    | Clustering and utility maximization model (80) .....                            | 29        |
| 4.2.5    | Statistical model: Cumulative survivability probability (CSP) curves (79) ..... | 29        |
| 4.2.6    | Stock model.....                                                                | 30        |
| 4.2.7    | Emissions model.....                                                            | 30        |
| 4.3      | Key opportunities and constraints (O&C) .....                                   | 31        |
| 4.3.1    | Consumer-driven opportunities and constraints.....                              | 31        |
| 4.3.2    | Policy-driven opportunities and constraints .....                               | 39        |
| 4.4      | Mitigation option results in the EU .....                                       | 42        |
| 4.4.1    | Ban on ICE vehicles in 2035 and GHG emissions reduction by 90% in 2050 .....    | 42        |
| 4.4.2    | Circulation bans.....                                                           | 44        |
| 4.5      | Relevance of the regional perspective .....                                     | 46        |

|          |                                                                              |           |
|----------|------------------------------------------------------------------------------|-----------|
| 4.5.1    | Ban on ICE vehicles in 2035 and GHG emissions reduction by 90% in 2050 ..... | 46        |
| 4.5.2    | Circulation bans.....                                                        | 48        |
| 4.6      | Conclusion .....                                                             | 49        |
| <b>5</b> | <b>Road freight to Rail freight as a mitigation option .....</b>             | <b>51</b> |
| 5.1      | Introduction.....                                                            | 51        |
| 5.2      | Methodology .....                                                            | 53        |
| 5.3      | Relevance of the regional perspective .....                                  | 54        |
| 5.3.1    | EU .....                                                                     | 56        |
| 5.3.2    | India.....                                                                   | 58        |
| 5.3.3    | South Africa .....                                                           | 61        |
| 5.3.4    | Türkiye .....                                                                | 63        |
| 5.4      | Link to Sectoral Conversation.....                                           | 66        |
| 5.5      | Conclusions.....                                                             | 66        |
| <b>6</b> | <b>Transport Sector Conclusions and Insights .....</b>                       | <b>67</b> |
| <b>7</b> | <b>References .....</b>                                                      | <b>69</b> |

### Figures

|                                                                                                                                                                                                                                                                                                                                                                          |    |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 1 Modal split for work related vehicle kilometers driven in selected countries .....                                                                                                                                                                                                                                                                              | 14 |
| Figure 2 Availability of digital resources and internet connectivity. ....                                                                                                                                                                                                                                                                                               | 17 |
| Figure 3 Download speeds in different regions .....                                                                                                                                                                                                                                                                                                                      | 18 |
| Figure 4 Annual power cuts in selected countries .....                                                                                                                                                                                                                                                                                                                   | 18 |
| Figure 5 Comparison of residential floor area and energy consumption in selected countries.....                                                                                                                                                                                                                                                                          | 19 |
| Figure 6 Transport emission reduction potential by teleworking in selected countries .....                                                                                                                                                                                                                                                                               | 21 |
| Figure 7 LCA based emission factors for LEVs and passenger cars .....                                                                                                                                                                                                                                                                                                    | 24 |
| Figure 8 Comprehensive methodology for stock and emissions forecasting: This diagram outlines the multifaceted methodology employed to forecast vehicle stock and emissions in the EU. The model's flexibility extends to accommodating different policy scenarios, offering insights into how these scenarios could potentially affect stock and emissions trends. .... | 27 |
| Figure 9 Weibull average lifespan in 2008, 2016 and 2021 for different European countries. ....                                                                                                                                                                                                                                                                          | 30 |
| Figure 10 Average price of vehicles sold in Germany in 2021 by powertrain and segment. ..                                                                                                                                                                                                                                                                                | 38 |
| Figure 11 Zero-emission vehicle mandates and internal combustion engine bans for passenger cars across the world. ....                                                                                                                                                                                                                                                   | 40 |
| Figure 12 Forecast of CO <sub>2</sub> emissions up to 2060 for EU-27+Norway.....                                                                                                                                                                                                                                                                                         | 43 |
| Figure 13 Forecast of the stock-fleet average CO <sub>2</sub> emissions (in g/km) for EU-27 countries and Norway. ....                                                                                                                                                                                                                                                   | 47 |
| Figure 14 Forecast of CO <sub>2</sub> emissions up to 2060 for EU-27+Norway. Countries are grouped as Western and Eastern. ....                                                                                                                                                                                                                                          | 48 |
| Figure 15 Forecast of the stock-fleet average CO <sub>2</sub> emissions (in g/km) for EU-27 countries and Norway. Countries are grouped as Western and Eastern. ....                                                                                                                                                                                                     | 48 |
| Figure 16 Effect in the stock-fleet average CO <sub>2</sub> emissions of circulation bans applied in 2035 for vehicles either older than 20, 25 or 30 years. Countries are grouped as Western and Eastern.....                                                                                                                                                           | 48 |

### Tables

|                                                                                    |    |
|------------------------------------------------------------------------------------|----|
| Table 3 Teleworkable jobs and related assumptions in selected countries .....      | 12 |
| Table 4 Commute distances (roundtrip) .....                                        | 13 |
| Table 5 Tank to wheel emission factor of vehicle modes in selected countries ..... | 15 |

|                                                                                                                                                                                                                                                                                                                                                                                                      |    |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| Table 6 Residential energy consumption in selected countries.....                                                                                                                                                                                                                                                                                                                                    | 20 |
| Table 7 effect of considering building emission and seasonality. Source for LCA , building emissions (13).....                                                                                                                                                                                                                                                                                       | 21 |
| Table 8 Forecast of EU new passenger car registrations (in millions) up to 2050 under two different scenarios. ....                                                                                                                                                                                                                                                                                  | 28 |
| Table 9 Top reasons for choosing an EV as next vehicle at a global level (left) and in the European Union (right).....                                                                                                                                                                                                                                                                               | 32 |
| Table 10 The 10 greatest concerns regarding BEV at a global level (left) and in the European Union (right) .....                                                                                                                                                                                                                                                                                     | 35 |
| Table 12 EU CO2 budget for the transport sector, road transport sector and passenger car sector in years 2021 – 2100 consistent with long term warming of 1.5°C. ....                                                                                                                                                                                                                                | 43 |
| Table 13 CO2 emissions and stock effects of circulation bans applied in year 2035, 2040, 2045 and 2050 for ICE passenger cars older than 20, 25 or 30 years.....                                                                                                                                                                                                                                     | 45 |
| Table 13 A Regional differences of circulation bans applied in year 2035 for ICE passenger cars older than 20, 25 or 30 years. Specifically, it is measured the CO2 emissions in 2050, CO2 emissions reduction potential until net-zero emissions are reached, number of vehicles removed from the EU road by applying the circulation ban and percentage of vehicles removed from the EU road. .... | 49 |
| Table 14 Freight transport indicators for selected countries .....                                                                                                                                                                                                                                                                                                                                   | 55 |
| Table 15 source: (229).....                                                                                                                                                                                                                                                                                                                                                                          | 64 |

### 1 Introduction to Sector

The transport sector has a major contribution to global emissions and accounted for 21% of global anthropogenic CO<sub>2</sub> emissions in 2015, which continues to grow due to increasing personal and freight travel demand (Teske, 2019). Of the global CO<sub>2</sub> emissions in the transport sector in 2018, 45% were from road-based passenger transport and 30% were from road-based freight transport (Hannah Ritchie, Max Roser and Pablo Rosado, 2020). In light of the Paris Agreement, nearly every country worldwide has committed to taking actions aimed at limiting global warming to 1.5°. However, how this converts to sector-specific shares and the associated policies needed is still open ended (Patrick Plötz et al., 2023). Based on the study (SLOCAT, 2022), the 2°C scenario share for transport ranges from 17%-25% below 2010 levels in 2050 and a 60% decrease for 1.5°C. Business-as-usual (BAU) annual emissions exceed the 2°C and 1.5°C scenarios by 64% and 84% in 2050, respectively. This shows the enormous effort that is needed to decarbonize the transport sector with growing transport demand in the future in a timely manner (an indicator of urgency is the average passenger stock turnover rate, which is in the range of 30 years (Held et al., 2021b)). Stronger and integrated policy commitment and implementation and fair share agreements on contributions, technology, resources and knowledge transfer are needed at the national and global levels to achieve transport climate goals and responsibilities. At the same time, nations and cities have the responsibility to provide and promote safe, inclusive, affordable and economy-supporting mobility systems.

Nationally determined contributions (NDCs) mark country-level commitments to contribute to battling climate change as part of the Paris Agreement (UNFCCC). In the first generation of NDCs submitted in 2015, 150 countries highlighted transport-related mitigation options, but only 35 included quantified targets specifically for the transport sector, with freight, demand reduction and shifting measures primarily underrepresented (WRI, 2019). There was also a lack of standardized benchmarks and indicators that countries should incorporate when detailing their NDCs. Accordingly, the following work in this document is carried out to increase the ambitiousness of future NDCs with respect to transport by providing a database of feasible mitigation options and quantifying their decarbonization potential. The work goes through selected mitigation options and provides results for the emission reduction potential of the mitigation options and the associated barriers in different regions so that they can be considered in increasing or negotiating NDC commitment levels.

The quantification of the potential of decarbonization of possible mitigation options is performed using models and frameworks that include data and research from previous research at national levels and global benchmarks. Inputs for the analysis also include sectoral conversations held by and in collaboration with WP1 with country experts for the mitigation options of shifting to light electric vehicles and rail-based freight transport. Analysis of transport related mitigation options encompassing their technical and social aspects was carried out as a part of this study. The proportion of transport related emissions that a specific mitigation option could evade is provided to assess relative importance and aid stakeholders in decision making. Mitigation options were seen from a regional perspective, and their transport, infrastructural and social contexts were expanded upon to highlight similarities and differences in plausibility and utility. This enables better cooperation and synergies in climate change actions and ensures fair climate shares.

The road sector is the primary focus of this work given its high share of transport emissions. The sectoral perspective for road transport emissions is almost equivalent to a country-level perspective for

the transport sector when international road and rail transport is not considered. Hence, country-specific analyses appear in the methodology and results.

The mitigation options were aligned with the transport strategies of 'Avoid, Shift, Improve (ASI)', a holistic way developed in the 1990s to structure environmental policy measures (TUMI, 2019). Avoid or reduce measures question and restructure the source of travel needs, Shift or maintain measures result in transport by less polluting and more inclusive modes, and finally, Improve measures for existing technology and provisions of vehicular modes. First generation NDCs prioritize Improve related options over Avoid and Shift measures (SLOCAT, 2022) which needs to be challenged and negotiated within the future NDCs.

- **Avoid transport:** This includes managing transport demand so that fewer passenger and freight kilometres are travelled through sustainable land use planning and distribution or virtual substitution of attraction centres (such as teleworking). Push measures such as congestion pricing or subsidy reduction can also have the direct effect of reducing transport demand. For this study, the mitigation option of teleworking was chosen for assessment given its widespread acceptability today and the basic human travel need that it is associated with. Work-related trips account for 25% and 23% of the total mileage driven in Germany and the USA, respectively, which is a major organized portion of the total mileage driven and can be targeted with more ease than other mileage categories.
- **Shift measures:** Shifting transport to low carbon modes would reduce the emission intensity of the travel demand. Measures and quantified targets that would encourage public transport, nonmotorized modes, lighter and electric personal transport options and rail freight instead of road-based freight transport need to be highlighted even more in future NDCs. In this work, light electric vehicles (LEVs) for passenger transport and rail freight for freight transport were assessed. An e-microcar emits 40% of lifecycle-based emissions in comparison to a medium-sized BEV (Ehrenberger et al., 2022). With growing urbanization, smaller electric vehicles should be further integrated to reduce pollution and increase liveability and strain on critical materials. Rail transport is also energy efficient, being four to six times more efficient per ton-km base than heavy truck transport and relatively easier to electrify (IEA, 2019a).
- **Improve measures:** This includes measures that improve existing transport modes with efficiency gains in the drivetrain technology, alternative drivetrains such as battery electric vehicles, plug-in hybrids, hydrogen, etc. For the focus of this work, opportunities and constraints of battery electric passenger cars were focused on. Within this, a model to analyse policy implications such as circulation bans to push faster stock turnover and EV adoption was used. Investigating circulation bans as an additional measure for decarbonization of passenger car fleets becomes important given the significant number of studies considering the effects of CO<sub>2</sub> emission standards and the 2035 ICE ban, an increase in the EU average stock fleet age since 2008, uncertainties surrounding how long internal combustion engine vehicles will be held post-2035 ban, and the need to align with the EU's 2050 goal of a 90% reduction in greenhouse gas emissions (GHG) within the passenger car sector while fulfilling commitments under the Paris Agreement.

The mitigation options are analysed quantitatively with respect to the proportion of transport demand and services that they refer to, existing and future infrastructural needs, economic viability and investments needed and other region-specific requirements for transformation. As a part of the assessment of the mitigation option, aspects of user acceptance, gender and care economy are also qualitatively

and quantitatively considered when applicable. These factors constitute the inherent environment of opportunities and constraints that mitigation options need to satisfy to contribute successfully. Within this context, the country emission reduction potential of the mitigation options is calculated, and policy changes are recommended.

In the following chapters, we expand on each mitigation option and quantify their emission reduction potential, region- and country-specific opportunities and constraints and thus coalesce their effectiveness and plausibility.

## 2 Avoid: Teleworking as a mitigation option

### 2.1 Introduction, Overview

Among the transport-related mitigation options possible, avoiding and reducing travel itself can lead to immediate transport-related greenhouse gas (GHG) emission reduction. Changes in urban structure and land use can reduce travel distances by reorganizing travel-inducing centres in a more optimized manner for economic growth and emissions (Bai et al., 2022). However, these are often long-term changes and slow to materialize. On the other hand, the option of teleworking presents the possibility of reducing travel demand without significant physical infrastructure changes. Commute to work is a globally common travel activity, and the COVID-19 pandemic provided accelerated simultaneous learning and proofs on how teleworking is functional in suitable jobs and reduced many cultural and technological barriers. 'Teleworking' implies working full- or part-time from home (or other locations). Teleworking has provided the option of having a more flexible lifestyle for many and helped improve work-life balance along with the negative effects of increased workload and reduced socioprofessional relationships (Vayre et al., 2022a).

The commute emission savings potential in a region depends primarily on the share of teleworkable jobs, the frequency of teleworking, commute distances and the emission intensity of commuting. Work- and home-related emissions also involve building-related emissions, and the exact savings depend on the differences in activities and intensities carried out in both these spaces and their regional differences (Yao Shi et al., 2023), which are often difficult to quantify. In the long term, rebound effects such as relocation of residences to further and cheaper areas, increased non-commuting trips (Fabienne Wöhner, 2022; Hostettler Macias et al., 2022), and changes in vehicle mode to more emission intensive ones can nullify the potential benefits (Waldemar Marz & Suphi Sen, 2021), and care must be taken through policy and planning to avoid this. Due to the various uncertainties in shifted energy consumption and long-term implications of home work locations, the literature has found high ambiguity in the overall potential benefits for a specific region and lifestyle (Andrew Hook: Victor Court, 2020). The commute emission savings potential in a region depends primarily on the share of teleworkable jobs, the frequency of teleworking, commute distances and the emission intensity of commuting. Work- and home-related emissions also involve building-related emissions, and the exact savings depend on the differences in activities and intensities carried out in both these spaces and their regional differences (Yao Shi et al., 2023), which are often difficult to quantify. In the long term, rebound effects such as relocation of residences to further and cheaper areas, increased non-commuting trips (Fabienne Wöhner, 2022; Hostettler Macias et al., 2022), and changes in vehicle mode to more emission intensive ones can nullify the potential benefits (Waldemar Marz & Suphi Sen, 2021), and care must be taken through policy and planning to avoid this. Due to the various uncertainties in shifted energy consumption and long-term implications of home work locations, the literature has found high ambiguity in the overall potential benefits for a specific region and lifestyle (Andrew Hook: Victor Court, 2020).

### 2.2 Methodology

#### 2.2.1 Chosen approach

The following report is based on a methodology that focuses on the emission reduction potential from commute-related vehicular activity. Mode of transport, actual commuting pattern, distance, congestion encountered, and seasonality during commute play an enormous role in obtaining accurate estimates. The methodology was based on a top-down approach using values of average commute distances and commute modal splits as done in (Carbon Trust, 2021). Other approaches, such as (IZT & Greenpeace, 2020), which uses national travel surveys for a bottom-up based approach, exist that would provide more accurate results. However, due to the lack of detailed travel survey data for the regions considered in this work, such an analysis could not be carried out uniformly. Further complexity in analysing the long-term teleworking effects of urban sprawl is not explored much in the literature, and most studies ignore the correlation of teleworkable jobs with sociodemographic or spatial factors due to a lack of evidence in identifying such trends. As identified in (Yao Shi et al., 2023), changes in emissions in the building sector are also often not modelled in studies and can have an enormous impact, as seen in (IEA, 2020) and (Carbon Trust, 2021). The study tries to quantify and mention the relative impact of these factors so that policy makers can be better informed of the range of benefits and constraints and areas to tackle so that teleworking can reduce overall GHG emissions. The following report is based on a methodology that focuses on the emission reduction potential from commute-related vehicular activity. Mode of transport, actual commuting pattern, distance, congestion encountered, and seasonality during commute play an enormous role in obtaining accurate estimates. The methodology was based on a top-down approach using values of average commute distances and commute modal splits, as performed in (Carbon Trust, 2021).

#### 2.2.2 Modelling

The emission reduction calculation from transport emissions is based on a top-down approach using national average values for teleworkable jobs and frequency, modal splits of work-related trips, and commute distances, as shown in (Carbon Trust, 2021).

$$\text{Transport emission reduction} = tj_c \cdot ft_c \cdot fw_c \cdot cd_c \cdot cef_c \quad (1)$$

where  $tj$  is the number of jobs in country  $c$  with  $ft$  fraction of jobs that are teleworkable that are teleworked  $fw$  times in a year. An average commute distance of  $cd$  is undertaken each day by commuters with a modal split of transport modes used for work, which leads to  $cef$ , which is the weighted emission factor for all the modes used in the country for travel.

Assumptions considered while modelling.

- Due to a lack of data availability from sources such as national transport surveys, average commute distances are considered instead of a distribution of commute distances.
- Average modal splits for countries and when available, specifically for commutes, have been considered.
- Tank-to-wheel emission factors were used for vehicular emission.
- The latest data available were considered for inputs of emission factors and for commute distances for the evaluation of emission reduction potential for the current year of 2023.
- When unavailable, occupancy factors were used to derive vehicle kilometres from passenger kilometres.
- Emission factors, travel distances and modal splits were used specifically only for work trips and not for teleworkable work trips due to lack of data.

### 2.3 Data

#### 2.3.1 Teleworking jobs

There exists a considerable difference in occupational structure between countries and regions that determines the maximum possible jobs suitable for teleworking in a country (International Labour Organization, 2020). Knowledge-, management-, service- and IT-intensive jobs, which make a large share of jobs in developed countries, are understandably more suitable for teleworking. Additionally, social factors, physical space and IT infrastructure also differ and make teleworking more conducive in developed countries. A clear correlation between GDP per capita and teleworkable jobs can be seen in (Nicolas Gomez Parra, 2020), with approximately 50% of jobs teleworkable in Luxembourg and 5.5% of jobs in Ethiopia. As countries develop, there would be a shift in the ratio of jobs in each industry with greater teleworkable jobs. Table 1 shows the inputs and sources for the data used to estimate the maximum teleworkable jobs in countries in the present day. The proportions of teleworkable jobs are approximately 39% and 27% in Germany and the USA, respectively, in comparison to approximately 10% in India and South Africa.

**Table 1 Teleworkable jobs and related assumptions in selected countries in 2020**

| Country        | Percentage of teleworking jobs (%)                | Potential number of teleworking jobs (millions) | Teleworking frequency assumed (days per week) |
|----------------|---------------------------------------------------|-------------------------------------------------|-----------------------------------------------|
| UK             | 44%                                               | 15 (Carbon Trust, 2021)                         | 3                                             |
| Germany        | 37%                                               | 17 (Carbon Trust, 2021)                         | 2.7                                           |
| Sweden         | 35%                                               | 2 (Carbon Trust, 2021)                          | 2.4                                           |
| Italy          | 31%                                               | 8 (Carbon Trust, 2021)                          | 1.9                                           |
| Czech Republic | 29%                                               | 1.8 (Carbon Trust, 2021)                        | 3                                             |
| India          | 12- 7% (International Labour Organization, 2020)  | 48 (World Development Indicators database)      | 1.9                                           |
| USA            | 29% (International Labour Organization, 2020)     | 47 (World Development Indicators database)      | 2.7                                           |
| China          | 19% (International Labour Organization, 2020)     | 150 (World Development Indicators database)     | 1.9                                           |
| SA             | 14%- 8% (International Labour Organization, 2020) | 2.2 (Statistics South Africa, 2022)             | 1.9                                           |
| Indonesia      | 7% (International Labour Organization, 2020)      | 9 (World Development Indicators database)       | 1.9                                           |

### 2.3.2 Commute distances

Commute distances would have a direct impact on the emission reduction potential by teleworking given that one avoids travelling this distance and thus the associated emissions by the mode used. We have no data to assume the commute distances of specifically teleworkable jobs (given that there is some correlation to income and ability to telework and hence also proximity to work) and rely on average commute distances irrespective of job type. The variation of commute distances depends on various historical, social, technological and physical contexts that have determined the urban form of that region (Duarte & Fernández, 2017). Mixed land use, effective polycentricity and high density lead to short distances, and given the long-lasting effects of urban planning, steering it towards enabling sustainability and equal accessibility should be a priority (Engelfriet & Koomen, 2018). South Africa, an extreme case of urban form as a result of its political and social history with apartheid, has widespread segregation and imbalanced land use and opportunities available in proximity. This results in its abnormally high average commute distance compared to other developing countries, as seen in **Table 2**.

As per (Shlomo & Alejandro), cities in the USA have developed to be a hybrid of monocentric and polycentric models with great reductions in average commute lengths seen in some cities due to better planning and distribution of employment subcentres when compared to average distance to CBDs or random points. Such urban planning for mixed land use can reduce travel distances and should be parallelly adopted in urban planning policy.

**Table 2 Commute distances (roundtrip)**

| Country        | Average commute distance (km)  |
|----------------|--------------------------------|
| UK             | 9 (Carbon Trust, 2021)         |
| Germany        | 34 (Carbon Trust, 2021)        |
| Spain          | 13 (Carbon Trust, 2021)        |
| Sweden         | 20 (Carbon Trust, 2021)        |
| Italy          | 12 (Carbon Trust, 2021)        |
| Czech Republic | 9 (Carbon Trust, 2021)         |
| India          | 21 (Soman & Kaur, 2019)        |
| USA            | 36 (Fucci, 2017)               |
| China          | 25 (Engelfriet & Koomen, 2018) |
| SA             | 62 (M Moselakgomo et al.)      |

### 2.3.3 Modal split for commute

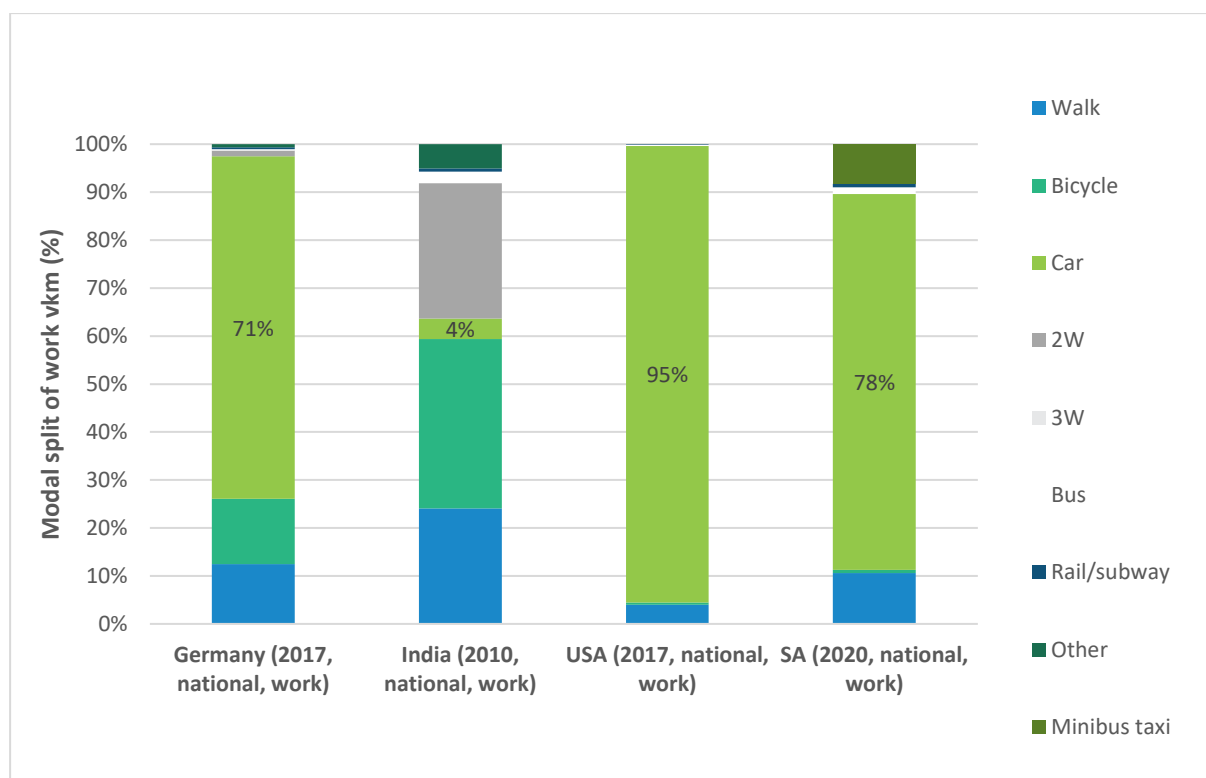
As explained in the work on LEVs in Annex3, there are great differences in car and vehicle ownership and use within global regions based on economic and land use factors. This is also reflected in the modal choice for work-related trips, as seen in Figure 1, with a large share of work-related mileage undertaken by cars in Germany and the USA. There exists a high share of trips for two-wheeler (2 W)- and three-wheeler (3 W)-based informal transport in India and the use of shared minibus taxis in South

Africa. When looking at mileage distribution by trip purpose, for the US, work and business trips comprise 19% of car-based person miles, followed by 24% for shopping and errands and 24% for social and recreational purposes (Fucci, 2017). In Germany, work and business comprise 44% of all car-based mileage, followed by 25% for leisure and 8% for shopping purposes (Infas, 2017).

### 2.3.4 Emission factors

Table 3 lists the emission factors used for the vehicle modes to determine the emissions evaded by teleworking. The weighted emission factors in CO<sub>2eq</sub> g/km are calculated using the emission factor of a specific mode and drivetrain and the associated fraction of vehicle kilometres for the mode in the region. It should be noted that the latest national survey including transport data in India is available only for 2010. To observe the change in usage of vehicle modes and hence a more recent representation, we see in Table 5 that the weighted emission factor in urban areas in 2016 based on calculations increased by 25% the national average for work trips in 2010. It can be seen that a worker in urban India emits 30% of a worker in the USA per km travelled for commuting.

The stock-averaged tank-to-wheel CO<sub>2</sub> emission factor of cars is expected to decrease substantially with increasing electric vehicle (EV) market share in the future. The decline is expected to be from 154 gCO<sub>2</sub>/km in 2020 to 16 gCO<sub>2</sub>/km in 2050 in Germany, 42 gCO<sub>2</sub>/km in the USA, and 79 gCO<sub>2</sub>/km and 65 gCO<sub>2</sub>/km in India (Feinauer et al., 2023).



**Figure 1 Modal split for work-related vehicle kilometres driven in selected countries**

Source: Germany (Carbon Trust, 2021), India (Goel, 2018), (Paladugula et al., 2018), USA (US Census Bureau, 2019a), South Africa (Roux, 2019), (Department Environmental Affairs, 2020),

Table 3 Tank-to-wheel emission factor of vehicle modes in selected countries

| Emission factor<br>(g CO <sub>2eq</sub> /km) | Car<br>(petrol) | Car<br>(diesel) | Car<br>(electric) | 2 W | 3 W | Bus  | Mini-<br>bus<br>taxi | Weighted<br>Emission<br>factor | Source                                             |
|----------------------------------------------|-----------------|-----------------|-------------------|-----|-----|------|----------------------|--------------------------------|----------------------------------------------------|
| Germany                                      | 154             | 135             | 0                 | 57  | na  | 1305 | na                   | 108                            | (Feinauer et al., 2023), (Infras, 2019)            |
| India                                        | 177             | 197             | 0                 | 59  | 156 | 1027 | na                   | 49                             | (Feinauer et al., 2023), (India GHG Program, 2015) |
| India (urban)                                | 177             | 197             | 0                 | 59  | 156 | 1027 | na                   | 62                             | Using VKT split from (TERI, 2018)                  |
| USA                                          | 214             | na              | 0                 | 86  | na  | 1764 | na                   | 207                            | (Feinauer et al., 2023)                            |
| SA                                           | 216             | 216             | 0                 | 86  | na  | 1911 | 720                  | 256                            | (Lewis & Cohen, 2016)                              |

## 2.4 Relevance of the regional perspective

The share of people working from home expanded throughout the world during the COVID-19 pandemic. The adoption of teleworking varied in region-based factors such as the occupational structures conducive to teleworking, ICT (information and communication technology) infrastructure and digital skills regulations and legal adaptations to enable telework and work culture. For example, in the EU, based on a survey, teleworkers rose from 15% of the workforce in 2019 (with 10% in 2006 for comparison of growth) to 36% because of the pandemic. EU countries that had better developed ICT infrastructure and regulations were able to adapt faster. (Policy Department for Economic, Scientific and Quality of Life Policies, 2021) Similarly, in the USA, based on a widespread survey with 30000 respondents, it was found that 48% of their workdays during the pandemic were from home in comparison to 4% before the pandemic, with 66% respondents wanting some form of hybrid work arrangement after the pandemic (Barrero et al., 2021). Teleworking was not as prevalent in India as in other developed countries before the COVID-19 pandemic due to infrastructure constraints, working cultures, space and conduciveness at home and child care, which were approached with accelerated solutions during the lockdown. This changed during the pandemic, where based on a survey of only IT sector employees in India, only 31% of employees completely or partially teleworked before the pandemic, which rose to 87% during the lockdown and was 76% post-COVID-19 (Nayak & Pandit, 2021). There was also a major shift in attitude and working culture in African countries in teleworkable jobs, with most enterprises adopting a hybrid arrangement of work post COVID-19 with a satisfactory gain in productivity

experienced (International Labour Office, 2022). It is observed through this study that there is a general lack of widespread and methodological data collection in developing countries to characterize and compare changes in working conditions and associated social, gender and cultural aspects.

The emission reduction potential of teleworking varies within regions and countries given the different occupational structures, spatial distribution of work locations, modes used to travel and their associated emission intensity, and home and office energy consumption. In addition to emissions saved by avoiding travel, heating and cooling demands are also very region specific (Li et al., 2021), which influence the net emission reduction. It is thus important to view the regions in a more clustered manner than having single benchmarks. Accordingly, the modelling in this work seeks to exemplify the regional differences and the range in the potential of emission reduction by teleworking through representative country examples. More in-depth analysis must be carried out for specific policy adoption; however, the variation and extent of teleworking as a mitigation option is addressed in this work.

### 2.5 Pathway

As mentioned, the latest data available for the regions were used to evaluate the emission reduction potential for the current time period. The rate at which the proportion of teleworkable jobs and the emission intensity of mileage travelled for work transform in the future, especially for developing and populous countries such as India, would determine the relative importance of emission reduction through teleworking (urban structures and the spatial distribution of work and business activity centres are comparatively slower to change to affect average commute distances). Comparing the teleworking potential of developed countries and developing countries gives an approximate idea of the range of increase in the emission reduction potential for developing countries. Exact modelling of future pathways of teleworking has thus not been addressed as a part of this work.

### 2.6 Link to the Sectoral Conversions regarding MOs

No link for this particular subject

### 2.7 Key opportunities and constraints (O&C)

The potential benefits of teleworking range from increased flexibility and autonomy, better work-life balance, and an opportunity for improved gender balance and thus improved performance and job satisfaction (Gajendran & Harrison, 2007; Ivasciuc et al., 2022). Aside from its transport emission reduction potential, teleworking can also reduce peak time demand on resources such as electricity, public transport and road congestion (Fabienne Wöhner, 2022). On a structural level, space consumption and costs for office buildings can be optimized and reduced (Policy Department for Economic, Scientific and Quality of Life Policies, 2021).

On the other hand, high levels of teleworking have also led to feelings of professional isolation, negative health and ergonomics, reduced relationships with coworkers, anxiety, and overwork among teleworkers (Vayre et al., 2022b). There is also a disparity in residential space per capita, which can enable a good working environment and hence productivity. In the current scope of work, we try to focus on the technological constraints to achieving maximum emission reduction potential within a regional context.

### 2.7.1 Digital connectivity and internet access

Globally, approximately 24% of all jobs present can be done from home, but this is reduced to 18% when adjusted for internet availability. This translates to a 30% decrease globally. This gap is even higher for developing countries, with 51% and 58% drops in Ethiopia and Nepal, respectively. (Nicolas Gomez Parra, 2020) As seen in Figure 2, there exists a great disparity in the ownership of computers at home and internet access at home (without using cellular data) and mobile data. There has been a steep increase in accessibility to the internet, especially the mobile internet, in developing countries (ICT Data and Analytics Division, 2022). For example, from 2010 to 2022, the percentage of the population in Africa covered by at least a 3G mobile network has increased from 1.7% to 82%. However, there still exists a considerable gap between the internet speeds for both uploading and downloading relevant for remote working, as highlighted in Figure 3. In low- and lower-middle-income economies, mobile broadband offers speeds much closer to fixed networks than high-income economies, where fixed-broadband speeds are 30-100% faster than mobile networks (hence the relevance of both mobile networks and fixed networks for remote working) (Ookla LLC, 2022). Approximately 82% and 78% of South African participants agreed that data and internet assistance and availability of more resources would help with better teleworking conditions in a survey conducted in (Sucheran & Olanrewaju, 2021). Sixty-five percent of respondents in (ILO, 2021) also felt the same in India.

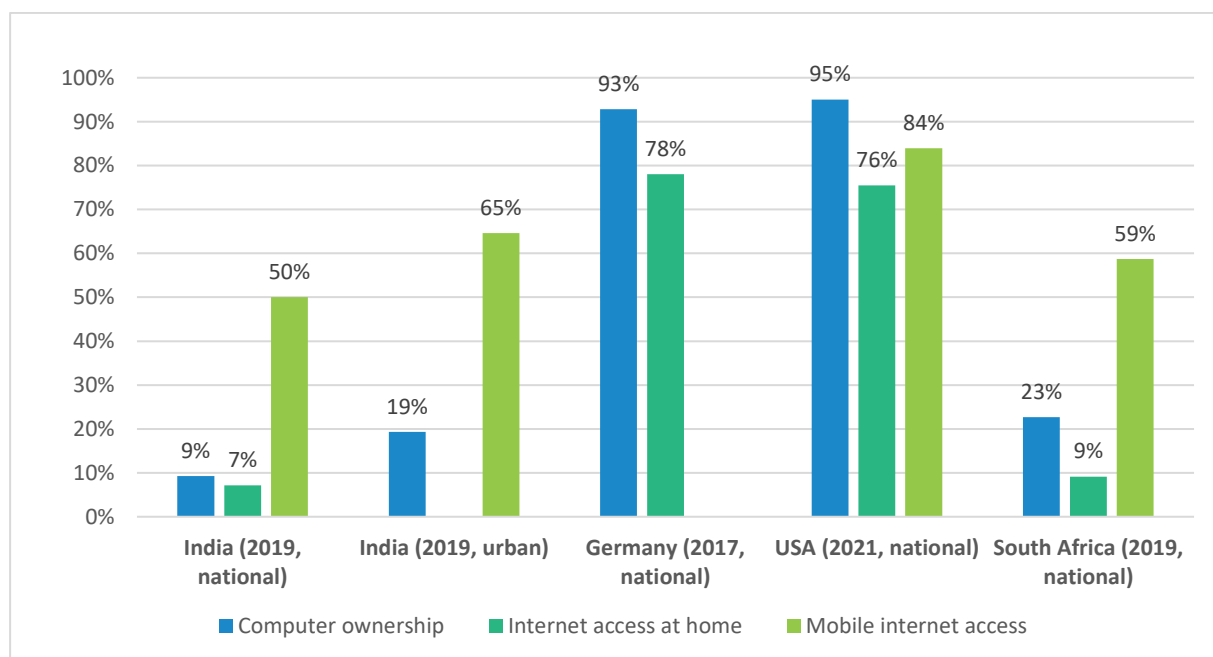


Figure 2 Availability of digital resources and internet connectivity.

Sources: India (International Institute for Population Sciences, 2022), Germany (OECD Stats, 2022), USA (US Census Bureau, 2019b) and South Africa (Roux, 2019).

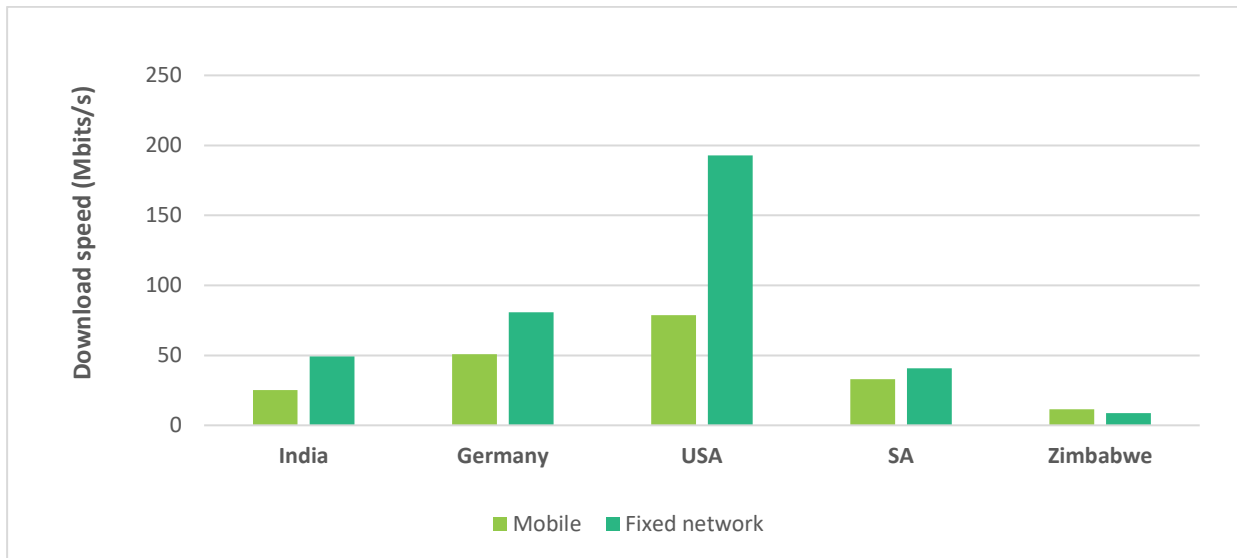


Figure 3 Download speeds in different regions

Sources: (Ookla LLC, 2022)

### 2.7.2 Power grid

Uninterrupted power supply is a prerequisite for smooth teleworking at home. Having a backup power supply is often not a feasible or affordable option, especially for households in developing countries. With aging coal power plants, employers in South Africa's stance on teleworking is shifting back due to unmanageable load shedding, as seen in Figure 4, to maintain employee productivity and reliance (John Jack; Matli, 2020). It is on its resistant path to shift to cleaner energy, where currently 85.7% of power generation (due to abundant coal reserves) is from coal and only 0.9% is from solar energy (Statistics South Africa). India has made great progress in the past decade, with 96% of households having access to electricity in 2020 compared to 67% in 2010 (CEEW, 2020). However, there still exist considerable power cuts per day where the average daily urban power supply can range from 23-19 hours depending on states and 23-16 hours for rural areas in India (CEEW, 2020). The USA, on the other hand, has just 7.3 hours of annual power cut, with variation in states from 80 hours to 102 minutes per year depending on the federal state (U.S. Energy Information Administration).

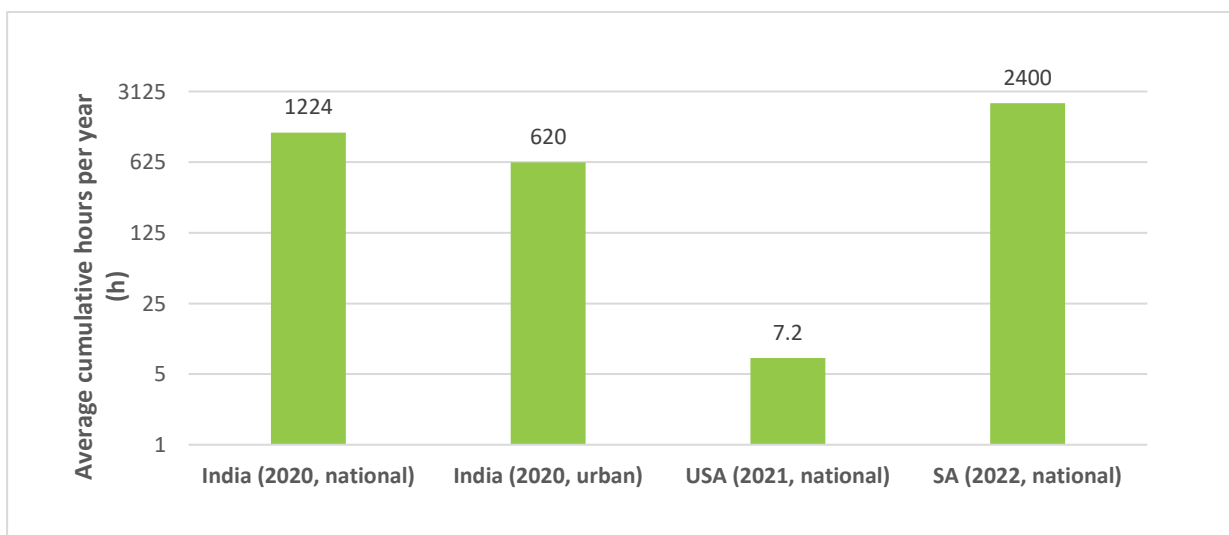


Figure 4 Annual power cuts in selected countries

Sources, India (CEEW, 2020), USA (U.S. Energy Information Administration), SA (Labuschagne, 2022)

### 2.7.3 Residential space and energy consumption

There exists an enormous disparity in being able to have the option of a quality work setup for all working members of households in global regions (Armillei et al., 2021). As seen from Figure 5, the residential area per person in urban India is 10 m<sup>2</sup>, which is approximately one-ninth that of an average person in the USA. Considering that an average dwelling in Europe was ~100 m<sup>2</sup> with 2.3 persons, one can observe the lack of space to have an independent work setup that exists.

Since larger spaces also lead to higher energy consumption for space cooling and heating depending on geographical location, the overall emission reduction potential of teleworking in high residential energy intensive countries is lower since commuting emissions are then replaced by increased residential space heating and cooling requirements.

Thus, as seen in Figure 5, space heating and cooling accounts for 70% of total residential energy consumption in Germany in comparison to 43% in the USA and 40% in urban India. The total residential energy consumption for India on a per capita basis is ~ one tenth that of the USA (despite having a higher carbon intensity of residential energy).

However, as with vehicle emission factors, emission intensity is expected to decrease in developed countries with the adoption of building emission mitigation options and renewable energy generation. Along with this, an increase in energy consumption in developing countries such as India with greater disposable income to own cooling equipment in larger spaces is also expected.

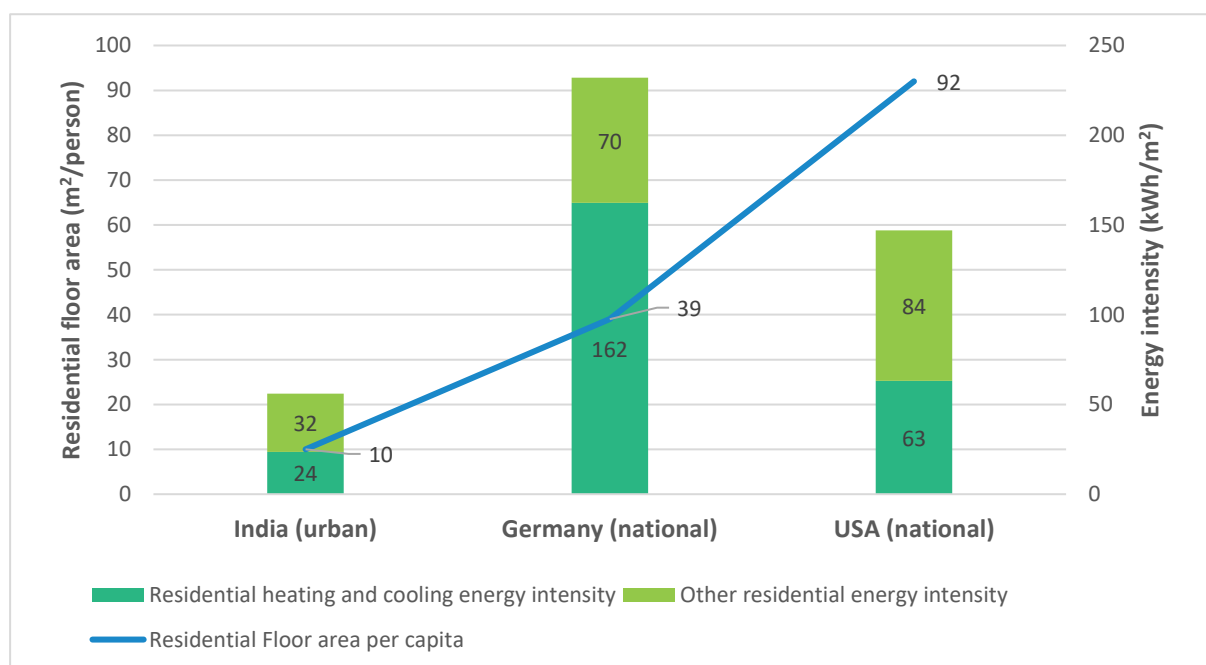


Figure 5 Comparison of residential floor area and energy consumption in selected countries.

Source: India (Tanmay Tathagat & Piyush Varma, 2020), Germany (Enerdata, 2022), USA (Center for Sustainable Systems, 2022)

**Table 4 Residential energy consumption in selected countries**

|                                                                            | India<br>(urban)     | Germany<br>(national) | USA<br>(national)                         |
|----------------------------------------------------------------------------|----------------------|-----------------------|-------------------------------------------|
| Residential heating and cooling energy intensity (kWh/person)              | 235                  | 6333                  | 5815                                      |
| Other residential energy intensity (kWh/person)                            | 324                  | 2714                  | 7708                                      |
| Residential energy mix carbon intensity used (kgCO <sub>2</sub> /kWh)      | 0.725<br>(IEA, 2021) | 0.414                 | na                                        |
| Total Residential GHG emission per capita (kgCO <sub>2</sub> /person/year) | 406                  | 3745                  | 4324<br>(Benjamin Goldstein et al., 2020) |

Quantifying the exact overall emission reduction potential would require the characterization of office activities and energy use, residential activities and bottom-up knowledge of the number of rooms, working status and lifestyle of members of households and technology used for managing space heating and cooling. An example of Germany used to exemplify the effect of not accounting for building-related emissions is shown in the results section.

## 2.8 Mitigation option results

Based on the methodology described in (Carbon Trust, 2021), the emission reduction potential for teleworking from the commute was calculated. Countries with a higher share of teleworkable jobs, larger commute distances and emission intensity of modes used for commuting, such as Germany and the USA, have transport-related emission reduction potentials of 7% and 5% of road passenger transport emissions, respectively. This is, however, much lower for the case of India and South Africa. Even with increasing activity, car ownership and the proportion of teleworking jobs for developing countries, as a proportion of passenger transport emissions, it can be assumed that the limit is already seen in developed countries and is only expected to further decline with increased public transport, electrification of passenger car fleets, transformation of cars as a commodity and urbanization in the near future for these countries.

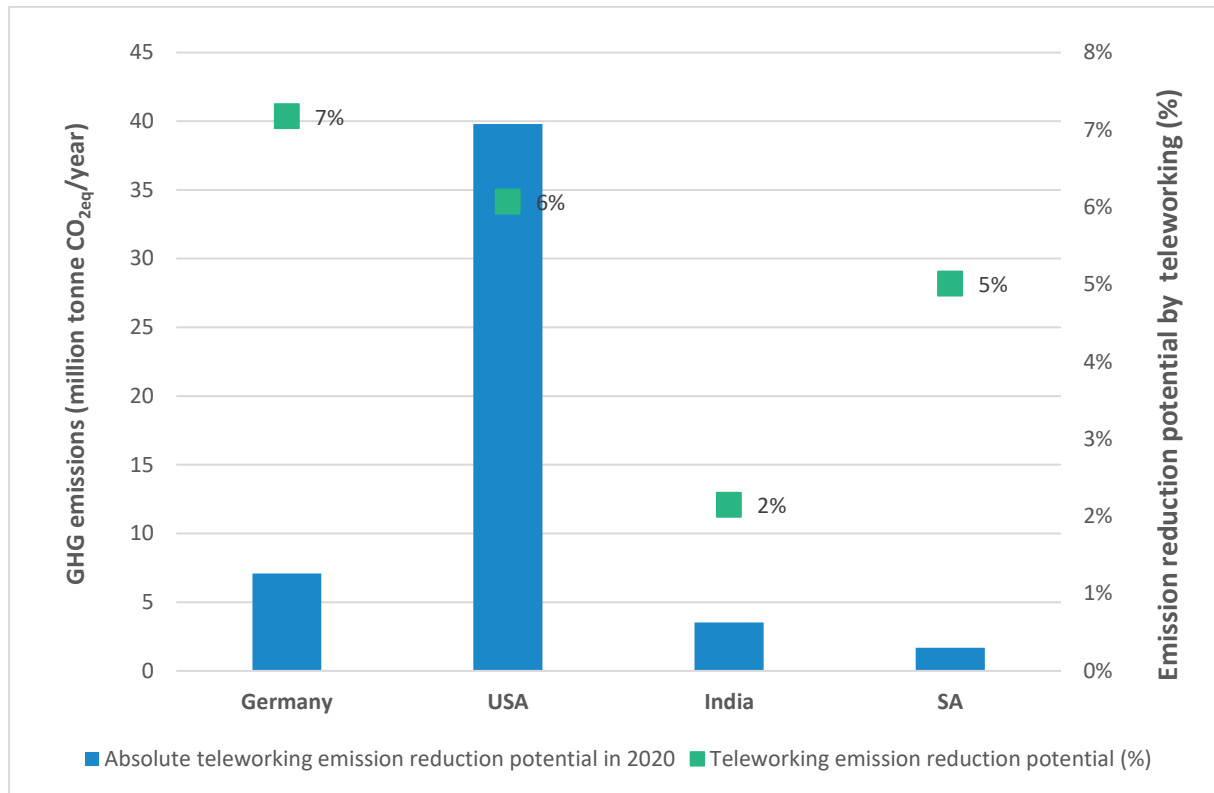


Figure 6 Transport emission reduction potential by teleworking in selected countries

To demonstrate the effect of not considering overall emissions from the building sector, we see in Table 1 the net reduction in emissions when subtracting increased domestic emissions from LCA transport and office emissions in winter for Germany. Based on these inputs, the seasonal variation in the emission reduction potential decreases by a factor of 7 from summer to winter, mainly due to residential space heating requirements.

Table 5 Effect of considering building emission and seasonality

| Emissions<br>(kg<br>CO <sub>2eq</sub> /day/<br>teleworker) | Tailpipe transport<br>emissions using<br>petrol car | LCA transport<br>emissions using<br>petrol car | Domestic<br>emissions | Office<br>emissions | Net<br>emission<br>reduction |
|------------------------------------------------------------|-----------------------------------------------------|------------------------------------------------|-----------------------|---------------------|------------------------------|
| Germany<br>(summer)                                        | 5.2                                                 | 7.8                                            | 4.4                   | 3.6                 | 7.0                          |
| Germany<br>(winter)                                        | 5.2                                                 | 7.8                                            | 12.7                  | 5.9                 | 1.0                          |

Source: LCA and building emissions (Carbon Trust, 2021)

The net emission reduction by teleworking considering building emissions varies in the literature depending on the methodology used to account for office and domestic emissions and their related inputs. For example, in (IEA, 2020) (which does not explicitly consider office emissions), we see the effect of seasonality, resulting in a 58% drop in emission reduction potential in the EU, 22% in the USA, and 107% in China (reduction potential in summer relative to winter). In summary, the effect of building emissions is region specific, seasonal and significant. They must thus be included to calculate the potential emission-related benefits of teleworking to avoid overestimation.

### 2.9 Gender differences

Ideally, the option to work from home should give genders an opportunity to equally contribute to care, parenthood and domestic chores and hence create more diverse employment opportunities.

However, this has not been the case all over the world, with teleworking having a gendered effect with varying degrees in global regions. Gender has a correlation with being employed, job type, job proximity to residence, vehicle mode selection and productivity during telework.

As described in the paper with LEVs with gender in the next chapter, the labor participation rate of females varies greatly in global regions, with it being 24% in India, 23% - 38% in South Africa depending on race and 56% in the USA. This reflects the societal and cultural differences in gender roles historically present in these regions, which can affect the work and additional responsibilities of employees at home. As an indicator of the disparity in the distribution of unpaid work, as per (Dunatchik et al., 2021), in the US, the percentage of time spent on housework is 76% more for women and 43% more for men compared to prepandemic times given that only responders stay and work at home. This shows the extra work carried out by women when at home. For South Africa, as per surveys conducted in the work of (Sucheran & Olanrewaju, 2021) only 63% of women found their homes to be conducive environments for teleworking compared to 90% men, indicating the extra distractions and work that are present for women workers at home. For the EU, when comparing individuals with a full-time job and children, women spend 83.5 hours per week of paid (41.2 h) and unpaid work (42.3), whereas men spend 70.6 hours per week of paid (45.4) and unpaid work (25.3). This shows how working from home is an opportunity to help women balance their time and men to bridge the gap in the EU (Nivakoski et al., 2022). Based on a survey of IT professionals in India surveyed before the COVID-19 pandemic, ~80% of males with children reported a productivity level greater than 75% when teleworking compared to only 30% of females with children (Nayak & Pandit, 2021). According to (ILO, 2021), in India, the key benefit to being able to work from home for 80% of women respondents was 'No commuting stress to office' and 'Better work life balance' for 65% of respondents.

Jobs that can be done remotely can have a gendered effect given that women work more in healthcare, education, food services, beauty and service industries with less possibility to work remotely (at the same time, they work less in construction and other labour-intensive roles that are also not suitable for teleworking). According to (Nicolas Gomez Parra, 2020), in India, no differences were found for the amenability of a job to be teleworkable by gender. In the EU, however, the percentage of jobs that were teleworkable was 29% for women and 22% for men (Nivakoski et al., 2022).

Thus, policy and attitude relating to teleworking should ensure that it is sensitive to the gender gap existing in domestic work and that all members of related households have an equal opportunity to productively work at home and equally contribute to other unpaid activities.

### 2.10 Conclusions

In this work, the emission reduction potential of teleworking is computed and compared for different representative countries. Relating constraints and regional specificities of occupation structure and telework supporting digital and power infrastructure, commuting vehicle mode use and related emission factors, residential energy consumption differences are discussed. The following key insights are derived.

- A higher fraction of teleworkable jobs and supporting infrastructure are present in countries with higher GDP. However, the pandemic changed and accelerated technological and cultural shifts to support teleworking worldwide.
- Maximum commute-related emission reduction potential from teleworking therefore also exists in developed countries given their higher fraction of teleworkable jobs and emission intensity of vehicle mode used for commute (which would not be used). The range of emission reduction potential varies from 7%-6% for Germany and the USA and 2%-5% for India and South Africa. The relatively higher reduction potential regions also coincide with higher heating and cooling demands, due to which the net benefit decreases based on season. Building demand and floor area per teleworker individually heated or cooled have a major impact, and parallel sector transformation would improve the potential of this mitigation option.
- While the mitigation potential in developing countries seems quite low today, it might change in the future due to changes in the economic structure and changing mobility habits. Therefore, it is important to anticipate such developments already today.

Care should be taken to avoid rebound effects (such as relocation of residences) and to avoid additional activities that would nullify the benefit of reduced commuting in terms of emissions.

- Reducing travel to work must be complemented with a lifestyle that supports reduction so that the overall effect is not offset. This extends to dwelling size and consumption, domestic activities and services used and substituting additional activities undertaken.
- Urban sprawl reduction policies must go hand in hand with teleworking to avoid shifts to lower density areas, which would increase personal transport for other purposes given that personal transport budgets are not altered.

Teleworking enables better work life balance with reduced time spent commuting and can reduce gender gaps in unpaid work and employment opportunities. Apart from the emissions perspective, teleworking and forms of hybrid working should still be encouraged when appropriate for better living and working conditions for all.

### 3 Shift: Light Electric Vehicles as a mitigation Option

The work carried out for this measure is part of the submitted article in Annex 3. A brief overview of the methodology and findings of the work are discussed here.

Light electric vehicles (LEVs) considered in this work range from e-scooters, e-bikes, and e-mopeds to quadricycles. Their lower mass-to-payload ratio in comparison to cars results in higher efficiency and much lower emissions. As seen in Figure 7, the LCA-based emissions for even the largest (and highest trip requirement satisfying) LEV are one third that of a battery electric SUV.

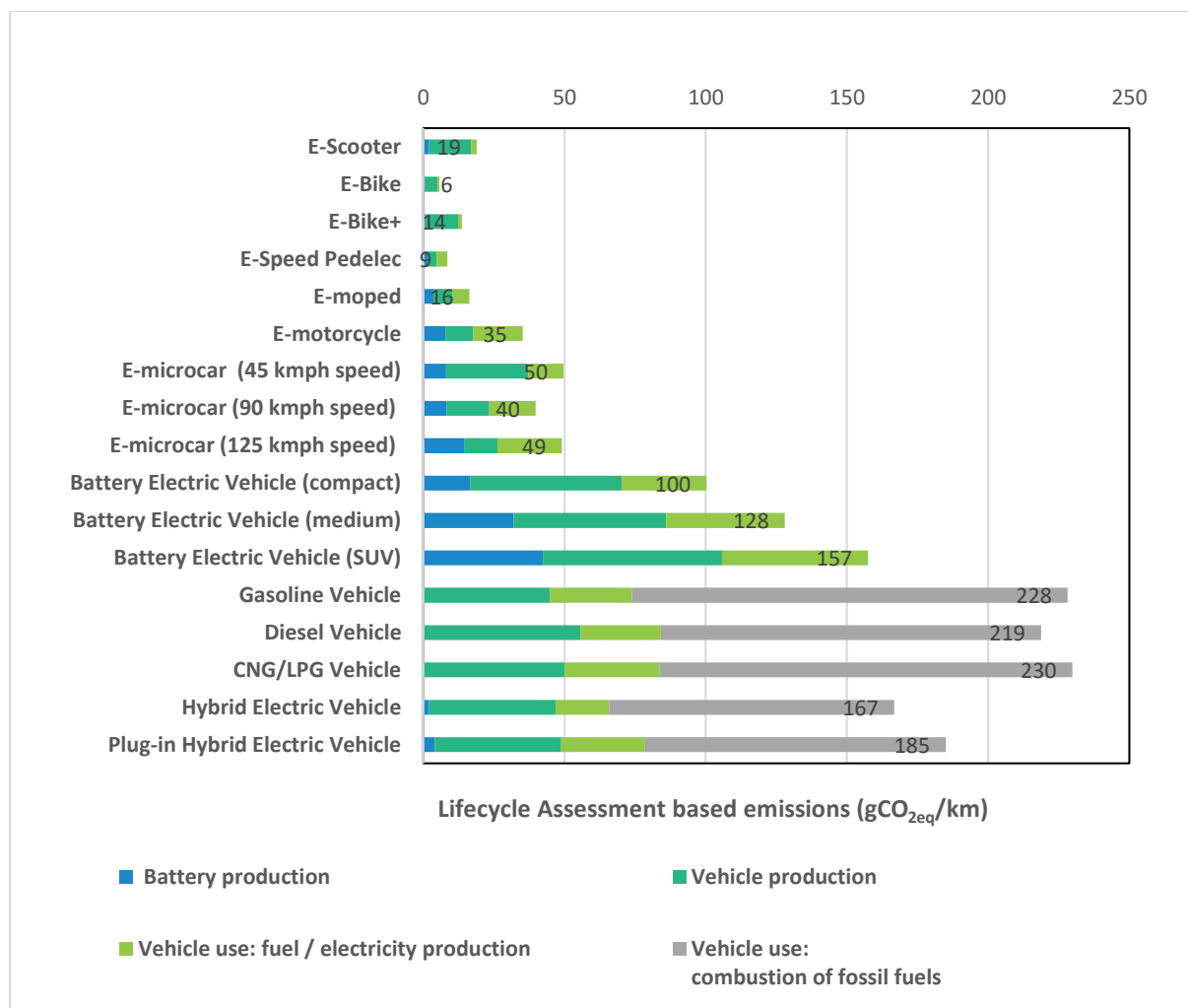


Figure 7 LCA-based emission factors for LEVs and passenger cars

Source: (Ehrenberger et al., 2022) and a result of current work

In this paper, we discuss the increasing popularity of LEVs across all global regions along with trends of increasing travel demand and car ownership in developing countries, SUV market shares (both conventional and battery electric drivetrains) and urbanization. Given that current emission regulations are based on tailpipe emissions, battery electric SUV sales are unhindered and are unchecked.

The potential of LEVs to substitute car and two- and three-wheeler passenger trips and thus to reduce GHG emissions is computed for the year 2030. The maximum tailpipe (direct) emission reduction potential of LEVs was found to be 50% for Germany and 34% for the USA with respect to total passenger car-based emissions in 2030 in the country. This is computed through a bottom-up approach using national travel surveys where in any trip that can be potentially substituted by an LEV which can satisfy

trip characteristics of trip length, accompaniments, trip purpose, driver, weather and accompaniments age and whether it is done with the least emitting LEV. Where national travel surveys were not available, an assumption of 50% maximum mileage substitution of cars by electric microcars is assumed (as is in Germany solely on the basis of trip characteristics) for South Africa and India. The maximum tailpipe (direct) emission reduction potential of LEVs was found to be 46% and 40% for India and South Africa, respectively. This was considering current plans of electrifying its predominantly 2 W and 3 W fleet of India, which would lead to a 15% emission reduction potential in 2030.

The realization of this theoretical potential is contingent on many factors covered in the study, such as vehicular costs, which are especially relevant for developing countries, charging infrastructure, safety- and security-related experiences and associated physical infrastructure for smaller LEVs. The aspect of gender is especially important for LEVs given how certain modes are more conducive for care and safety (against harassment). These are discussed in detail in Annex 3 with appropriate indicators to highlight the regional specificities.

The major conclusions drawn from the work were as follows:

- LEVs offer great potential to substitute cars and two-wheeler trips and thus reduce GHG emissions given that a large proportion of daily travel needs fit within the ranges and provisions of LEVs. The reduction potential is higher for car-dependent countries with shorter travel distances. While maintaining modal splits in developing countries is important, especially for urban living conditions, and avoiding a lock-in, a major shift is needed for developed countries to ensure fair per capita emission reduction shares and responsibilities. The current SUV trend is negating efficiency improvements and electrification, which must be immediately addressed for mid-range length daily trips with smaller and electric cars.
- LEVs should ideally complement public transport and other nonmotorized transport to avoid rebound effects. Data-based consumer requirements and travel needs, infrastructure, financial instruments and land use planning are crucial to achieving sustainability goals while satisfying travel needs.
- LEVs in a shared and digitally enabled environment could further reduce space consumption and emissions and improve inclusivity.

Gaps found that require further research and inclusion in policy:

- Discussion of lighter vehicles is largely missing in international policy forums. Since fleet targets are based on tailpipe emissions and not on LCA-based emissions or energy efficiency, no incentive exists for smaller electric vehicles for manufacturers.
- Regulatory provisions currently lag in terms of definitions, testing, safety standards and flexibility to adapt to newer LEV types.
- Large-scale experiments using LEVs need to occur for the right momentum to increase user acceptance.
- Further push pull measures based on vehicle weight, space and LCA emissions need to be tested to encourage a shift towards LEVs.
- Rebound effects such as LEVs replacing nonmotorized transport such as walking and cycling where suitable should not occur and discouraged through interventions.

# 4 Electrification of passenger cars as mitigation option

## 4.1 Introduction

Transport greenhouse gas (GHG) emissions can be mitigated by 3 main measures: reducing vehicle travel (avoid), shifting transport to more sustainable modes such as light electric vehicles (LEVs) and improving vehicle efficiency, for example, to electric vehicles (improve). The potential of teleworking for avoiding vehicle travel has already been studied earlier in this paper. A potential of 5% or 7% GHG reduction exists in the USA and Germany, respectively. Then, the potential of shifting transport from passenger cars to LEVs was studied. In this case, the potential is much higher. However, the acceptance of LEVs still faces social apprehension and is still subject to institutional and attitudinal constraints. In this work, the last measure discussed to reduce GHG emissions from passenger transport is the improvement of vehicle efficiency. The rapid development of electric vehicle (EV) technology, infrastructure deployment in different world regions and increased consumer acceptance indicate the major role that electrification will play globally for the passenger car segment in the near future (Patrick Plötz, 2022).

The Paris Agreement could be achieved by fast electrification of the passenger car sector, but most of the decarbonization targets put forward by countries are currently not binding or not enough to contribute to fast decarbonization (Patrick Plötz et al., 2019). The European Union (EU) has become the first major region globally to establish a 100% reduction binding target for CO<sub>2</sub> tailpipe emissions from all newly registered cars starting in 2035. Smaller regions, such as British Columbia in Canada (by 2040) and the State of Washington, Oregon, California, Vermont, Massachusetts and New York in the United States (by 2035), have also adopted binding targets, permitting only EVs (both battery electric vehicles, BEVs; and plug-in hybrid electric vehicles, PHEVs) and fuel-cell electric vehicles (FCEVs) for new registrations (Dornoff, 2023). In other major regions, such as China, targets have been proposed, with aims to achieve 20% EV sales by 2025 and 50% by 2030. However, a 100% zero-emission vehicle sales target has not yet been proposed (73).

Binding targets contribute to a faster intake of alternative powertrains because CO<sub>2</sub> reduction targets set a clear signal to manufacturers and boost investments and innovation (Axsen et al., 2022). This is relevant because EVs are a nonmature technology, and there are different barriers seen by customers, such as lack of infrastructure, range, charging time, and upfront costs (Deloitte), which have improved markedly owing to policy targets. To improve customer adoption, the actions of different stakeholders, such as governments, car manufacturers and infrastructure operators, are needed (ACEA, 2022b).

In combination with demand-side oriented measures, there are different policy measures that governments can set to accelerate EV uptake and to reduce GHG emissions, such as yearly CO<sub>2</sub> emission standards, ZEV mandates, or bans on ICE vehicle new registrations. These measures set a clear path on the expected EV adoption. For example, they have had a strong effect on the boost of EV uptake in the EU in the period 2020-2022 (Transport & Environment, 2021a).

Apart from the uptake of EVs for decarbonizing the passenger car sector, the fleet electrification savings potential in a region depends on vehicle fleet renewal, which in turn depends on the survival rates of all the vehicles registered (new and used). It is important to see that even banning sales of new EV sales as different regions of the world have set (Feinauer et al., 2023), reaching a zero-emission fleet will differ significantly from region to region and will depend on the import used market and on the survivability of the vehicles (Alarfaj et al., 2020). The CO<sub>2</sub> emissions reduction potential with current CO<sub>2</sub> emission reduction targets is quantified and studied in different countries across the EU. Additionally, there is a risk that after banning ICE vehicles for new registrations, used ICE vehicles are held for longer periods (Held et al., 2021a). Circulation bans, scrappage schemes or heavy taxation of used vehicles are different measures to accelerate stock fleet turnover and have an electrified fleet faster. This work

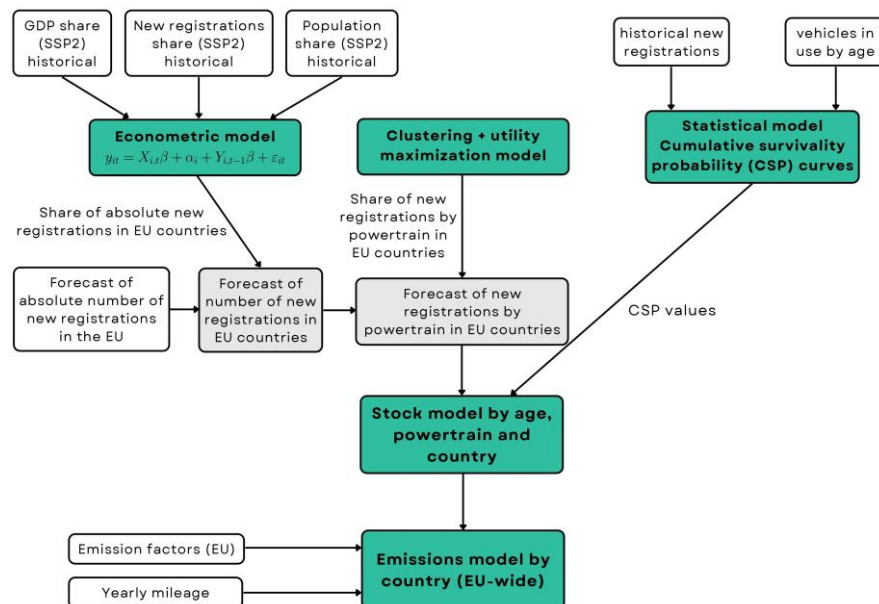
tries to quantify the effect of such policies, which would reduce the emission intensity of the existing fleet and push newer EVs into the stock.

To analyse how governments globally can accelerate EV uptake and reduce GHG emissions, an overview of the opportunities and constraints of EVs from the demand-side perspective is carried out based on customer surveys and a literature review. Then, different policy measures for the new vehicle market and for the used car market are analysed that can accelerate GHG reduction potential based on a literature review. Finally, a forecast of emissions in the EU is carried out in a reference scenario and evaluated with different policy measures to reduce GHG emissions.

## 4.2 Methodology

### 4.2.1 Chosen approach and scientific concept

The following report is based on a methodology that focuses on the emission reduction potential from the electrification of the passenger car fleet<sup>1</sup>. New vehicle registrations, used vehicle registrations, the survival probability, the mileage distribution and the pollutants for each vehicle type play an enormous role in obtaining accurate estimates. The methodology was based on a combination of models (cf. Figure 8), an econometric model, a utility maximization model (Möring Martínez et al., 2023), a statistical model (Held et al., 2021a) and a bottom-up approach model, which all together allow us to forecast the stock and emissions of the passenger car sector in different regions. The methodology has been applied at the EU level. The study tries to quantify the fleet structure and emissions based on different characteristics (age, powertrain, pollutants, mileage and country of the vehicles). It allows us to quantify the stock structure and emissions reduction potential when different policies such as CO<sub>2</sub> emission standards and circulation bans are applied. Using this model, insights to policymakers can be transferred. Such analysis can better inform policy makers of the range of benefits and constraints of different policies and which policy mix can be optimal to reduce overall GHG emissions.



**Figure 8 Comprehensive methodology for stock and emissions forecasting:** This diagram outlines the multifaceted methodology employed to forecast vehicle stock and emissions in the EU. The model's flexibility extends to accommodating different policy scenarios, offering insights into how these scenarios could affect stock and emissions trends.

<sup>1</sup> Zero-emissions in the passenger car sector can be achieved both with BEV and FCEV. However, FCEV are highly unlikely to be competitive with BEV and are expected to play a minimum role in the future Patrick Plötz (2022).

### 4.2.2 Data

The methodology presented can be applied for any world region if there is data availability. We mainly focus on studying at a quantitative level the emissions reduction potential of the EU Member States.

### 4.2.3 Econometric model

#### 4.2.3.1 Fixed effect model with lagged dependent variable

The econometric model uses two independent variables: economic indicators and one dependent variable. The model gives the share of new passenger car registrations in each EU country. The three variables are:

- GDP share with respect to the EU (independent variable)
- Population share with respect to the EU (independent variable)
- New registrations share with respect to the EU (dependent variable)

The results of the forecast of the dependent variable depend on the forecast of the independent variables. The forecast of the economic indicators comes from the Shared Socioeconomic Pathways Database (IASA, 2018). Specifically, we focus on scenario SSP2 ("Middle of the road"). The SSP2 scenario does not shift markedly from historical patterns and assumes a moderate growth trajectory and moderate convergence between developing and advanced countries at a global level (Crespo Cuaresma). The econometric model is calibrated with historical data of the economic indicators, GDP and population from 1996 to 2021. 1996 is selected based on the oldest year of data availability for the 27 EU countries. The new registration data are extracted from (ACEA, 2021b, 2022a).

#### 4.2.3.2 Forecast of absolute EU registrations

The stock of a country changes yearly based on yearly registrations and yearly deregistrations. A higher number of registrations, with a constant number of deregistrations, car efficiency in terms of CO<sub>2</sub> emissions, and mileage implies higher emissions. The forecast of absolute EU registrations comes from 2 different sources, which we consider and can be modelled under 2 different scenarios (CAM, 2021; Deloitte, 2023).

Table 6 Forecast of EU new passenger car registrations (in millions) up to 2050 under two different scenarios.

| Scenario                              | 2020        | 2025         | 2030         | 2035         | 2050         |
|---------------------------------------|-------------|--------------|--------------|--------------|--------------|
| Deloitte EU 27 (Deloitte, 2023)       | 9.73        | 11.04        | 11.11        | 10.84        | 10.84        |
| <b>CAM: 2030 recovery (CAM, 2021)</b> | <b>9.73</b> | <b>10.66</b> | <b>13.01</b> | <b>13.01</b> | <b>13.01</b> |

There is a significant amount of difference in the registrations forecast in both scenarios by 2035. The CAM scenario assumes that sales recover values prior to COVID-19 by 2030. From 2023 until 2035 (the period where new vehicles registered can still be nonzero emissions), there are 1.2 million more vehicles newly registered under CAM or, in relative terms, 9.3% more new vehicles registered than in the Deloitte scenario. As discussed, selecting one or the other scenario will have effects on the total

amount of emissions obtained in the model. We focus only on forecasting stock and emissions under the CAM scenario.

### 4.2.4 Clustering and utility maximization model (Möring Martínez et al., 2023)

The model uses the forecast of new registrations by type of powertrain for all EU countries coming from (Möring Martínez et al., 2023). The forecast shows significantly different trajectories to achieve the net-zero emissions target set by the EU in 2035 (European Commission, 2022). For example, in 2030, Eastern countries will have approximately 30% BEV sales, Southern countries will have approximately 50% BEV sales, Central European countries will have approximately 70% BEV sales and Scandinavian countries will have close to 100% BEV sales. The forecast of (Möring Martínez et al., 2023) is up to 2035.

### 4.2.5 Statistical model: Cumulative survivability probability (CSP) curves (Held et al., 2021a)

CSP represents the likelihood of a car from a particular year remaining in a country's vehicle fleet, considering factors such as scrappage and exportation to other countries. To obtain CSP curves, data on the age distribution of vehicles in stock and new vehicle registrations are needed. For 2016, a substantial dataset was compiled by (Held et al., 2021a) to calculate CSP curves. We update CSP values for 2021, drawing from a combination of sources, including (Held et al., 2021a) and new data sources.

It is important to note that the quality and resolution of vehicle stock data by age can vary significantly from one country to another, which can impact the accuracy of our distribution fitting and the  $R^2$  values obtained in our simulations. The age distribution data for vehicle stock primarily come from national statistical offices and other official sources such as Ministries. Similarly, data on new vehicle registrations are sourced mainly from national statistical offices. In cases where such data were not available, we refer to (ACEA, 2021b, 2022a; Held et al., 2021a).

We obtain CSP curves for 2021, and we observe that the survival rate of the vehicle fleet changes over time, as previously discussed in (Cabrera Serrenho & Allwood, 2016; Held et al., 2021a; Oguchi & Fuse, 2015). One key parameter of interest is the Weibull average lifespan, denoted as  $\lambda$ , which directly correlates with the average age of the vehicle fleet. Figure 9 illustrates that in all countries, the Weibull average lifespan ( $\lambda$ ) has increased from 2008 to 2021, except for Denmark, where it has remained almost constant. Furthermore, from 2016 to 2021, most countries experienced a significant or moderate increase, except for Finland, which saw a significant reduction, and Denmark, where it remained constant. Figure 2 underscores the trend of increasing average lifespans (thus increasing the average age of vehicle fleets) in recent years. This trend has a negative impact on GHG reduction efforts, acting in the opposite direction."

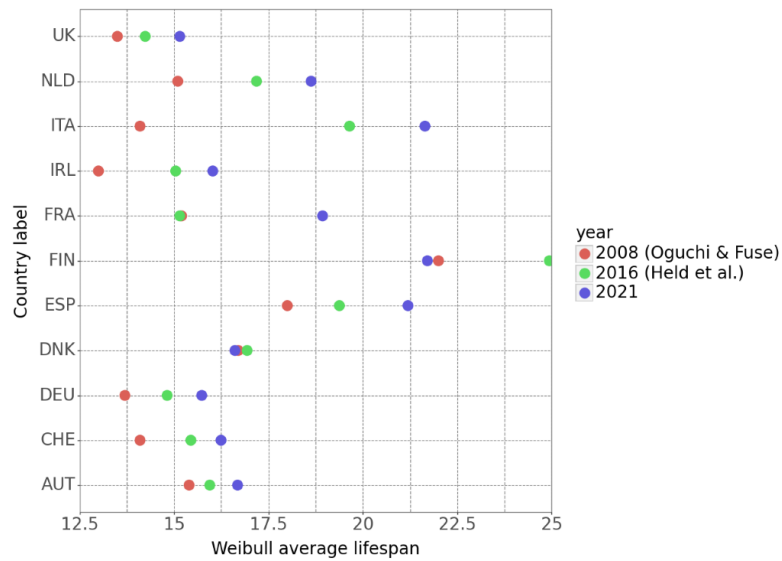


Figure 9 Weibull average lifespan in 2008, 2016 and 2021 for different European countries.

Source: Data from 2008 and 2016 come from (Oguchi & Fuse, 2015).

### 4.2.6 Stock model

The stock model calculation depends on a model that combines different inputs already described in the previous sections.

### 4.2.7 Emissions model

The emission model uses the stock model results and two external inputs, yearly mileage and emission factors.

The average yearly mileage is obtained for 2019 due to the lack of homogenous data for more recent years. The data sources used are national statistical offices, namely, OECD (OECD, 2023), Eurostat (Eurostat, 2023e, 2023f) and Enerdata (Enerdata, 2020). There is a large discrepancy in the average annual distance travelled by car between countries. It ranges from less than 7500 km in the Czech Republic, less than 9000 km in Italy and Poland to more than 12000 km in France and Germany and to more than 16000 km in Ireland. The average yearly mileage has a linear effect in the emission calculation. In this study, we do not focus on how yearly mileage and travel demand will develop in the future<sup>2</sup>.

Finally, the emission factors are obtained from HBEFA (Infras, 2022). The emission factors are not available for all EU countries. Average emissions factors for the EU are available, and they are selected. The emission factors depend on the powertrain type and Euro-class, which can be related to the year of introduction and hence the year of the first registration of the vehicle. Emission factors are available for CO<sub>2</sub> and for different pollutants, such as NO<sub>x</sub> and PM.

Emission factors and fuel efficiency have improved for most pollutants, with each tightening Euro-class and year (Infras, 2022). However, CO<sub>2</sub> emission factors have increased primarily due to the increase in SUV vehicles with higher mass and fuel consumption. An average Euro 6d diesel vehicle in the EU emits more in 2021 as an average Euro 3 diesel vehicle in 2001 (184 g/km of CO<sub>2</sub> in 2001 vs. 188 g/km in 2021). To reduce emissions, we need to improve the current vehicle fleet structure. Apart from electrifying the fleet, it is important to promote the registration of smaller and less powerful passenger cars (P. Plötz et al., 2021; Transport & Environment, 2021a), including shifts to LEVs where possible.

<sup>2</sup> In Europe travel demand is expected to stabilize in future years Seum and Eisenmann (2020b).

### 4.3 Key opportunities and constraints (O&C)

Before applying a quantitative analysis in the EU for analysing the effect of specific policies for reducing GHG, the current understanding of opportunities and constraints for electrifying passenger car fleets across the world is analytically and qualitatively examined through a systematic literature review. The growth of EVs is shaped by both demand-side factors (consumer-driven) and government policies (policy-driven) (Demeulenaere, 2019; Freeman, 1996; Kemp & Soete, 1992). The evolution of battery technology due to advances in lithium-ion batteries has strengthened the competitiveness of EVs against traditional internal combustion engine (ICE) cars (Hasselwander et al., 2023; Korthauer, 2013). However, due to its maturity, ICE technology currently holds advantages in line with consumer preferences (Tschöke et al., 2019), such as purchase price, a widespread infrastructure, rapid refuelling and absence of range anxiety.

A faster electrification of the passenger car fleet and transformation of the energy sector will contribute to the reduction of GHG emissions and local pollution. Therefore, different regions of the world and specific countries have put in place targets (Feinauer et al., 2023), policies (Axsen et al., 2022; Dornoff, 2023; (EU) 2019/631, 2021) and investments; i.e., purchase incentives for EVs (Münzel et al., 2019) and infrastructure investment or subsidies (Dimanchev et al., 2023; Kumar et al., 2021) to speed up technology improvements and stimulate the demand side. The measures have contributed to enhanced vehicle specifications (e.g., extended range, lowered pretax prices), faster infrastructure deployment, and lower gross prices after taxes and incentives. Collectively, these factors have improved the competitiveness of EV technology, propelling higher regional and worldwide EV adoption rates.

Conversely, policy-driven measures are also very effective. For example, policies such as the European Commission's objective to gradually decrease the allowed standard level of specific CO<sub>2</sub> emissions, accompanied by steep penalties for noncompliance (European Commission, 2022), have driven significant transformation. These CO<sub>2</sub> targets push EU countries to reduce emissions and car manufacturers to invest more in improving EV technology. Although not currently used on a large scale, other policy measures, such as circulation restrictions, scrappage schemes, or substantial levies on the purchase of used vehicles, have the potential to significantly reduce emission levels. Some policy-driven measures and regional variations in the EU are analysed qualitatively in Sections 4.4 and 4.5.

#### 4.3.1 Consumer-driven opportunities and constraints

Different factors affect customers' purchase decisions, which may differ across world regions. BEV intake presents significant differences across global regions, and customer preferences are good indicators of the country environment (taxation, infrastructure, model availability and vehicle price) to understand the share of customers who feel ready to buy EV vehicles.

A customer survey that includes all TIER 1 countries<sup>3</sup> and two TIER 2 countries, Türkiye and Japan, is conducted by (Deloitte), and it is a good starting point for analysing the motivations and constraints customers have when purchasing an EV.

##### 4.3.1.1 Motivations for choosing an EV

BEV uptake has increased significantly in recent years globally but at very different levels across countries. In all global regions surveyed by (Deloitte), there has been an increase in BEV vehicles as customer preferred options since 2019. In 2023, it remains under 10% in large economies such as India, the USA and some EU countries such as Poland. In 2023, China experienced a significant increase with

---

<sup>3</sup> TIER 1 countries are composed by China, European Union, India, Indonesia, South Africa and United States. Southeast Asia includes Indonesia among other countries

respect to 2022, going above 25%, followed by Germany, a western country that is slightly above 15%. It can be observed that the willingness to buy a BEV differs significantly across world regions. At this point, it is important to know which are the main reasons because customers decide to buy BEV vehicles. In Table 7, we can see the top reasons globally and in the EU for buying a BEV.

**Table 7 Top reasons for choosing an EV as the next vehicle at a global level (left) and in the EU (right)**

| Top reasons for customers to choose an EV in TIER 1 countries and 2 TIER 2 countries (Türkiye and Japan) | Score | Top reasons for customers to choose an EV in the EU      | Score |
|----------------------------------------------------------------------------------------------------------|-------|----------------------------------------------------------|-------|
| <b>Lower fuel costs</b>                                                                                  | 0.99  | <b>Lower fuel costs</b>                                  | 1.00  |
| <b>Better driving experience</b>                                                                         | 0.83  | <b>Government incentives/subsidies</b>                   | 0,73  |
| <b>Concern about climate change</b>                                                                      | 0.53  | <b>Concern about climate change</b>                      | 0,71  |
| <b>Less maintenance</b>                                                                                  | 0.56  | <b>Less maintenance</b>                                  | 0,61  |
| <b>Government incentives/subsidies</b>                                                                   | 0.50  | <b>Better driving experience</b>                         | 0,54  |
| Potential for extra taxes/levies applied to ICE vehicles                                                 | 0.33  | Potential for extra taxes/levies applied to ICE vehicles | 0,45  |
| Concern about personal health                                                                            | 0.38  | Concern about personal health                            | 0,34  |
| Ability to use the vehicles as a battery/power source                                                    | 0.39  | Ability to use the vehicles as a battery/power source    | 0,14  |
| Peer pressure                                                                                            | -     | Peer pressure                                            | -     |

*Source: Data extracted from (Deloitte)*

Lower fuel costs are the 1<sup>st</sup> reason to buy an EV globally and in the EU. This was already the main reason in 2022 (Deloitte). However, this has increased in 2023, when customers are pressured by hyper-inflationary conditions and look to lower their operating costs. Then, government subsidies play an enormous role in EV customers in the EU as the 2<sup>nd</sup> reason for considering purchasing a BEV. Conversely, globally, subsidies are relegated to the 5<sup>th</sup> position. A better driving experience is the 2<sup>nd</sup> reason globally. In China, India, the USA and Southeast Asia are the 2<sup>nd</sup> most important reasons. The 3<sup>rd</sup> reason is climate change both globally and in the EU. Environmental awareness plays an important role in customers choosing an EV. In the 4<sup>th</sup> position, less maintenance is the reason for selecting an EV globally and in the EU. Then, other reasons are less important for EV customers in selecting a BEV. It is important to highlight concern about personal health. In Poland and China, this is the 3<sup>rd</sup> and 4<sup>th</sup> reason, respectively.

### Operating costs

The primary benefit of an EV for customers is the reduced operating costs (cf. Table 7). In the US, a customer can save \$500 to \$1000 a year (Graham & Brungard, 2021). Enhancing operating cost savings and mitigating price uncertainty can be achieved through the implementation of a suitable domestic energy generation system that minimizes reliance on fossil fuels.

### Maintenance

The lower maintenance of EVs is the 3<sup>rd</sup> reason globally and the 4<sup>th</sup> in the EU for selecting an EV vehicle (cf. Table 7). Electric drivetrains have fewer moving parts, which translates to easier maintenance, in addition to avoiding the replacement of parts. According to Arval, which has a dataset of more than

200,000 vehicles on behalf of customers around the world, the service, maintenance and repair costs of battery EVs are approximately 50% lower than those of equivalent ICE vehicles (Fleet logistics, 2022).

However, it is still uncertain for customers the lifetime of batteries, and the consequence of a failure could cost more than 10.000€ (Graham & Brungard, 2021). As a result, the cost savings in maintenance become less significant, and customers become more concerned about the probability of battery failure. It is important to mention that a recent study (Wassiliadis et al., 2022) shows that aging tests demonstrated a reduced rate of aging compared to the figures reported in the literature. Overall, the real-world cycles significantly exceed both the manufacturer's mileage and operating time warranty, as well as the assumptions typically found in the literature. The analysis was conducted for VW ID3 under different driving conditions. It has only a capacity loss of 8% after 8 years and 160.000 km. The same methodology can be used for analysing different models and reduce concerns about the battery lifetime. Other options to remove battery failure uncertainty are battery as a service (Baas) models, where customers have a battery subscription instead of battery ownership. This has been successfully rolled out in China (Graham & Brungard, 2021).

### Climate change

The concern about climate change is the 3<sup>rd</sup> reason in the EU and the 4<sup>th</sup> globally for selecting an EV (cf. Table 7). Reducing anthropogenic GHG emissions is crucial to addressing climate change. Transportation, a major contributor, particularly stands out. It is responsible for roughly a quarter of energy-related GHG emissions, with road transport alone accounting for a substantial 72% (Feinauer et al., 2023). Passenger cars play a pivotal role here. The Paris Agreement outlines that transport should be climate-neutral, aiming for net zero GHG emissions within just a few decades (Patrick Plötz, 2022).

The achievement of this objective has a twofold approach, as already described in Section 4.1. On the one hand, technological changes and demand-side changes that stimulate the uptake of passenger cars with alternative powertrains contribute to GHG emissions reduction. On the other hand, nontechnological changes, including a reduction in travel (due to, for example, remote work), a shift to more sustainable modes of transport (such as rail and bikes), and a faster fleet stock turnover, can and should also contribute to GHG emissions reductions in road transport.

### Local pollution

While customers may place less emphasis on personal health and local pollution concerns (cf. Table 7), it is nevertheless crucial for governments to acknowledge the importance of clean air for people's health. Various pollutants, such as NO<sub>x</sub>, VOC, NH<sub>3</sub>, primary PM<sub>2.5</sub>, and SO<sub>2</sub>, contribute to health issues linked to vehicle emissions. Despite extensive environmental research, (Choma et al., 2020) emphasizes the insufficient focus in the literature on the health benefits of EVs.

In (Wassiliadis et al., 2022), the study assesses health benefits from adopting EVs in a large U.S. cities. Electrification leads to large benefits, even if powered exclusively by fossil fuel plants. While the extent of benefits varies across cities, they are consistently present in all cases. This suggests varying incentives per city, targeting EV deployment towards maximum health advantages. The negative health effects of ICEV tailpipe emissions in densely populated areas justify an accelerated fleet turnover. To conclude, electrification and fast fleet turnover offer significant health advantages for densely populated areas.

In (Wassiliadis et al., 2022), health benefits are quantified. The health benefits in the USA associated with driving a BEV instead of an ICE 150,000 miles over a 15-year period amount to an average of \$8,600, with variations ranging from \$5,100 in Rochester to \$17,200 in New York. These results underline the substantial differences among cities and the substantial potential for justifying notable subsidies for BEV registrations in urban areas by focusing on air pollution reduction and health improvement. By adopting this approach, subsidies for densely populated cities worldwide could be directly justified. In some cases, these subsidies could exceed €10,000, primarily based on the adverse health effects of air pollution. It is worth noting that this calculation does not include other factors, such as noise and additional environmental effects. In addition to urban EV subsidies, other measures, such as

implementing bans on older vehicles or establishing low emission zones (Bigazzi & Rouleau, 2017) in densely populated areas, are used in different cities and contribute to enhancing both public health and air quality.

### Noise

EVs bring about a notable improvement in noise and vibration levels experienced by vehicle users. The enhanced comfort resulting from reduced vibration and noise enhances the driving experience and contributes to driver well-being (Demeulenaere, 2019). Furthermore, taxi driver studies reveal that the quieter driving experience of EVs promotes improved mental health, reducing stress and increasing happiness (Graham & Brungard, 2021).

Beyond the advantages for vehicle users, the electrification of transportation holds significant benefits for urban populations by mitigating traffic-related noise. The escalating threat of traffic noise to urban dwellers arises due to close proximity to roads, high traffic volume, and congestion during peak hours (Tsoi et al., 2023). Prolonged exposure to such noise has been linked to adverse health effects, including sleep disturbances, cardiovascular diseases, and general annoyance (Fyhri & Aasvang, 2010; Münzel et al., 2019; Ndrepepa & Twardella, 2011). In fact, recent research spanning 31 European countries underscores that millions of adults endure annoyance from road traffic noise, while nearly 60 million are subjected to noise levels that detrimentally affect health (Khomenko et al., 2022).

To alleviate this problem, traffic noise regulations and abatement measures are needed. Electric mobility has emerged as a clear solution capable of directly addressing traffic noise at its source, the vehicles (Milford et al., 2012). With the growing adoption of EVs in private cars and public transport fleets, substantial potential exists for noise reduction in urban environments. Studies demonstrate varying degrees of noise reduction: replacing conventional car fleets with hybrids or fully electric vehicles can lead to reductions of approximately 2 to 4 dB (Campello-Vicente et al., 2017; Jabben et al., 2012). Moreover, the implementation of EVs in passenger cars and buses has been projected to potentially reduce preventable deaths and diseases by notable margins through reduced air and noise pollution, underscoring the far-reaching positive impact of electrification on noise and public health (Tsoi et al., 2023).

#### 4.3.1.2 Concerns regarding BEV

Once the main incentives for buying EV vehicles have been described, it is also important to know which are currently the biggest concerns hindering EV adoption globally and in the EU (cf. Table 8). The 5<sup>th</sup> largest concerns are the same globally as in the EU. More than one-third of all the surveyed people globally and in the EU are concerned about these 5 topics: public electric vehicle charging infrastructure, charging time, driving range, cost of the vehicle (and subsidies) and a lack of a charger at home.

In the EU and in other world regions, the main concerns are related to infrastructure, range of vehicles and price. A more detailed analysis is performed on these topics.

### Infrastructure

EV intake is slow not only because of the high vehicle purchase cost but also due to the scarcity of adequate charging infrastructure (Szumska, 2023). Public and private investments are needed for generating the maximum EV demand and market share in future years (Kumar et al., 2021). For example, in the EU, to reach the 2030 target, a very fast EV charging infrastructure rollout (a 9-fold acceleration versus 2021 levels) is needed for smooth customer adoption (ACEA, 2022b).

Both public and private electric charging infrastructure deployment is necessary. Charging point needs will vary from country to country. Additionally, it will depend on the geographical territories inside countries: cities, towns and rural areas. In the EU, cities are expected to need a higher rate of charger

points per vehicle. This is because there are lower opportunities in cities to install private charging points, thus obliging EV owners to rely more on public-charging infrastructure.

According to (ACEA, 2022b), for a quick and smooth transition to electric vehicles, it is crucial to deploy the necessary public charging infrastructure at both the national and local levels. Timely deployment is also crucial to avoid slowing down the adoption of electric vehicles. Additionally, it is important to consider long-distance travel and address concerns regarding charging times. For private infrastructure, facilitating and accelerating the installation processes is important. Below is a list of the main current infrastructure and charging time issues and concerns along with possible solutions:

**Table 8** The 10 greatest concerns regarding BEV at a global level (left) and in the EU (right)

| Greatest concerns regarding BEV for customers to choose an EV in TIER 1 countries and 2 TIER 2 countries (Türkiye and Japan) | Score | Greatest concerns regarding BEV for customers to choose an EV in EU countries | Score |
|------------------------------------------------------------------------------------------------------------------------------|-------|-------------------------------------------------------------------------------|-------|
| Lack of public electric vehicle charging infrastructure                                                                      | 45%   | Driving range                                                                 | 52%   |
| Time required to charge                                                                                                      | 44%   | Cost/price premium                                                            | 48%   |
| Driving range                                                                                                                | 43%   | Time required to charge                                                       | 47%   |
| Cost/price premium                                                                                                           | 40%   | Lack of public electric vehicle charging infrastructure                       | 44%   |
| Lack of a charger at home                                                                                                    | 37%   | Lack of a charger at home                                                     | 38%   |
| Ongoing charging and running costs                                                                                           | 33%   | Ongoing charging and running costs                                            | 32%   |
| Safety concerns with battery technology                                                                                      | 32%   | Cold weather performance                                                      | 29%   |
| Cold weather performance                                                                                                     | 31%   | Lack of sustainability (i.e., battery manufacturing/recycling)                | 28%   |
| Lack of sustainability (i.e., battery manufacturing/recycling)                                                               | 29%   | Lack of alternate power source (e.g. solar) at home                           | 26%   |
| Lack of alternate power source (e.g. solar) at home                                                                          | 28%   | Safety concerns with battery technology                                       | 25%   |

Source: Data extracted from (Deloitte)

- Public charging

- Charger amount and infrastructure deployment: Lack of public electric vehicle charging
  - **Solution:** Deploy the necessary infrastructure needed. Different steps are needed:
    - Define a CO<sub>2</sub> target reduction or number of EV vehicles in a certain year (Möring Martínez et al., 2023).
    - Forecast the expected number of EV vehicles in the future (Feinauer et al., 2023; Rietmann et al., 2020).
    - Define the number of chargers needed based, for example, on a criterion for the number of vehicles per public charger point (Directive 2014/94/EU of the European Parliament and of the Council of 22 October 2014 on the deployment of alternative fuels infrastructure Text with EEA relevance, 2014/12/11/2021).

- Define and invest the necessary amount in public chargers to reach the targets.
- **Charger location:** Lack of real-time information on charger location and availability
  - **Solution:** Implement real-time maps that centralize information from multiple operators onto one single platform for easy access.
- **Charger access:** fully charged EVs occupying charging points or plug incompatibility.
  - **Solution:** Enforce adequate restrictions to avoid charger blockage and use time-based tariffs.
- **Charging experience:** Incompatible payment methods, accounts, and location safety and comfort.
  - **Solution:** Standardize payment systems and enhance the transparency regarding charging point locations and comfort.
- **Infrastructure deployment on time:** Extended waiting periods for permit approvals, grid connections, and hardware delivery impede progress (Kumar et al., 2021).
  - **Solution:** Streamline infrastructure planning by creating standardized approval procedures, minimizing stakeholder interactions, and providing clear guidelines.
- **Central coordination:** Central coordination bodies inside a country and across countries are vital to efficient rollout.
  - **Solution:** Monitor the progress of deployment, manage the allocation of funds and ensure resource efficiency through coordinated efforts.
- **Smart charging:** Current charging methods lack flexibility in managing peak demand and incorporating renewable energy.
  - **Solution:** Implement smart charging for optimized vehicle charging, reducing peak grid load, prioritizing renewable sources, and enabling cost savings through time-of-use tariffs and vehicle-to-grid capabilities.
- Charging at home (ACEA, 2022b)
  - No charger at home because it is not feasible or because the price is prohibitive (Deloitte).
    - **Solution:** Deployment of an efficient and widespread public charging infrastructure.
  - Charger installation feasibility in single and multifamily homes.
    - **Solution:** Strengthen EV-ready building codes and establish a "right to socket" policy.
  - Charger installation: Difficult to find a certified installer and to understand the installation process.
    - **Solution:** Ensure clear guidelines about installation.
  - Home charging experience and transparency about the charging cost need to be improved.
    - **Solution:** Enhance cost transparency for installation and charging. Additionally, this can raise consumer awareness of off-peak benefits and lessen grid impact.
- Long-distance travel and legal framework
  - Lack of charging point standardization.

- **Solution:** Ensure a legal framework across neighboring countries. AFID (Directive 2014/94/EU of the European Parliament and of the Council of 22 October 2014 on the deployment of alternative fuels infrastructure Text with EEA relevance, 2014/12/11/2021) and AFIR (EAFO) applied in the EU.
- The time needed for charging is too high in long-distance trips.
  - **Solution:** Deployment of fast chargers along main roads and corridors between countries
- Lack of fast chargers and very high price. They are too expensive for private investors.
  - **Solution:** Public investments in fast chargers along the main roads of a country and for connecting different countries. The EU set targets for the deployment of fast chargers in TEN-T corridors in the whole EU.
- Charging time
  - Time charging expectations are not met.
    - **Solution 1:** Level 3 and level 4 batteries can charge with fast chargers from 0 to 80% in less than 30 minutes. However, fast and ultrafast chargers are expensive, reduce battery life and can overload the grid (Khalid et al., 2022; Neaimeh et al., 2017).
    - **Solution 2:** Battery swapping. It allows the battery to be changed in less than 5 minutes. However, there is no standardization in the design and location of battery packs in vehicles.
    - **Solution 3:** An increased battery range reduces the time charging requirements (Aljazeera, 2023; Graham & Brungard, 2021; Yang et al., 2021).

### Range

Driving range is the biggest concern in the EU for the survey respondents and the third globally. Consumer expectations regarding range remain above vehicles that are technically and economically feasible. Thirty-nine percent of consumers globally and 47% of consumers in the EU expect vehicles with a range higher than 500 km globally (Deloitte). Current EVs of the medium segment in the EU market typically have a range between 300 and 450 km (Hecht et al., 2021). Passenger cars with a range above 500 km exist, but they have a prohibitive purchase price for most consumers.

The range anxiety problem can be solved in two different ways. On the one hand, is the option of battery technology improvements. The largest single contributor to the cost of a PEV is the lithium-ion battery pack. If battery prices continue to decrease, it will be economically feasible to offer vehicles with ranges higher than 500 km. According to (Bajolle et al., 2022), there are different possible battery price forecast scenarios. Two scenarios where the price stabilizes, one due to insufficient raw material supply and the other because of a more disintegrated form of supply chains. The third scenario considers the possibility of market disruption through novel technologies such as solid-state technology, which could lead to sustained price decreases in the future. If the third scenario is accomplished, then the range of vehicles could be increased in the future. On the other hand, it can reduce psychological barriers. A study from the USA (Pearre et al., 2011) with 500 drivers found that drivers surpass 100 miles (approximately 161 km) less than 18 times a year and 150 miles (approximately 240 km) less than 9 times a year. Most of the current BEV models can cover 240 km. Additionally, drivers experienced range as sufficient after 3 months of electric vehicle use (Franke & Krems, 2013). Then, there is no real need to have ranges higher than 500 km. The optimal solution from an environmental and cost perspective would be to reduce customer psychological barriers and have vehicles with ranges from 200 km to 400 km rather than keep increasing range through increasing the battery.

### Purchase price

The second biggest concern in the EU is the cost of a vehicle, and the fourth biggest concern globally. The market uptake of EVs is directly correlated with a country's GDP per capita, showing that affordability remains a major barrier to consumers (ACEA, 2021a). We can observe in Figure 10 the significant price difference between BEV vehicles and ICE options sold in Germany in 2021 before taxes and subsidies. In the small and medium segments, BEV vehicles were on average 10000€ more expensive than gasoline. Taxation schemes that favour EV vehicles against ICE vehicles have been used across Europe to increase EV new registrations (Dimanchev et al., 2023; Kumar et al., 2021). One of the main reasons that consumers choose EVs in the EU is the incentives (cf. Table 7) and taxation schemes. The taxation schemes and subsidies vary widely across the world and across the EU and have a significant impact on the final purchase price. For example, in EU-27+Norway, the taxation amount favouring purchase price of BEVs changes substantially among countries, ranging from 5,000€ in Poland to 18,500€ in Norway (Möring Martínez et al., 2023).

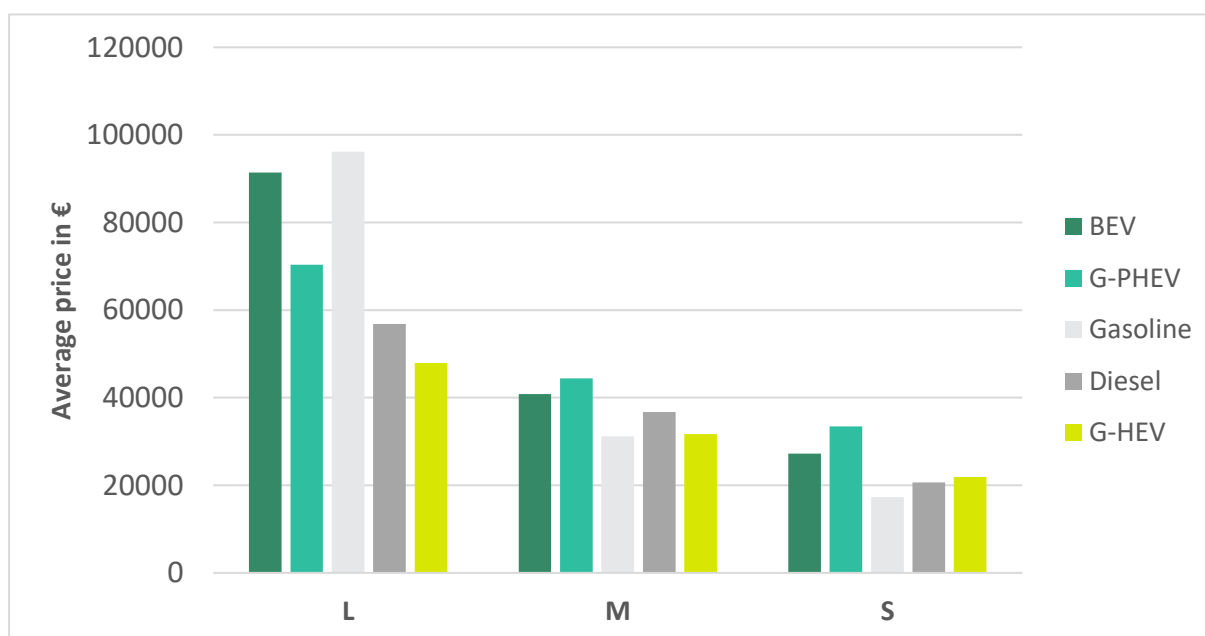


Figure 10 Average price of vehicles sold in Germany in 2021 by powertrain and segment.

Source: Data of sales and models extracted from KBA and ADAC

Apart from taxation and subsidies, a decrease in the price of a BEV vehicle can come through battery developments. As previously mentioned, the most significant cost factor for an EV is the lithium-ion battery pack. While the cost of a vehicle could decrease with lower battery prices, there is no guarantee. If consumers anticipate an improved range and increased power in EVs, the pace of price reduction might diminish because productivity gains could be redirected toward enhancing performance rather than reducing prices. Conversely, a shift towards smaller, less powerful electric vehicles would likely drive a decline in prices, and as discussed, it would be more environmentally friendly.

#### 4.3.1.3 Transport demand

All the previous factors influence the purchase of EV vehicles. However, it is important to mention transport demand because it significantly influences the reduction of GHG emissions. This importance persists despite having cleaner car fleets; a surge in transport demand has the potential to counteract emission reduction efforts (Feinauer et al., 2023). Transport emissions are strongly related to transport

demand. Currently, most of the transport demand comes from North America and Europe. However, according to (Seum & Eisenmann, 2020b), the landscape is projected to shift by 2050, with India and China expected to increase its transport demand while North America and Europe stabilize.

### 4.3.2 Policy-driven opportunities and constraints

Governments stimulate the demand side for EVs through various actions. They are responsible for the deployment of public infrastructure, the taxation of internal combustion and electric cars, car subsidies and private infrastructure subsidies. These are different demand-side oriented measures to encourage customers to choose EVs (Hardman, 2019; Hardman et al., 2018).

Additionally, there are policy-driven measures (or regulations) that can speed up the adoption of EVs and push car manufacturers to develop competitive technologies (Axsen et al., 2022). These include rules such as CO<sub>2</sub> emission targets, ZEV mandates, bans on older vehicles and scrappage schemes.

A combination of consumer-oriented measures along with policy-driven measures can effectively accelerate the transition to electric vehicle fleets. Consumer-oriented measures have already been described in Section 4.3.1. In this chapter, different policy-driven measures are described, and in Section 4.4, a quantitative analysis of selected policy-driven measures in the EU is performed.

#### 4.3.2.1 Targets and bans

Car bans have the potential to contribute to both climate change and air quality goals. Essentially, the idea of a car ban involves banning vehicles with ICE, which run on diesel or petrol (Green, 2018). Numerous regions have already legislated or declared intentions to ban ICE vehicles in 2023. The years 2022-2023 marked the introduction of significant policies in the EU and the US—the CO<sub>2</sub> standards and the Inflation Reduction Act (IRA), respectively. These policies are expected to profoundly influence the transition towards zero-emission road transport (IEA, 2023a).

For passenger cars, approximately half of annual global sales are covered by targets for 2035 or earlier, increasing only slightly to 55% by 2050 (cf. Figure 11). While the vast majority of this coverage comes from China, the EU and the USA, there are promising increases in other markets. However, most bans will not be effective for significantly reducing GHG because (Patrick Plötz, 2022):

- many would still allow the sale or use of hybrid or gasoline vehicles (100% electrified sales)
- all but a few are proposals, and not yet enacted or legislated
- most bans merely state targets, without mechanisms of enforcement or other aspects of implementation

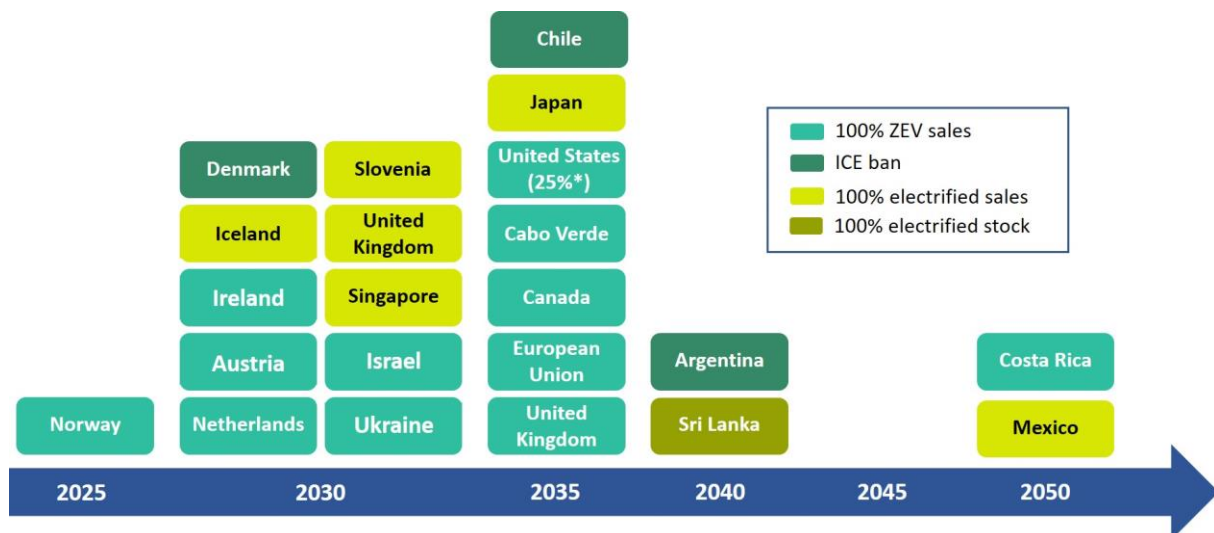


Figure 11 Zero-emission vehicle mandates and internal combustion engine bans for passenger cars across the world.

Source: Data and concept extracted from (IEA, 2023a). Only countries that have legislated or proposed an ICE ban or 100% electrification target have been included.

As observed in Figure 11, the announced car bans differ significantly in their details, including spatial coverage, technology coverage (which vehicles are banned) and year of implementation. Notably, only a few ICE bans are backed by plans for legal enforcement, and these laws have been officially passed in only a limited number of regions. The EU is the first and currently only major region where to introduce a 100% CO<sub>2</sub> emission reduction target for all cars and vans newly registered from 2035 onwards (Dornoff, 2023).

An ICE car ban is not the only possible policy to support the transition to zero-emission vehicles. The EU and other regions in the US, Canada and China rely also on ZEV mandates. Instead of banning fossil fuel vehicles, this strategy involves gradually raising the market share of ZEVs (IEA, 2023a). An interesting example is British Columbia, which announced a ZEV mandate that bans ICE vehicles by 2040 (Dornoff, 2023). ZEV mandates and CO<sub>2</sub> emissions standards help to decrease GHG and guide the path towards electrification before reaching an ICE ban.

### CO<sub>2</sub> emission standards

Binding CO<sub>2</sub> emission standards and ZEV mandates in 2025 and 2030 are set in the EU. These policies can send a strong signal for automakers to channel their efforts into ZEV innovation, bringing down costs and improving product variety, availability, and quality in the long run (Axsen et al., 2022).

The existing light-duty vehicle CO<sub>2</sub> emission performance standards, (EU) 2019/631, were revised and amended and were adopted by the Council on March 28, 2023 ((EU) 2019/631, 2021). Compared to the current regulation, the 2030 reduction target for new cars increased from -37.5% to -55% with respect to the 2021 baseline. In addition, a 100% reduction target was set for 2035, while the -15% target for 2025 remained unchanged, with no new annual or intermediate targets introduced between 2025 and 2030 (Dornoff, 2023).

The zero- and low-emission vehicle (ZLEV) threshold for 2025–2029 was raised from 15% to 25% for cars. This adjustment is a reaction to the fast-growing share of zero- and low-emission vehicles. However, the threshold adjustment is too small. In 2022, the ZLEV share in the EU was 22% (EAFO, 2022). Considering the current EV share, the ZLEV is suboptimal, and Europe will see little push to increase the supply of electric vehicles throughout the 2020s. This means that limited progress will be needed

by carmakers up to 2029 (just before the entry into force of the 2030 target), undermining efforts to ramp up e-mobility just as electric models become affordable and the transition to zero emissions mobility needs to accelerate.

Another problem of the new legislation is the ZLEV credits. Considering that EU manufacturers in future years can reach 30% ZLEV sales, CO<sub>2</sub> targets can increase from 93 g/km up to approximately 98 g/km (Dornoff, 2023). At the moment, ICE vehicles sold between 2025 and 2029 can be more CO<sub>2</sub> intensive, with an increasing share of BEV sales and ZLEV credits magnifying this effect. This is not optimal for reducing GHG, but it is optimal for manufacturers to increase their profits by increasing the sale of SUV vehicles.

### ICE phase out

EU-wide CO<sub>2</sub> standards serve as the optimal legal means to establish the trajectory toward achieving 100% zero-emission new passenger car registrations throughout the single market (Transport & Environment, 2021a). As discussed, such a trajectory would provide clear guidance to the automotive market on the investments while providing a specific timetable for industry and governments to prepare supply chains, infrastructure and workforce transition.

Another point that is relevant is that the EU is a major region with countries following very diverse decarbonization paths (Möring Martínez et al., 2023). Countries should be legally allowed to tighten their CO<sub>2</sub> standards individually given the urgency of climate action.

According to (Transport & Environment, 2021a), ICE vehicles must be phased out in 2035 to ensure that net-zero emissions stock is reached or is close to being reached in 2050. This is based on assuming that 97% of the vehicles are retired when they are 20 years or older. According to the data collected in this study, only 80% of the vehicles are retired when they are 20 years or older. Thus, additional policies are needed to achieve deep decarbonization of the passenger car sector in 2050. A deeper analysis of stock fleet turnover is carried out in Section 4.4.2.

### Regulatory improvements

#### 5-year vs annual targets

In the EU, 5-year targets are given, and this is suboptimal compared to yearly targets from a climate point of view. It is suboptimal because car manufacturers often prioritize their profit strategies, which can involve recouping investments into high-emission SUVs, rather than making prompt investments into cleaner technology. It would be more efficient to use annual CO<sub>2</sub> reduction targets, as is done by the USA and China. For the EU, if annual targets are not possible to set between 2025 and 2030, at least a binding target in 2027 or 2028 could be helpful to increase the manufacturer's efforts and investment and ensure a more progressive and gradual emissions reduction (Transport & Environment, 2021a).

#### ZLEV threshold

As mentioned before, exceeding the zero-low emission vehicle (ZLEV) benchmark threshold, achieved through increased sales of EVs, allows car manufacturers to obtain a CO<sub>2</sub> bonus (Dornoff, 2023; Patrick Plötz et al., 2022). This bonus can lead to a relaxation of their CO<sub>2</sub> reduction targets for the entire car fleet by up to 5%, adjusting them from 93 g/km to 98 g/km in 2025. This is translated into the allowance of more pollutant ICE vehicles as SUV on the road during the 2020s. ICE vehicles should be capped separately from BEVs; in other words, they should have specific CO<sub>2</sub> targets for ICE vehicles. This would ensure that not a higher number of high-polluting SUVs are sold between 2025 and 2029 to maximize OEM benefits.

### Plug-in hybrids

The real-world fuel consumption of PHEVs in Europe is on average three to five times higher than WLTP type-approval values (Patrick Plötz et al., 2022). The PHEV count was 0.7 to reach the ZLEV threshold, and the BEV count was 1. The reality indicates that PHEVs are significantly more polluting than the test results. Then, the 0.7 coefficient for reaching the ZLEV threshold and obtaining super credits should be drastically reduced or removed.

#### 4.3.2.2 Stock fleet turnover and circulation bans

Stock fleet turnover has a large effect on the decarbonization of the passenger car fleet. The presence of electric vehicles (EVs) within the passenger car stock is influenced by the turnover of vehicles, a process constrained by both the adoption rate of new vehicle technology and the timing of vehicles leaving the fleet (Alarfaj et al., 2020). Limitations in stock turnover, in conjunction with the timing of new vehicle technology deployment, have implications for overall emissions and fuel efficiency (Keith et al., 2019). Current data regarding passenger car survival curves indicate that the complete replacement of the existing EU passenger car stock typically takes approximately 30 years to remove approximately 95% of the stock. Vehicle age and survivability have increased from 2008 to 2021 (Held et al., 2021a). Additionally, technological disruptions such as BEVs can significantly impact survivability curves. Different policy measures, such as circulation bans or scrappage schemes, can be applied to affect stock turnover rates externally and thus to reduce GHG and to ensure that net-zero emissions are reached. Circulation bans are analysed at a quantitative level in Section 4.5.2.

### 4.4 Mitigation option results in the EU

As described before, there are several mitigation options to reduce GHG that can be applied in different regions globally. At a quantitative level, we focus on different policy-driven effects and the expected outcome in the EU as a whole and at a regional level up to 2060. We study the effect of different mitigation options. On the one hand, mitigation options have already been approved by the European Commission as the CO<sub>2</sub> emission standards and the ban of ICE vehicles in 2035 (European Commission, 2022). On the other hand, other mitigation options have been used on some occasions in the past but could be applied in a homogeneous way throughout the EU. For example, a ban on the circulation of vehicles based on emission standards (Holman et al., 2015), scrappage schemes (Eurostat, 2020), and taxation on registrations of used passenger cars.

#### 4.4.1 Ban on ICE vehicles in 2035 and GHG emissions reduction by 90% in 2050

The allowed standard level of CO<sub>2</sub> emissions for new passenger cars is reduced progressively in 2021, 2025 and 2030, which is already influencing and benefiting EV uptake (Dornoff, 2023). The final stage is the ban of ICE vehicles in 2035. Since then, the EC expects to be able to reduce emissions by 90% in 2050 compared to 1990 levels.

The 90% reduction of GHG in 2050 of the passenger car sector in the EU is not aligned with the Paris Agreement. The Paris Agreement searches to limit global warming to 1.5°C. GHG emission budgets for accomplishing the Paris Agreement are estimated for two different pathways (P. Plötz et al., 2021). The first pathway involves achieving the 1.5°C warming target throughout the 21st century without any overshooting. In contrast, the second pathway aims to stay within 1.5°C of global warming by 2100 but allows for a controlled amount of overshoot, ensuring that the peak temperature rise remains well below 2°C.

Table 9 EU CO<sub>2</sub> budget for the transport sector, road transport sector and passenger car sector in 2021 – 2100 consistent with long-term warming of 1.5°C.

| Pathways                         | Transport GHG budget (in GT CO <sub>2</sub> ) | Road GHG budget (in GT CO <sub>2</sub> ) | Passenger cars GHG budget (in GT CO <sub>2</sub> ) |
|----------------------------------|-----------------------------------------------|------------------------------------------|----------------------------------------------------|
| For 1.5° no overshoot            | 10.2                                          | 9.7                                      | 6.01                                               |
| For 1.5 ° with limited overshoot | 12.1                                          | 11.5                                     | 7.13                                               |

Source: Budget data extracted from (P. Plötz et al., 2021)

Based on an analysis from (P. Plötz et al., 2021), we can extract that there are 7.13 gigatons (GTs) of CO<sub>2</sub> budgets for passenger cars still available from 2021 in a 1.5° with limited overshoot scenario (cf. Table 9). Compliance with the Paris Agreement budget and the EU 90% emissions reduction target is discussed below.

We use the model described in Section 4.2.1 to forecast emissions up to 2060. The model considers the expected fleet structure development under a stated policies scenario for new registrations, constant yearly mileage<sup>4</sup> and constant cumulative survival probability curves<sup>5</sup>. Under these considerations, the forecast obtained for the EU is presented in Figure 12.

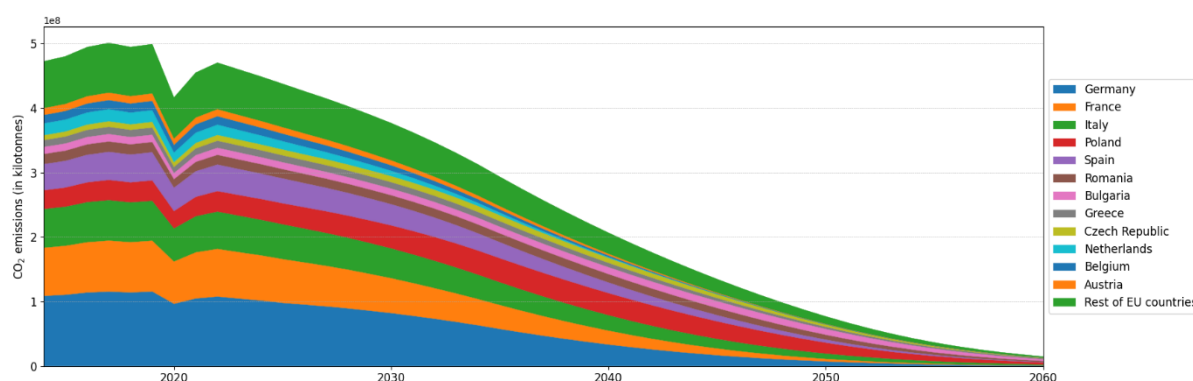


Figure 12 Forecast of CO<sub>2</sub> emissions up to 2060 for EU-27+Norway.

Note: The methodology used for the forecast is described in Section 4.2

In Figure 12, we can see the expected CO<sub>2</sub> emission reduction in the passenger car sector in future years in the EU. CO<sub>2</sub> fleet targets play an enormous role in CO<sub>2</sub> emission reduction in the EU. As discussed, manufacturers must sell more EVs to avoid paying penalties. To achieve this and be competitive in the long term, manufacturers are prone to invest in EV dedicated plants, the development of new battery cell technologies and other technology and production innovations. Then, they affect and have already affected the customer side and indirectly the demand side. All these efforts by manufacturers accelerate technology readiness and, together with adequate infrastructure deployment and a taxation model that benefits alternative powertrain vehicles over ICE, Europe is leading EV uptake with China (IEA, 2023a).

Despite the CO<sub>2</sub> emission standards (and the 2035 ICE ban), the infrastructure deployment plans, the taxation schemes in different EU countries favouring EVs, and the CO<sub>2</sub> emission reduction is falling short of the 90% reduction target set for 2050. The CO<sub>2</sub> emissions in 2050 will be 77 million tonnes of

<sup>4</sup> Different studies suggest that travel demand will stabilize in future years Seum and Eisenmann (2020a).

<sup>5</sup> CSP curves are assumed constant. However, they have been increasing since 2008 (cf. Figure 9). The effect of older survivability curves should be studied in the future.

CO<sub>2</sub>, which equals a 79.7% reduction with respect to 1990 levels<sup>6</sup>. It is also not accomplishing the Paris Agreement. The GHG budget of 1.5° with limited overshoot is surpassed, with cumulative CO<sub>2</sub> emissions of 8.80 Gt from 2021 to 2060 (it should not surpass 7.13 Gt).

The EU is currently the most ambitious region for decarbonizing the passenger car sector. Banning ICE new passenger car registrations in 2035 is key and is pushing the CO<sub>2</sub> reduction of the EU up to 2050. However, CO<sub>2</sub> emission standards should be strengthened to further accelerate EV intake, and the 2035 ban could be advanced in some years to reduce GHG and be closer to the budget of 1.5° with limited overshoot.

Additionally, the used car market must be taken into consideration. Vehicle survivability and vehicle stock turnover are also key factors for reaching net zero emission sales. Mitigation options such as circulation bans, scrappage schemes or heavy taxation in used vehicles (for example, in the Netherlands, when importing a used vehicle, you must pay the BPM tax (Netherlands Tax Administration), which is determined by the vehicle's CO<sub>2</sub> emissions and age. Additionally, there is an annual MRB tax for all vehicles (Netherlands Tax Administration), calculated based on the type of fuel the car uses. These taxes serve as examples of how countries can impose significant taxation on used and polluting vehicles) can boost the CO<sub>2</sub> emission reduction potential to reach the 90% reduction target and approach the Paris Agreement. We will focus on the effects of applying circulation bans.

Circulation bans are addressed because studies typically focus on the effects of CO<sub>2</sub> emission standards and bans to nonzero emission vehicle effects to boost the decarbonization of the passenger car sector. This has a direct effect on new vehicle registrations but not on stock fleet turnover. Conventional models often assume constant stock fleet turnover rates for future predictions, yet the actual average age of stock fleets has notably increased across EU countries with available data (cf. Section 4.2.5). Technological disruptions, such as Battery Electric Vehicles (BEVs), have the potential to alter how long a vehicle remains in service. However, it remains uncertain whether Internal Combustion Engine (ICE) vehicles will see extended usage after the 2035 ban.

The significance of this uncertainty becomes evident when considering the substantial presence of older vehicles within the EU's existing stock. There are 51 million vehicles older than 20 years, constituting 20% of the total fleet, and 21 million vehicles older than 25 years, accounting for 8% of the total fleet. Notably, Eastern European countries exhibit a significantly higher proportion of older vehicles in their stock fleet, with 34% older than 20 years (19 million vehicles) and 16% older than 25 years (9 million vehicles). With the EU currently falling short of its 2050 goal for a 90% reduction in greenhouse gas emissions (GHG) within the passenger car sector and struggling to meet commitments under the Paris Agreement, the exploration of circulation bans as a complementary measure is necessary to strengthen GHG reductions and align with established targets.

### 4.4.2 Circulation bans

We study the CO<sub>2</sub> emission reduction potential of banning the circulation of ICE vehicles of different ages and in different years<sup>7</sup> (cf. Table 10). We can observe that banning old vehicles has a significant impact on CO<sub>2</sub> emission reduction potential and could allow the EU to reach the 90% reduction target for 2050. Without banning old vehicles, the EU 2050 90% reduction target would be reached in 2055. By banning vehicles older than 25 years in 2035, the CO<sub>2</sub> target is almost achieved in 2050 (88.3% emissions reduction with respect to 1990 levels). It is achieved in 2051.

---

<sup>6</sup> CO<sub>2</sub> emission for the passenger car sector were 380 million tonnes in 1990 (Source: EEA)

<sup>7</sup> Banning the circulation of ICE vehicles means that such vehicles cannot operate within the EU territory. These vehicles may either be scrapped or exported outside of the EU. However, this decision is outside the scope of this paper.

## Transport Sectoral Modelling - 'Avoid-Shift-Improve' measures

Banning vehicles older than 25 years could be an optimal policy because it allows almost reaching the 2050 target by removing a reduced number of vehicles; 7.4% of the EU stock fleet vehicles if the ban is applied in 2035 or 6.1% of the fleet vehicles if the ban is applied in 2040. Another important point to mention is that the earlier the ban is applied, the higher the CO<sub>2</sub> emission reduction potential. For example, by banning vehicles older than 25 years in 2035, almost 900 million tonnes of CO<sub>2</sub> are reduced, which is close to the 2 years of emissions at 2019 levels. In this case, the Paris agreement of 1.5° with limited overshoot is still not reached. 7.96 GT are emitted to the air. Nevertheless, significant improvements are made, and in combination with the strengthening of CO<sub>2</sub> emission standards between 2025 and 2030, the Paris agreement could be reached.

Finally, if vehicles older than 20 years are banned, the CO<sub>2</sub> emission reduction potential increases notably, and the 2050 reduction target is achieved in 2047. The Paris Agreement with limited overshoot is achieved as well. However, the number of vehicles removed from the road in the EU would be 45 million, which is 17% of the whole EU fleet, and this can be negative from a social point of view.

**Table 10 CO<sub>2</sub> emissions and stock effects of circulation bans applied in 2035, 2040, 2045 and 2050 for ICE passenger cars older than 20, 25 or 30 years**

| Circulation ban applied                  | CO <sub>2</sub> emissions in 2050 (in million tonnes) | CO <sub>2</sub> emissions reduction in 2050 vs 1990 (in %) | Year when CO <sub>2</sub> target 2050 is met | CO <sub>2</sub> emissions reduction potential (in million tonnes) | Vehicles removed from the EU road (in millions) | % of vehicles removed from the EU road | CO <sub>2</sub> emissions reduction at the year of application (in %) |
|------------------------------------------|-------------------------------------------------------|------------------------------------------------------------|----------------------------------------------|-------------------------------------------------------------------|-------------------------------------------------|----------------------------------------|-----------------------------------------------------------------------|
| No ban                                   | 77.0                                                  | 79.7%                                                      | 2055                                         | -                                                                 | -                                               | 0.0%                                   | -                                                                     |
| 2035 ban (Vehicles > 30 years)           | 63.7                                                  | 83.2%                                                      | 2054                                         | 406.4                                                             | 5.8                                             | 2.2%                                   | 5.5%                                                                  |
| <b>2035 ban (Vehicles &gt; 25 years)</b> | <b>44.6</b>                                           | <b>88.3%</b>                                               | <b>2051</b>                                  | <b>895.2</b>                                                      | <b>19.6</b>                                     | <b>7.4%</b>                            | <b>14.0%</b>                                                          |
| 2035 ban (Vehicles > 20 years)           | 12.6                                                  | 96.7%                                                      | 2047                                         | 1.688.6                                                           | 45.0                                            | 17.0%                                  | 28.9%                                                                 |
| 2040 ban (Vehicles > 30 years)           | 63.7                                                  | 83.2%                                                      | 2054                                         | 323.3                                                             | 5.1                                             | 1.8%                                   | 7.4%                                                                  |
| <b>2040 ban (Vehicles &gt; 25 years)</b> | <b>44.6</b>                                           | <b>88.3%</b>                                               | <b>2051</b>                                  | <b>707.6</b>                                                      | <b>17.1</b>                                     | <b>6.1%</b>                            | <b>17.2%</b>                                                          |
| 2040 ban (Vehicles > 20 years)           | 12.6                                                  | 96.7%                                                      | 2047                                         | 1.248.8                                                           | 47.0                                            | 16.7%                                  | 42.0%                                                                 |
| 2045 ban (Vehicles > 30 years)           | 63.7                                                  | 83.2%                                                      | 2054                                         | 254.7                                                             | 4.2                                             | 1.4%                                   | 9.5%                                                                  |
| <b>2045 ban (Vehicles &gt; 25 years)</b> | <b>44.6</b>                                           | <b>88.3%</b>                                               | <b>2051</b>                                  | <b>520.7</b>                                                      | <b>18.4</b>                                     | <b>6.1%</b>                            | <b>27.3%</b>                                                          |
| 2045 ban (Vehicles > 20 years)           | 12.6                                                  | 96.7%                                                      | 2047                                         | 838.9                                                             | 44.1                                            | 14.7%                                  | 56.0%                                                                 |
| 2050 ban (Vehicles > 30 years)           | 63.7                                                  | 83.2%                                                      | 2054                                         | 187.1                                                             | 5.5                                             | 1.7%                                   | 17.2%                                                                 |
| <b>2050 ban (Vehicles &gt; 25 years)</b> | <b>44.6</b>                                           | <b>88.3%</b>                                               | <b>2051</b>                                  | <b>346.8</b>                                                      | <b>18.3</b>                                     | <b>5.8%</b>                            | <b>42.1%</b>                                                          |
| 2050 ban (Vehicles > 20 years)           | 12.6                                                  | 96.7%                                                      | 2050                                         | 480.2                                                             | 41.0                                            | 13.0%                                  | 83.6%                                                                 |

*Note: Specifically, CO<sub>2</sub> emissions are measured in 2050, CO<sub>2</sub> percentage of emissions reduction with respect to 1990 levels, year when the EU 2050 CO<sub>2</sub> target is achieved, CO<sub>2</sub> emissions reduction potential until net-zero emissions are reached, number of vehicles removed from the EU road by applying the circulation ban and percentage of vehicles removed from the EU road.*

### 4.5 Relevance of the regional perspective

The EU presents significant socioeconomic differences among its member states. EV new registrations and EV stocks vary significantly from country to country, and countries follow different paths (Möring Martínez et al., 2023). We group countries in Western-Eastern groups to be able to easily see these differences<sup>8</sup>.

#### 4.5.1 Ban on ICE vehicles in 2035 and GHG emissions reduction by 90% in 2050

First, we show the stock-fleet average CO<sub>2</sub> emissions at the country level in different years (cf. Figure 13). We can observe significant differences in 2025 that still exist in 2050. For example, in 2025, Bulgaria, Romania and Greece have average CO<sub>2</sub> emissions above 175 g/km, while Norway and Sweden are slightly above 100 g/km. In 2035, Bulgaria, Romania and Poland are slightly below 150 g/km, while Norway and Sweden are slightly below 50 g/km. In 2035, Germany and France are slightly below 100 g/km. In 2050, Norway, the Netherlands and Sweden have almost 0 g/km emissions, the EU-27+Norway average is close to 25 g/km, and Greece, Poland and the Czech Republic remain above 50 g/km.

There are significant regional differences in the decarbonization of the passenger car fleet across EU member states. In Figure 14, we can observe that in 2020, Eastern countries were responsible for approximately 100 million tonnes of CO<sub>2</sub> emissions, 20% of the total EU emissions, while Western countries were responsible for 400 million tonnes. In 2040, Eastern countries are responsible for 95 million tonnes, more than 40% of the total EU emissions, while Western countries are responsible for only 111 million. In Figure 15, we can observe the stock-fleet average CO<sub>2</sub> emissions for Western and Eastern countries as well as the EU-27 average. The average CO<sub>2</sub> emissions difference between Western and Eastern China is relatively small in 2020, and it reaches a maximum difference of more than 50 g/km in 2040.

Western countries are leading the CO<sub>2</sub> emissions reduction first because they have higher EV uptakes, but mainly because there are nonimporters of used vehicles. Eastern countries are high importers of used vehicles. For example, two-thirds of Poland's vehicle registrations are imported used vehicles. Poland is the world leader in imports of used vehicles, and in the last decade, the average age of imported vehicles was between 9 and 11 years. Most used cars were imported from Germany (Kolsut, 2020).

The import of used vehicles significantly reduces the benefits of the ICE ban and slows down CO<sub>2</sub> emission reduction in eastern countries. The Western-Eastern flows of used vehicles must be considered for reducing CO<sub>2</sub> emissions faster in the whole EU, and when applying different policies, the outcome and the effects in the fleets will be significantly different.

---

<sup>8</sup> Western EU countries are formed by Austria, Belgium, Germany, Denmark, Spain, Finland, France, Ireland, Italy, Luxembourg, Malta, Netherlands, Norway, Portugal and Sweden. Eastern countries are formed by Bulgaria, Cyprus, Czech Republic, Estonia, Croatia, Hungary, Lithuania, Latvia, Poland, Romania, Slovakia and Slovenia.

## Transport Sectoral Modelling - 'Avoid-Shift-Improve' measures

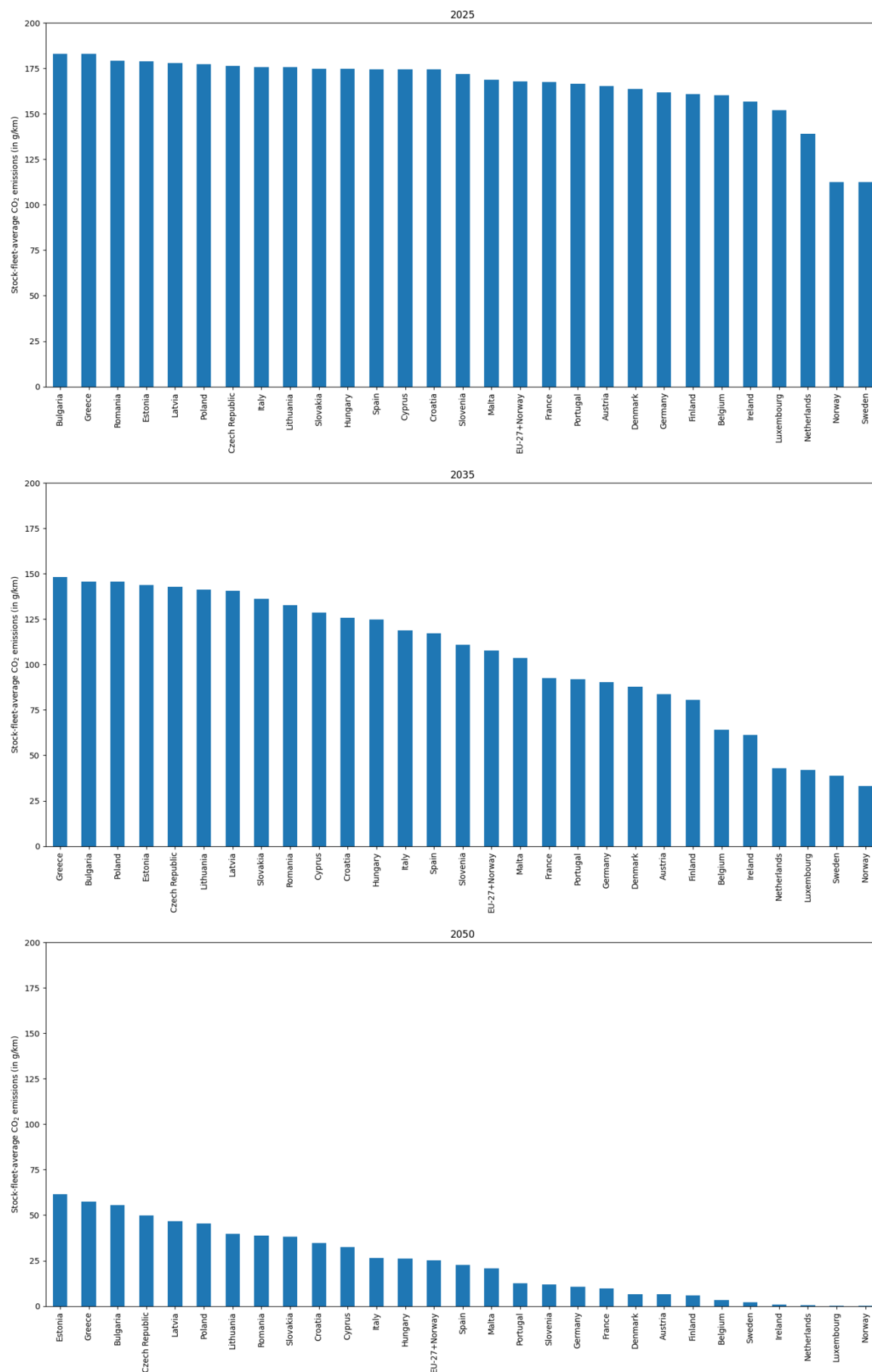


Figure 13 Forecast of the stock-fleet average CO<sub>2</sub> emissions (in g/km) for EU-27 countries and Norway.

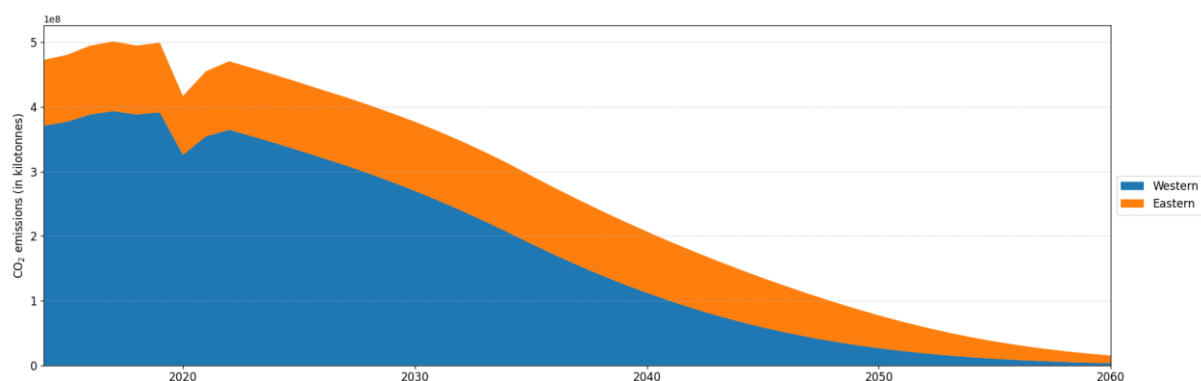


Figure 14 Forecast of CO<sub>2</sub> emissions up to 2060 for EU-27+Norway. Countries are grouped as Western and Eastern.

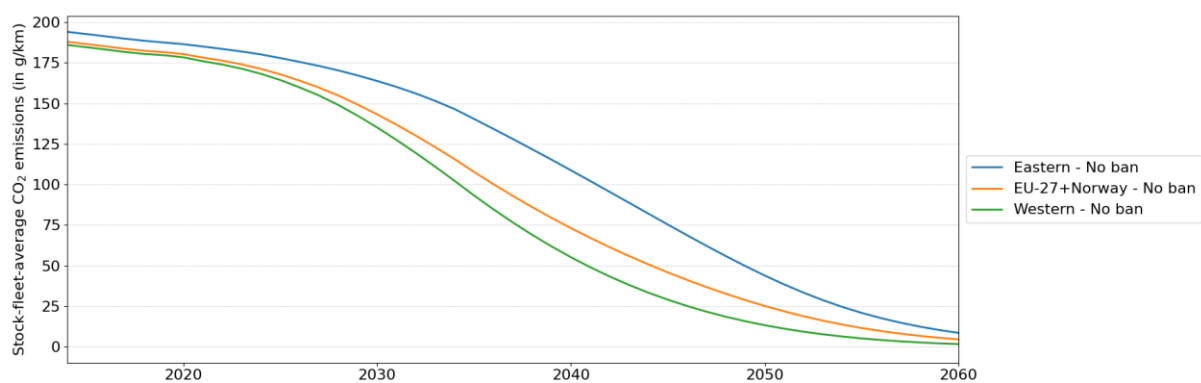


Figure 15 Forecast of the stock-fleet average CO<sub>2</sub> emissions (in g/km) for EU-27 countries and Norway. Countries are grouped as Western and Eastern.

### 4.5.2 Circulation bans

Banning ICE vehicles in 2035 older than a certain age has more CO<sub>2</sub> emission reduction potential than doing so later<sup>9</sup>. Considering that 2035 could be an optimal year for reducing CO<sub>2</sub> emissions, we analyse the regional differences in applying circulation bans in 2035 (cf. Figure 16).

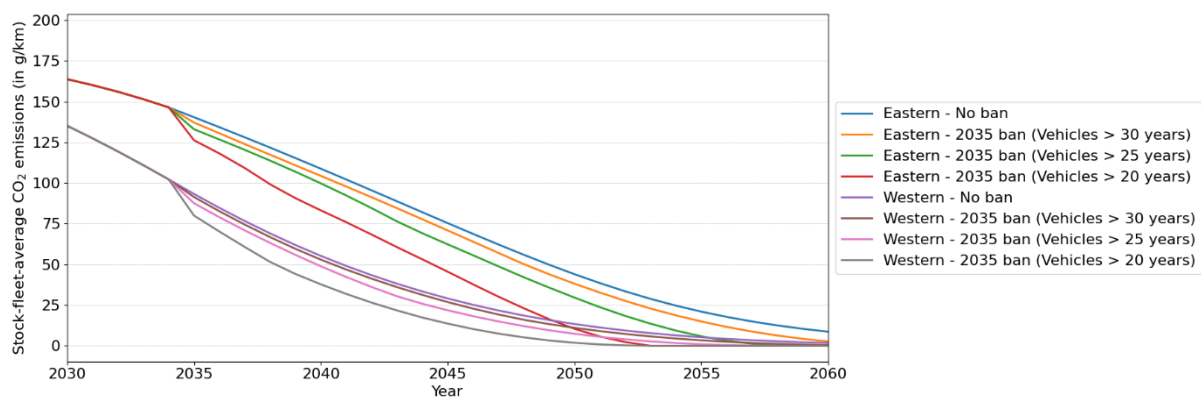


Figure 16 Effect on the stock-fleet average CO<sub>2</sub> emissions of circulation bans applied in 2035 for vehicles older than 20, 25 or 30 years. Countries are grouped as Western and Eastern.

<sup>9</sup> Year 2035 is considered the first year of implementation of the ban because, before 2035, ICE vehicles could still be replaced by new ICE vehicles.

We can see that the stock-fleet average CO<sub>2</sub> emission reduction is higher in Eastern countries than in Western countries. For example, if vehicles older than 25 years are banned, Eastern countries present a reduction of 7 g/km, while Western countries a reduction of 6 g/km in 2035. This reduction is almost the same for both groups. However, in 2045, this ban reduction reduces the Eastern stock-fleet average CO<sub>2</sub> emissions by 13 g/km and only by 7 g/km for the Western CO<sub>2</sub> emissions fleet average. Once the stronger effect in Eastern countries with respect to Western countries is clearly seen, it is important to analyse how many vehicles will be removed in each region (cf. Table 11).

**Table 11** Regional differences in circulation bans applied in 2035 for ICE passenger cars older than 20, 25 or 30 years. Specifically, the CO<sub>2</sub> emissions in 2050, CO<sub>2</sub> emissions reduction potential until net-zero emissions are reached, number of vehicles removed from the EU road by applying the circulation ban and percentage of vehicles removed from the EU road are measured.

| Region  | Circulation ban applied        | CO <sub>2</sub> emissions in 2050 (in million tonnes) | CO <sub>2</sub> emissions reduction potential (in million tonnes) | Vehicles removed from the EU road (in millions) | % of vehicles removed from the EU road |
|---------|--------------------------------|-------------------------------------------------------|-------------------------------------------------------------------|-------------------------------------------------|----------------------------------------|
| Eastern | No ban                         | 50,7                                                  | -                                                                 | -                                               | -                                      |
| Western | No ban                         | 26,3                                                  | -                                                                 | -                                               | -                                      |
| Eastern | 2035 ban (Vehicles > 30 years) | 42,0                                                  | 275,7                                                             | 2,9                                             | 4%                                     |
| Western | 2035 ban (Vehicles > 30 years) | 21,7                                                  | 130,6                                                             | 2,9                                             | 2%                                     |
| Eastern | 2035 ban (Vehicles > 25 years) | 30,2                                                  | 550,8                                                             | 9,5                                             | 12%                                    |
| Western | 2035 ban (Vehicles > 25 years) | 14,3                                                  | 344,4                                                             | 10,2                                            | 6%                                     |
| Eastern | 2035 ban (Vehicles > 20 years) | 9,1                                                   | 973,9                                                             | 20,3                                            | 25%                                    |
| Western | 2035 ban (Vehicles > 20 years) | 3,5                                                   | 714,6                                                             | 24,7                                            | 13%                                    |

The number of vehicles removed from the road that are not to circulate after 2035 if a ban for ICE vehicles older than 25 years represents 12% of the share in Eastern countries and 6% of the share in Western countries. This type of policy has a significant impact in Eastern countries because the average age of the fleet is higher and the countries are high importers of used vehicles. Banning ICE vehicles of a certain age can be applied, but regional effects, including measures to mitigate costs for lower income groups, must be considered.

## 4.6 Conclusion

Electrification is often considered a significant step towards reaching net-zero emissions. In 2022 and 2023, a significant number of policies were applied in China, the EU and the USA. More than 55% of sales are in countries with electrification targets from 2035 or earlier until 2050. Most of the targets, however, are not binding. The EU is leading EV uptake with China. However, the EU is falling behind the 90% reduction target set for 2050 and the Paris Agreement of 1.5° with limited overshoot. This indicates that there is still significant room for improvement, and additional mitigation options are needed.

We study the constraints that different customers have in different world regions. Globally and in the EU, the major constraints are infrastructure (public and private), charging time, range and purchase price.

Regarding public infrastructure, it is important to set enough public charger infrastructure, reduce lead times for deploying infrastructure on time, define a central coordination body, consider the customer charger experience (charging location safety and comfort, and correct charging access), and deploy fast chargers across main roads for long distance travel. Regarding private infrastructure, establish "right to socket" policies and develop smart charging solutions. Regarding charging time, fast chargers and future vehicle models with increased range can solve the problem for a specific group of customers. Another solution can be battery swapping. Regarding price, taxation schemes and subsidies as well as further battery price reductions can boost EV intake.

From the policy perspective, CO<sub>2</sub> emission standards, ZEV mandates, and, ultimately, ICE bans send a strong signal for automakers to channel their efforts into ZEV innovation, bringing down costs and improving product variety, availability, and quality in the long run. The EU is the first major region across the globe to set a 100% reduction binding target for all cars newly registered from 2035 onwards. In the EU, current CO<sub>2</sub> emission standards are not enough to reach the 2050 target and the Paris Agreement. To get closer to the Paris Agreement targets, different measures the EU can take are annual CO<sub>2</sub> emission standard targets, increasing the CO<sub>2</sub> emission standards, removing the ZLEV supercredits and shifting the 100% reduction binding target before 2035.

Other measures to reduce GHG consist of focusing on vehicle stock turnover policies. Different measures, such as banning ICE vehicles older than a certain age and scrappage schemes, can have a significant impact on CO<sub>2</sub> emission reduction. Using our emissions model, we find that banning vehicles older than 25 years in the EU can help save almost 0.9 GT and almost reach the EU 2050 90% GHG reduction target, with no other policies needed. A combination of stock turnover policies with a strengthening of CO<sub>2</sub> emissions standards should be carried out in the future to see which policy mixes allow the Paris Agreement to be reached.

Finally, apart from GHG mitigation, we conclude that demand-side policies such as BEV incentives are justified in densely populated areas because of the significant improvements in noise reduction and health.

# 5 Road freight to rail freight as a mitigation option

## 5.1 Introduction

Freight transport accounted for 41% of total transport emissions in 2015, which was 2.5 Gt of CO<sub>2eq</sub> annually, with a projected increase of 100-230% in the BAU scenarios in 2050. This was primarily arising from emerging economies. (ETC, 2018; WRI, 2019) As hinted earlier, the freight sector is underrepresented in first-generation NDCs, with only 30% mentioning the subsector, mostly with an intention to shift to rail and shipping (IEA, 2017). This shows the enormous gap that remains in the level of commitment to quantify targets for such an important and slow to decarbonize sector.

Today, alternative technologies based on hydrogen and battery electric drivetrains are being rapidly tested and pushed for in national policies with increasing conduciveness. Along with this, digital-based logistic and supply chain solutions are being planned for existing truck freight, which would improve efficiency and thus decrease emissions. This includes optimized routing, loading, vehicle utilization, decentralized delivery systems, etc.

Given that most future freight growth would be concentrated in economies such as India, Brazil, ASEAN and African countries with rail conducive scales and distances (ETC, 2018) along with high fragmentation of truck ownership, railways offer an enormous potential for freight decarbonization in these countries. (ETC, 2018) estimates a global contribution of 0.5 Gt CO<sub>2</sub> evasion through a modal shift of 35% freight demand with rail in 2050. In this work, we try to find hurdles to achieving (and increasing) such a modal shift from road-based to rail-based freight transport by reviewing the current country status and constraints and its plans to achieve the potential benefits and opportunities that rail freight offers. As a consequence of the long-term investments and implications of rail, it is important to first assess existing environments.

In the following section, we explain the general characteristics of rail-based freight, which shows the high benefit of shifting to rail in terms of emissions and energy consumption, available technological improvements in rail and the inherent large time and resource requirements for any rail-related transformation.

- Energy efficiency of rail freight against other freight modes

Rail is the most energy-efficient land-based freight transport mode. It is on average approximately four to six times more efficient on a per ton-km basis than heavy truck transport (IEA, 2019b). The IEA reports a range of ca. 2 toe/million ton-km (0.0837 MJ/ton-km) to 11.5 toe/million ton-km (0.481 MJ/ton-km) at an average of 3.75 toe/million ton-km (0.157 MJ/ton-km) in comparison to an average of 30 toe/million ton-km (1.25 MJ/ton-km) for medium trucks (IEA, 2019a).

Electric traction enables high-capacity heavy freight trains to also operate on steep slopes and is very energy efficient. Because of high costs, only high-capacity lines justify full-track electrification. For the rest of the lines, cost-efficient decarbonized powertrain and fuel alternatives should be considered.

Rail can make use of its technological advantages, especially for bulky and containerized freight, while small-scale and low-density-high-value goods are usually less suitable for rail freight and qualify more for road and air freight transport.

- Increasing energy efficiency in rail freight:

The quantity of rail-prone bulk goods has declined in several high-income countries over the past years, and containerized transport has gained importance, as shown in (ECM Ventures, 2022) for the EU 27.

Thus, measures to increase the energy efficiency of such intermodal trains have gained relevance.

Generally, higher capacity utilization through increased load factors will reduce specific energy consumption and thus downstream emissions (in the case of diesel traction) and upstream emissions (electric traction).

Additionally, enabling smoother train runs will reduce energy consumption stopping and consecutive acceleration of heavy trains. This can be achieved through improvement of traffic management, e.g., through ERTMS implementation, and track upgrades such as the installation of passing/overtaking tracks. Intelligent traffic and logistics management avoids detours and increases the load factor.

Furthermore, friction reduction of running gears and aerodynamic drag of wagons reduces energy demand.

The use of electric locomotives with high-efficiency (low-loss) electric drivetrains uses regenerative braking, which can retain some energy otherwise transferred in heat while mechanically braking.

Lifting up energy efficiency measures requires large funds in both rolling stock renewal and infrastructure upgrades. Realization periods can take a decade or considerably longer in the railway sector, especially when new signalling, train management and electrification upgrades are to be realized.

- Decarbonization using electricity and alternative fuels

The rail energy demand is approximately 2% of the final energy use in transport but is 8% of the total passenger-km and 7% of the total tonne-km. (IEA, 2019a)

In 2017, diesel use on rail worldwide was 29 MToe (1214 PJ), and electricity use was 290 TWh (1044 PJ). On a global level, freight rail accounts for 45% of total rail diesel consumption and 85% of total rail electricity consumption. Most diesel in rail vehicles is used in North America and in China (at a decreasing rate), whereas most electricity is consumed in China, Europe and Russia.

The share of electric traction in freight rail is highest in Japan, Russia and Europe (all above 80%) and increasingly in China (nearly 70%), all figures from 2016.

The electrification of routes and terminal tracks enables the substitution of diesel locomotives by electric locomotives (mainline locomotives and shunting locomotives). Electric trains produce no GHG emissions at the point of use; if the electricity generation is fully based on nonfossil fuels, the well-to-wheel emissions are also zero. Electrification pays off economically for high-capacity routes and for important transport detour corridors. As a downside of full track electrification, the realization duration of track electrification can take 10 years or longer and requires considerable funds.

In track sections or regions that do not justify full-line electrification from an economic point of view (e.g., marshalling yards), independently powered freight locomotives based on batteries, hydrogen or other carbon-neutral fuels will likely play a role in the future.

Locomotives equipped with batteries can bridge nonelectrified track sections or operate only battery-electric in marshalling yards being recharged only at night. There are battery locomotives in development, especially for use in North America and South America, particularly in mining environments. (BNSF, 2021), (Rollingstockworld.com, 2023)

Hydrogen and ammonia can be used as substitutes for diesel and NG locomotives on nonelectrified routes. A couple of demonstration and large-scale implementation initiatives have emerged over the past years.

Hydrogen has the advantage of producing no GHG emissions at the point of use while not being dependent on cost-intensive wayside electrification. For deep decarbonization, green hydrogen is needed. Hydrogen can be applied in fuel cells and in internal combustion engines. There are a couple of development and demonstration projects underway worldwide. For shunting locomotives used in marshaling yards, these are mainly retrofit projects that focus on the conversion of existing diesel to hydrogen locomotives, for example, in Poland (PESA, 2022), Germany (Railvolution, 2022) and France (Railpage.com.au, 2022a).

Hydrogen powertrain systems have also been developed and tested in mainline freight locomotives worldwide, such as in Canada (Canadian Pacific, 2020), South Korea (Chang-won, 2021), Spain (Railway Gazette International, 2022), Bolivia (Bnamerica, 2022) and Namibia (Railpage.com.au, 2022b). However, it is still a long way to go before these test and demonstration projects will be transferred to widespread commercial operation.

Ammonia and methanol are further decarbonization options for freight trains, provided that the hydrogen for NH<sub>3</sub> is produced using renewable power plants. Ammonia as fuel has the advantage that it surpasses the energy density of hydrogen and thus enables higher ranges of locomotives. (Zhang et al., 2023)

Hydrogen and ammonia require the construction of dedicated refueling stations and transport infrastructure.

Biobased fuels such as hydrogenated vegetable oils (HVO) and renewable natural gas (RNG) are short-term options to reduce CO<sub>2</sub> emissions. First generation bio fuels made from food crops result in 'food vs fuel dilemma'. The second generation largely avoids this problem. One fuel that has recently entered commercial application is HVO. With it, 90% CO<sub>2</sub> reduction is reported to be possible. (RailTech.com, 2022), (Cohen et al., 2022)

## 5.2 Methodology

Transport of freight by railways instead of roads, especially for long-distance and high-density routes, is globally agreed upon as a more economical and sustainable solution to freight transport. However, despite its recurrent mentions in country policy and planning globally, implementation and operational issues have persisted. Rail freight infrastructure, given its long-term investment in the backdrop of prevailing rail systems, high impact on land use and strategic matching of demand and supply sites, needs detailed country- and region-specific planning and targeted investment, which is lacking in emerging countries (Aritua et al., 2018). Given the enormous scope of analysis and economic investment needed to procure land, identify routes for modal shift and fulfil an ecosystem of services such as intermodality and operational competitiveness with road freight, the study tries to focus on already identified avenues by independent researchers and policy makers. Thus, as a part of the study, we first

characterize the current state and the existing plans for rail freight transport in selected countries and world regions. Due to the complexity involved in freight demand and supply by type, data collection, and routing and thus being able to quantify future possibilities and emission reduction potential, it was deemed appropriate to evaluate existing long-term national plans and research already done in the freight transport sector. Comparison of the ambition level of existing plans and implementation must be performed with respect to the regional context for utility and plausibility. A framework is developed to compare the levels of rail freight status and potential by characterizing the existing rail infrastructure status and identifying its technical, operational, and institutional barriers to demonstrate the regional challenges to this transformation.

### 5.3 Relevance of the regional perspective

A key driver for the shift to railways for long-distance and high-density lines is the economic advantage (which furthers global competitiveness for trade and export) that rail usually provides above 300 km (J. H. Havenga & Z Simpson, 2021; J Rodrigue, 2016), which would reduce the logistics cost of freight transport for a country. The exact correlation of rail and road freight rates per tonne kilometer (tkm) with distance varies with the operational, technical and intermodal infrastructure characteristics of freight in a given region. As seen in Table 12, the logistic cost for India in comparison to its counterparts is higher than for similar large area developing countries with long distance freight trips such as Brazil and Russia (J. H. Havenga et al., 2016). An indicator of the presence of long-distance freight trips that are to be undertaken to fulfil freight demand is the average distance between the origin and destination for goods represented by the lead distance. Economic viability for countries such as EU member states where the average truck trip length is in the range of 140 km is low for rail and thus hinders rail freight growth beyond the current status due to the inherent spatial distribution of supply and demand centres. Longer distances, however, also translate to higher long-term investments, which are especially difficult in emerging or politically unstable countries.

Shift to rail is also driven by sustainability and reduction of air pollution. Trucks running on fossil fuels pose a major threat to countries and their inhabitants given their high contribution to NO<sub>x</sub> and PM emissions, especially in urban driving conditions. Heavy-duty vehicles contribute to 70% of NO<sub>x</sub> and PM emissions, half of energy consumption and emissions in India despite constituting only 3% of the total vehicle fleet (IEA, 2023b). Strong electrification and stock turnover measures are thus being pushed in the freight sector for India along with modal shifts. In comparison, heavy duty vehicles account for 28% of the total transport emissions with 8% mileage share and 39% of NO<sub>x</sub> emissions (IFEU, 2014; Transport & Environment, 2021b). The emission intensity of rail freight on average is 15 gCO<sub>2</sub>/tkm with variations from 20 gCO<sub>2</sub>/tkm in Japan - 15 gCO<sub>2</sub>/tkm in the EU based on (UIC, 2017). In comparison to the emission intensity of road freight in countries as shown in Table 12 with 112 gCO<sub>2</sub>/tkm for the EU and 169 gCO<sub>2</sub>/tkm for South Africa and, it translated into a 86%-92% reduction in gCO<sub>2</sub>/tkm based on and average 15 gCO<sub>2</sub>/tkm emission intensity for rail.

We further elaborate on the regional specificities that enable and hinder the shift to rail in the next section by expanding on the opportunities and constraints for a freight modal shift from road to rail in selected countries.

## Transport Sectoral Modelling - 'Avoid-Shift-Improve' measures

Table 12 Freight transport indicators for selected countries

|                                                 |                                                                             | USA                             | EU                                     | India                                                         | South Africa                                                                | Türkiye                                                                 |
|-------------------------------------------------|-----------------------------------------------------------------------------|---------------------------------|----------------------------------------|---------------------------------------------------------------|-----------------------------------------------------------------------------|-------------------------------------------------------------------------|
| <b>Efficiency Indicators</b>                    | GDP [trillion]                                                              | 25<br>(The World Bank, 2023a)   | 16.6<br>(The World Bank, 2023a)        | 3.3<br>(The World Bank, 2023a)                                | 0.4<br>(The World Bank, 2023a)                                              | 0.9<br>(The World Bank, 2023a)                                          |
|                                                 | Road freight volume [trillion tkm]                                          | 3.0<br>(OECD Data, 2023)        | 1.9<br>(Eurostat, 2022b)               | 2.4<br>(OECD Data, 2023)                                      | 0.3<br>(J. H. Havenga et al., 2016)                                         | 0.3<br>(OECD Data, 2023)                                                |
|                                                 | Logistics cost of GDP [%]                                                   | 8<br>(RMI & NITI Aayog, 2021)   | 10<br>(RMI & NITI Aayog, 2021)         | 14% with 5% being inventory costs<br>(RMI & NITI Aayog, 2021) | 11.8<br>(J. H. Havenga et al., 2016)                                        | 8-10                                                                    |
| <b>Spatial indicators</b>                       | Mean lead distance rail [km]                                                | 400<br>(RMI & NITI Aayog, 2021) | 256<br>(Eurostat, 2023c)               | 550<br>(RMI & NITI Aayog, 2021)                               | 626<br>(Department of Transport, 2008)                                      | 445<br>(TCDD Taşımacılık, 2018)                                         |
|                                                 | Mean lead distance road [km]                                                | na                              | 141                                    | na                                                            | 184<br>(Department of Transport, 2008)                                      | 346<br>(Ulaştırım Etütleri Şubesi Müdürlüğü, 2022)                      |
|                                                 | Surface area [million km <sup>2</sup> ]                                     | 9.3<br>(Worldometer, 2023)      | 4.2<br>(Eurostat, 2023a)               | 1.2<br>(Worldometer, 2023)                                    | 1.2<br>(Worldometer, 2023)                                                  | 0.7<br>(Worldometer, 2023)                                              |
| <b>Emission intensity of freight indicators</b> | Rail freight modal share of tkm [%]                                         | 30<br>(IEA)                     | 16<br>(Eurostat, 2023d)                | 25                                                            | 36<br>Apart from major export lines, 11%<br>(Department of Transport, 2008) | 4.8<br>(Ministry of Environment, Urbanisation and Climate Change, 2023) |
|                                                 | Road freight tkm weighted emission factor in 2020 [gCO <sub>2eq</sub> /tkm] | 120<br>(Teske, 2019)            | 112<br>(Teske, 2019) based on Germany  | 141<br>(Teske, 2019)                                          | 169<br>(Teske, 2019)                                                        | na                                                                      |
|                                                 | Rail electrified of freight tkm [%]                                         | Ca. 0<br>(IEA)                  | 80<br>(Federal Ministry for Transport) | 57<br>(IEA)                                                   | 35<br>Based on route                                                        | 47<br>Based on route km for all lines                                   |

|  |  | USA | EU                                | India | South Africa                       | Türkiye                               |
|--|--|-----|-----------------------------------|-------|------------------------------------|---------------------------------------|
|  |  |     | and Digital Infrastructure, 2017) |       | km for all lines (Transnet, 2021a) | (Turkish Statistical Institute, 2022) |

### 5.3.1 EU

#### 5.3.1.1 Status of the rail freight sector

Rail freight performance stagnates in the EU; in 2021, EU rail freight accounted for 399 billion tkm compared to 381 billion tkm in 2011. The largest share of tonne km was by Germany at 31%, followed by Poland and France for the EU. (Eurostat, 2022a)

Overall, the modal split of rail freight in total freight tonne-kilometres is low and, in addition, has decreased from 6.0% in 2011 to 5.4% in 2021 (including maritime, inland waterways, air and road freight). If only land-based freight transport is considered, in 2021, rail had a share of 17% compared to roads with 77.4% and inland waterways with 5.7%. (Eurostat, 2023b) Thus, road transport by trucks is by far dominating land freight transport.

International and transit rail freight transport accounts for approximately 50% in the EU, with the remainder being national transport. (Eurostat, 2022a)

The main transported goods on rail in terms of ton-kilometres are bulk goods such as ore, metals, coke and petroleum goods, chemicals, coal and agricultural products, which together make up more than 50% of ton-kilometres. (Eurostat, 2022a) The importance of coal, gas and oil transport on rail, however, has declined over the past years, and raw materials, chemicals and food decreased in tonnes transported. (ECM Ventures, 2022) The relevance and number of tonnes transported in containers, swap bodies and trailers grew considerably. From 2003 to 2019, its share in transported tonnes increased from 18% to 29% of total rail freight transport according to (ECM Ventures, 2022) using Eurostat data.

In 2016, the tonne-km share of electric freight trains was 80%, with the remainder being diesel-hailed freight trains. (IEA, 2019a) Diesel consumption in rail freight was 1.7 Mtoe (71.2 PJ), and electricity consumption was 2.2 Mtoe (92.1 PJ) in 2017. (IEA, 2019a) This underlines the considerably higher energy efficiency of electric rail freight over diesel rail freight.

Although an increase in rail freight at the cost of road transport is high on the political agenda both in the EU and in most of the member states, there is a multitude of structural, operational, technical and regulatory constraints that have hindered goods transport on rail from expanding clearly in Europe. First, there is a constraint in physical tracks and terminal structures for additional freight trains on many rail corridors. A large portion of rail freight traffic in the EU is transnational. Different electrification systems in the countries and missing electrification of border sections hamper cost-efficient freight train operation. (RailTech.com, 2020) Additionally, different gauge and track dimensions and a shortage of rolling stock material certified for international transport impede cross-border rail traffic. (European Union Agency for Railways, 2022). There are also few detour capabilities in the case of constructional works. Next, special technical solutions at the national level, especially in the field of rail traffic management systems, block a transition to smooth interoperable transport. In that context, in addition to slow and costly ERTMS in the EU roll-out, regulation is an issue. (ECM Ventures, 2022) Rail traffic management procedures hinder freight transport, e.g., because of shared paths with passenger trains and the inflexible planning procedures of infrastructure managers. (European Court of Auditors,

2016) Finally, there are many regulatory issues, such as slow market liberalization, bureaucratic procedures, the requirement for multilingual locomotive drivers, country-specific locomotive acceptance requirements and other points, together with fierce competition with comparatively less regulated road freight transport.

### 5.3.1.2 Plans to develop/increase rail freight share

There are initiatives and legislative actions with the aim of increasing rail freight at both the national level and supranational EU level by various stakeholders.

Many EU member states have initiated plans and legislation to promote rail freight on a national scale, but at different speeds. Just to give two examples of important European rail freight countries, the German federal government committed in its coalition agreement in 2021 to increase the modal split of rail in freight to 25% until 2030 (from current 18%), speeding up the implementation of the DAC (digital automatic coupling), support of single-wagonload transport, additional sidings and electrification. (Noll, 2021) Rail operator 'Deutsche Bahn' issued a "Strong Rail" masterplan aiming at increasing freight volume on rails by 70% until 2030 by expanding terminal and network infrastructure, digitization and additional rolling stock. (DB Cargo)

France announced plans to double the market share of rail from then 9% to 18% by 2030. (Guihery, 2021) In 2021, the rail freight share increased to 10% in France thanks to governmental support, but with electricity prices increasing starkly in 2022/2023, the uptake of rail freight is in danger, and transport is increasingly shifted to road transport. (Ashcroft, 2023) Many infrastructure enhancement plans, however, are embedded into EU legislation and initiatives, which must be transposed to national law by the member states.

On the EU level, the focus is on supranational legislation, standardization and corridor planning. In 2011, the European Commission formulated ambitious targets on transport, concerning rail freight, among others, with the goal of '2030, 30% of road freight over 300 km should shift to other modes such as rail or waterborne transport, and more than 50% by 2050' and to 'deliver a fully functional and EU-wide core network of transport corridors, ensuring facilities for efficient transfer between transport modes (TEN-T core network) by 2030, with a high-quality high-capacity network by 2050 and a corresponding set of information services.' (EUROPEAN COMMISSION, 2011)

General activities at the EU level, helping to increase rail freight market share, include the harmonization of legislative and regulative bodies (e.g., Technical Specifications of Interoperability, market entry deregulation, implementation of the European Railway Agency). The European Commission has issued four "railway packages" over recent years containing standards and regulations for a harmonized European rail market. (EUROPEAN COMMISSION) All this is part of the 'Single European Railway Area' covering also fewer barriers to new market entrants, the ERTMS (European Rail Traffic Management System) and harmonized railway certification procedures. (European Union Agency for Railways, 2023) In that context, over recent years, the EU has set up dedicated rail freight corridors across EU states implemented in the TEN-T (Trans-European Network – Transport). (EUROPEAN COMMISSION; Federal Ministry for Digital and Transport, 2021),

Planning and implementation of infrastructure upgrades on track infrastructure, terminals and ERTMS implementation is effective at the member state level, but the states partly receive EU funds.

Private sector entities, such as sea ports, also play a role in supporting rail freight development. In particular, strengthening hinterland rail freight transport, such as the Hamburg port, by upgrading their

rail infrastructure resulted in an increase in the hinterland Hamburg port rail market share from 30 to 51%. Other major ports have a much lower share of rail in hinterland operations, such as Antwerp with only 8%, which is why there is a large potential for an increase in rail freight share across European sea ports. (Chapuis et al., 2022)

DHL, a large logistics company, proposed focusing on a set of measures in rail freight, such as automated coupling and braking procedures, extension of the track network and its capacity, standardization of cross-border processes, improvement of interfaces with other transport modes, e.g., through intermodal terminals and acceleration of the uptake of ERTMS/ETCS. (DHL, 2023). Generally, rail support measures should aim to attract long-distance road freight to rail to substantially increase rail freight market share. (Chapuis et al., 2022)

In a scenario study, (Bänsch & Weidner, 2022) showed that in the EU 28 including Switzerland and Norway, a 31% increase of rail transport volume (tonnes) and 72% in rail transport performance (tonne-kilometers) could be possible until 2030 against 2015, provided considerable portions of market segments transported with trucks today is shifted to freight rail. It is currently uncertain whether such a substantial increase in rail freight and thus CO<sub>2</sub> reduction will effectively materialize in the EU within the coming years.

There are ambitious plans at the EU level and national levels for an increase in rail freight market share at the cost of road freight until 2030 and beyond. However, it is highly uncertain if these targets can be met because of a variety of blocking stones structurally and in terms of slow standardization and harmonization processes and a lack of funding (e.g., the EU commission plans to reduce CEF (Connecting Europe Facility) funds for TEN-T infrastructure projects (rail, ship, road) in 2024 compared to 2023. (EUROPEAN COMMISSION, 2023; Hütten, 2023) However, there are many promising technical solutions, such as the DAC and digital traffic management, that could substantially promote rail transport. Additionally, there are some promising best-practice initiatives that boosted rail freight regionally, such as in the Hamburg port hinterland corridor.

### 5.3.2 India

#### 5.3.2.1 Status of the rail freight sector

Indian Railways is the 4th largest railway network in the world, with 121,407 kilometers of total track over a 67,368 km route with a 95% broad gauge network (Ministry of Railways, 2023). A total of 872 billion tkm per year was carried in 2022 by rail in comparison to 707 billion tonne kilometers (btkm) in 2019.

Rail freight accounts for 26% of the modal split today in 2022 in comparison to roads (RITES, 2020). This has dropped from 80% in the year 1960 due to increased competitiveness by the road sector given the growing demand and insufficient rail capacity. The NDC submitted in 2015 outlines the role of increasing the rail freight share from 36% to target 45% by 2030 and 100% electrification by 2024 (Government of India, 2015).

The main transport goods by rail in India are coal, which constituted 31% of the total tonne kilometres, followed by food grains (11%), cement (10%), iron ore (7%) and food grains (%) in 2021 (Ministry of Railways, 2023). Approximately 70% of tonne km in India is bulk goods, which is more suitable for rail freight, of which 40% is carried by trucks, which shows the high potential that exists for a shift to rail. (RMI & NITI Aayog, 2021).

Geographical constraints: In comparison to other major economies such as Europe with long coastlines (15 m/km<sup>2</sup> coast to land mass area ratio) and China with economic activity concentrated near the coasts, India's upper region is landlocked (with 2 m/km<sup>2</sup> coast to land mass area ratio), which has significant freight demand and movement, especially from mining and agriculture, and has thus relied on road freight transport. The average freight distances are also higher in India, with 550 km in India in comparison to 130 km in Europe (RMI & NITI Aayog, 2021). This is both an opportunity to shift long-distance travel to rail given its economic suitability for long-distance travel and has historically been a constraint in terms of infrastructure building and network expansion.

Since the 1960s, freight and passenger loading by railways have increased by 1344% and 1642%, respectively. However, route kilometres have only grown by 23%, and track doubling has increased by only 289% (*DECARBONIZATION of TRANSPORT SECTOR in INDIA*). The shared rail infrastructure has thus been unable to deal with the growing demand, leading to significant operational constraints. Competing with passenger rail in terms of track sharing with lower priority has led to low scheduling and reliability, with 65% capacity allocated to passenger transport in comparison to 29% in China (Aritua et al., 2018). Higher last mile included costs, unreliability, lack of scheduling and tracking, and inability to book portions of trains, leading to poor efficiency. This is expected to change by segregating the movement of passengers and freight by rail using freight corridors.

On the other hand, there has been tremendous improvement in the electrification of rail networks in the recent past. In 2023, 90% of the total broad-gauge route kilometres were electrified. Fifty percent of the total electrification of routes has occurred in the past 5 years. (Central Organization for Railway Electrification, 2023). The national policy aims to reach 100% electrification by 2024.

Emissions from railways and freight: Currently, the CO<sub>2</sub> emissions from the freight sector amount to 220 million tonnes of CO<sub>2eq</sub>, of which road freight is responsible for 95%. Road freight carbon intensity in India is 101-140 gCO<sub>2</sub>/tkm for road-based transport vs 11.5 gCO<sub>2</sub>/tkm for rail (RMI & NITI Aayog, 2021). Despite constituting 3% of the total vehicle stock, trucks were responsible for 53% of PM emissions and pose a great threat to the air quality standards in India (RMI & NITI Aayog, 2022).

The projected freight activity from all modes is expected to grow from 3 trillion tkm in 2020 to 15.6 trillion tkm in 2050 with increasing GDP and consumption (RMI & NITI Aayog, 2021). A modal shift to railways and an integrated logistic system is needed and recognized in India to decrease logistics costs, improve export competitiveness and manufacturing within the country, reduce oil import dependence and reduce emissions.

### 5.3.2.2 Plans to develop/increase rail freight share

Logistics costs account for 14% of the economy in comparison to other countries, where it is 7% for the USA and 10% for Europe (RMI & NITI Aayog, 2021). Only in 2019 has the National Logistics Policy emerged to structure the logistics issue of India. Its goal is to reduce logistics costs in India by 5% of GDP from the current 14%. As such, the logistics sector in India suffers from fragmentation and is largely unorganized (Aritua et al., 2018). With interstate transport, this is further complicated by multiple authorities and regulations. To integrate railways as a competitive mode, a national, transparent and technology-based system of logistics for all modes is needed, which is exactly what the National Logistics Policy is hoping to achieve. (Logistics Division Ministry of Commerce and Industry, 2021).

The National Rail plan aims to have a 45% freight share by 2030, and its key strategy is the Dedicated Freight Corridors (DFC), mentioned in its NDC, which segregates passenger traffic and freight traffic

(PIB Delhi, 2022). The golden quadrilateral network connecting major metropolitan cities in India, where the 5 DFCs are planned, accounts for 16% of the route length but 58% of the freight traffic with an average corridor distance of 1420 km (Aritua et al., 2018). The eastern (1337 km) and western corridors (1506 km in total) have been constructed since 2014 and are at 86% and 90% financial completion in 2023, respectively, and are expected to be completed by 2024 (Dedicated Freight Corridor Corporation of India Limited, 2023). The remaining 3 DFC corridors are planned to be operationalized phase-wise by 2031 and 2041. (Ministry of Railways, 2020). An exponential increase in investments was made from 2016-2020, with 8500 bn INR of the total 1399 bn INR since 1995, which has been primarily spent on the 2 DFCs alone (Aritua et al., 2018). The majority of the investments were from 2014 - 2016 for land acquisition (Dedicated Freight Corridor Corporation of India Limited, 2022). Historically, land clearance has been a major hurdle for implementing DFCs with compensation and resettlement costs for affected inhabitants. With the implementation of digital tools such as the GIS-based digital platform Gati Shakti (launched in 2021) for national infrastructure projects, feasibility studies and approvals have expedited and are expected to improve.

Technical improvements: The DFC planning phase started as early as 2006 with the first operational trains and routes in 2020. The track has an axle load of 32.5 tonnes in comparison to the current 25 tonnes. Automatic signalling every 2 km is implemented to ensure 120 trains on each corridor with a time gap of 12 mins. This allows the current average speed of trains on the DFCs commissioned to date to be 50-60 kmph in comparison to 25 kmph by the old shared network with an average running speed of 99 kmph (Dedicated Freight Corridor Corporation of India Limited, 2022).

Operational improvements: There is a growing shift in Indian policy now to create government financed base enabling infrastructure and then shift operations and improvements to the private sector. The objective of the Gati Shakti Multi Modal Cargo Terminal (GCT) policy released in Dec 2021 is to boost investment from industry in the development of additional terminals for handling rail cargo and goods sheds. Multiple schemes were introduced in 2020 to let private players invest and own rail wagons either in a particular route or of a specialized type. (Ministry of Railways, 2022). Apart from this, they are also expected to participate in multimodal infrastructure and logistics parks. Thirty-five multimodal logistic parks (MMLPs) have been identified to support logistics plans. However, apart from 4, there have been investment issues from private industry players.

Digitalization and a structured distribution system have been largely missing in both road and rail modes, leading to large-scale inefficiencies such as overloading in railways and empty movement of trucks on roads. This is reflected in low truck utilization and high empty running of trucks. The national policy of PM Gati Shakti is thus in the process of establishing a unified platform for finding correct intermodal solutions using data-based decisions for tracking, matching and site selection of multimodal parks. With 75% of the truck fleet by small owners with up to 5 trucks, consolidating them on the same platform to improve the efficiency of the logistics problem will be a challenge.

Emission savings: In the absence of DFCs, in the eastern corridor, the annual emissions are expected to increase from 2.7 to 6.2 million tonnes CO<sub>2</sub> from 2021 to 2040, and in the western corridor, they are expected to increase from 6.42 to 26.8 million tonnes CO<sub>2</sub>. This is expected to decrease to 2.1 in the eastern corridor and 3.83 million tonnes of CO<sub>2</sub> in the western corridor in 2040 in the presence of the two DFCs. Cumulatively, in a 30-year period, emissions are expected to decrease from 582 to 124 million tonnes of CO<sub>2</sub> by the 2 DFCs (a 78% reduction) (Ernst & Young, 2011). It is expected from the policy think tank NITI Aayog that by a modal shift to rail, 21% of the cumulative emissions from the freight sector from 2020-2050 can be evaded. Optimized truck use would contribute to 14%, and im-

provement of truck technology would further contribute to 16%, which would amount to a 52% reduction overall (RMI & NITI Aayog, 2021). With growing demand, improvement in conventional truck technology will have to be supplemented with ZETs (zero emission trucks). It is expected with supporting policies that the penetration rate will be 87% by 2050, with 57% in truck stock (120). The upfront cost for medium-duty trucks and heavy-duty trucks remains an enormous barrier for the majority, i.e., small fleet owners in India.

### 5.3.3 South Africa

#### 5.3.3.1 Status of the rail freight sector

South Africa has the 11<sup>th</sup> largest rail network with 22000 route km, which has played a major role historically in the country's development since first operating in 1860. 384 billion tkm was carried by rail freight in 2019 (J. H. Havenga & Z Simpson, 2021). However, there has been a loss of share in its domestic freight transport network to road freight due to both performance challenges and institutional and technical barriers.

Mining, automotive sector, steel and other metals and FMCG are the main transported goods on freight transport in South Africa, and due to spatial specificities of natural resource locations being in the middle of the country and thus population and manufacturing sites, transport is over higher distances than similar countries by size. This is demonstrated in (J. H. Havenga & Z Simpson, 2021) where GDP per tonne km is very low for South Africa in comparison to global standards.

Freight transport routes in South Africa can be categorized as bulk mining for export, corridor, rural and metro types. The rail share has remained approximately the same since 2011 at 36% of the total tonne km. However, excluding the bulk mining freight share, the general freight rail market share was only 10% in 2019, with the corridor rail share decreasing from 18% in 2003 to 6% in 2019 (J. H. Havenga & Z Simpson, 2021)

After the deregulation of road freight transport, which unprotected railways in 1989, road freight took over in South Africa, and rail freight competitiveness was ignored and underinvested. As a result, over the years, roads have become overcongested and damaged by heavy trucks. Limited funds for the expansion and maintenance of roads are now an issue (Department of Transport, 2022b). Overloading of trucks has resulted in deteriorating conditions of roads, with maximum loads per truck being 55% higher than those in the USA and 40% higher than those in Germany. The implementation of regulations related to weight, emissions and congestion charges has been identified to be poor and has led to the current status (David Williams, 2021).

The monopolistic nature of the rail freight service in South Africa is identified by the government in its National rail policy paper in 2022 (Department of Transport, 2022b) as institutional barriers that have led to its reduced performance and competitiveness. Poor freight service provision and future vision by Transnet has resulted in a loss-making organization, resulting in even lower investments and hence reduced performance. Allowing and encouraging more private sector competition is thus high on the agenda to tackle underinvestment, ageing, deteriorating and underutilized infrastructure and old technologies.

The crime and security with theft and vandalism of railway infrastructure has also degraded the reliability and efficiency of rail freight, and incidents have increased by ~110% since 2013 in comparison to 2021, as identified in the rail policy paper. (Department of Transport, 2022a) Cable theft and metal stripping for scrap markets have increased rapidly (especially during the COVID-19 lockdown) (David

Williams, 2021). Hence, for South Africa, asset protection, maintenance and upgradation investment are to be seen in the context of poverty, social inequality and unemployment amidst political turbulence, state capture and colonial rule.

Thirty-five percent of the total route km are branch lines (of which only 56% are operational), and almost the entire network is a narrow gauge. A narrow track gauge was constructed during colonial rule and has not since been upgraded. The narrow gauge track carries 16 tonnes/axle compared to 31 tonnes/axle for general freight on broad gauge lines. (Department of Transport, 2022b) Lower axle speed and load therefore have reduced the efficiency of rail performance.

Freight road vehicles contribute ~30 MtCO<sub>2eq</sub> of the total 55 MtCO<sub>2eq</sub> emitted from road transport (which contributes to 90% of total transport-related emissions) (Climate transparency, 2020b). As of 2021, 65% of the rail route km was operated by diesel-based traction (Transnet, 2021b). However, electrified lines are also currently emission intensive. The electricity mix is currently one of the most carbon intensive in the world, with 1059 g CO<sub>2eq</sub>/kWh in 2020. This is expected to decrease with increasing solar capacities installed and natural gas-fired capacity. (Climate transparency, 2020a)

### 5.3.3.2 Plans to develop/increase rail freight share

The most recent development on rail freight is included in the National Transport Policy White Paper, which identifies the technical and institutional challenges and the roles and responsibilities of institutions as a basis to develop a National Rail Master Plan (currently ongoing). Investments for track gauge expansion and conversion, stock, institutional and market structure reforms are focused on transforming rail freight. The government also critically acknowledges the operations of their state-owned entities of energy and railways and suggests measures to improve their performance, accountability and coordination (National Planning Commission South Africa, 2020).

The current National Rail Policy target aims to convert the national long-distance network by the government to standard gauges by 2050 to ensure competitiveness (Department of Transport, 2022a). It suggests conducting feasibility and techno-economic studies of upgradation, extension and expansion for this conversion. South Africa also faces the challenge of balancing rail connectivity to neighbouring African countries (with narrow-gauge infrastructure) while increasing competitiveness. Job creation through rail freight transformation is also an added opportunity that is focused on in the policy. The national policy acknowledges the role of digital solutions for tracking, informing and warehouse management, which would improve transparency and reliability (Department of Transport, 2022a). Due to low incentive towards planning by the monopolized state of rail freight, South Africa wants to diversify its rail freight operations and let private players own and invest in the rolling stock and branch lines. However, the varied gauge sizes currently make ownership of rolling stock and in-track infrastructure subject to risk. (Department of Transport, 2022b)

In the past, the Green Transport Strategy in 2018 aimed to shift general freight transport from road to rail by 30% (Department for Transport South Africa, 2018). However, it lacked a clear outline of how this was to be achieved and was thus largely not successful. Despite multiple policies and development plans that have been devised for transport and rail, implementation and mode-specific strategies without a long-term vision have been the key hurdle for rail freight and other sectors (Department of Transport, 2022a), (Jan Havenga & Z Simpson, 2021), (J. H. S. Havenga, 2014)

Independent researchers have identified potential shifts of 11 b tkm in export mining corridors, which can be easily shifted, and 30 btkm in general freight corridors (Jan Havenga & Z Simpson, 2021). Detailed model outputs show that rail-friendly routes can and should have supported 47 btkm within the freight corridors but only do so for 18 btkm. Demand in the general freight corridors up to 2050 is

expected to be 77 bTkm, which would have to be planned for and heavily invested in. Palletized long-distance freight, which is suitable for rail, is a major opportunity that has a 2% rail share today because of the failure to develop intermodal solutions (Jan Havenga & Z Simpson, 2021). Research and reactions to national policy recognize a lack of data-driven strategic planning and resource allocation.

### 5.3.4 Türkiye

#### 5.3.4.1 Status of the rail freight sector

Türkiye's railway system represents a notable but relatively modest portion of the country's transportation infrastructure, as indicated by the data from the 2021 annual report by the General Directorate of Turkish State Railways (TCDD). Combining both conventional and high-speed train lines, the total railway length in Türkiye amounts to 13,022 kilometers.

Over the observed period from 2004 to 2022, the tonne-kilometer values for Turkish railway freight transportation have experienced substantial growth. Starting at a value of 9.4 billion tonnes and peaking at 16.6 billion tonnes in 2022, these figures indicate a significant increase in the volume of goods transported by rail in Türkiye (TurkStat, 2023b). On the other hand, from 2000 to 2021, the domestic freight ratios (% share of tonnes-km) of the railway in terms of domestic freight transport exhibited limited change, with a minor decrease in share. In 2000, the railway accounted for a share of 5.3%, which slightly declined to 4% in 2021. Conversely, during the same time period, the share of road transport experienced growth, increasing from 87% to 92%. As a result, the shares of railway and maritime transport have diminished in comparison (Ministry of Environment, Urbanisation and Climate Change, 2023a).

Unlike most European countries, a large portion of Türkiye has mountainous geography. Especially in eastern Türkiye, mountains create extra difficulties for the development of the regions there. The western part of Türkiye offers favourable geographical conditions for railway construction, coupled with its proximity to the sea (Turgut Mehmet Burak). Moreover, the western part of Türkiye has higher economic activity and wages. Given that there is a large altitude gap between the east and west of the country, railway transportation could only be possible in a small portion of the cities in the east of the country. On the other hand, in Istanbul, Ankara, and the Izmir triangle, there are many different railways with high-speed and electrified lines (TCDD Taşımacılık, 2023).

In 2022, the average freight transport distance in Türkiye was 416 kilometers, exceeding the average distance of 259 kilometers observed in EU countries, with the exception of Greece, which had an average distance of 441 kilometers (General Directorate of Turkish State Railways, 2023). Since 2005, the share of the transport and storage sector in GDP has remained stable, ranging between 8% and 10% annually (TurkStat, 2023a).

In the analysis of freight production by material type in 2022, ore and metal residues constitute the largest share at 35.4%, followed by produced minerals and construction materials at 20.8%. The vehicle and machinery category holds a share of 15.4%, while solid mineral fuels account for 11.3%. Chemical substances contribute 3.9%, and additional material groups, including timber and wood products, foodstuffs, and iron and steel products, also play significant roles in freight distribution (TCDD Taşımacılık, 2023).

As of 2021, maritime transport remains the dominant mode for both import and export activities, with road transportation accounting for approximately 5.36% of imports. In contrast, the share of railway transportation has remained less than 1% over the past decade. A significant landmark was reached

on November 6, 2019, when Marmaray, a sub-Bosphorus rail tunnel, saw the successful passage of its first freight train carrying 42 containers of electronic products from China to the Czech Republic in a mere 18 days. Current initiatives are targeted at redirecting approximately 30% of the annual 5,000 block trains on the northern route from China-Russia (Siberia) to Europe through Türkiye. Ambitious goals have also been set for the Baku-Tbilisi-Kars railway, aiming to elevate its freight-carrying capacity to 20 million tons by the end of 2024. These developments form part of a broader strategy to leverage Türkiye's railway network, with a target to increase its share in total freight transportation to 10% by 2023 (Utikad, 2022).

The implementation of electric lines covers approximately 47% of the railway network, accounting for 5,986 kilometres, while signalling has been implemented on 55% of the total network, corresponding to 7,094 kilometres (General Directorate of Turkish State Railways, 2022). In terms of final energy consumption, the transport sector accounted for a total of 29,940 thousand tons of petrol equivalent in 2021. Among the different transport types, motorways had the highest energy consumption, reaching 28,513 thousand tons of petrol equivalent. Railways, on the other hand, had a comparatively low energy consumption of 105 thousand tons of petrol equivalent (Ministry of Energy and Natural Resources, 2022). As a result, railways are responsible for only 0.4% of greenhouse gas emissions from transportation in 2021, with a total of 323 kiloton CO<sub>2</sub>eq (Ministry of Environment, Urbanisation and Climate Change, 2023a, 2023b).

### 5.3.4.2 Plans to develop/increase rail freight share

Enhancing the role of railways in both passenger and freight transportation is one of the top infrastructure priorities for Türkiye. With this purpose in mind, substantial attention has been devoted to the extensive proliferation of railway transportation in various official documents, including the activity reports formulated by the Ministry of Transportation and the government's comprehensive 30-year master plan.

The 2053 transportation plan in Türkiye outlines several targets aimed at developing and improving the railway transportation sector in the country (Ministry of Transport and Infrastructure). These objectives include:

- **Increased Passenger and Freight Share:** The plan aims to raise the share of railway transportation in both the passenger and freight sectors. The target is to increase the passenger share from 1% to 6% and the freight share from 5% to 22%.
- **Expansion of High-Speed Train Network:** The plan sets a goal to expand the High-Speed Train (HST) network by increasing the number of provinces with HST connections from 8 to 52.
- **Growth in Passenger and Freight Transport:** The plan targets significant growth in annual passenger transport, with a goal to increase it from 19 million to 270 million. Additionally, the plan aims to raise annual freight transport from 55 million to 448 million tons.
- **Development of a Sustainable and Technologically Advanced Railway Sector:** The plan emphasizes the importance of developing a sustainable, liberalized, economically profitable, and technologically advanced railway sector.

Table 13 source: (General Directorate of Turkish State Railways, 2022)

| Short-term objectives                                                                                                                                           | Middle-term objectives                                  | Long-term objectives                                   |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------|--------------------------------------------------------|
| To increase the total length of branch lines to 580 km in order to provide connectivity between logistics centers, plants, industry, industrial zones and ports | To increase the rate of signalled lines to 90% from 65% | To increase the length of railway network to 28.590 km |

## Transport Sectoral Modelling - 'Avoid-Shift-Improve' measures

| Short-term objectives                                                                     | Middle-term objectives                                                            | Long-term objectives                                                                   |
|-------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|----------------------------------------------------------------------------------------|
| To manufacture rail system vehicles and sub-components with at least 80% domestic content | To increase the annual freight amount carried by TCDD Transport to 50 million ton | To increase the total number of High Speed Train (HST) and rapid train journeys to 272 |
| To increase the share of rail freight transport within inland transport to 11%            | To increase the railway network length to 21.130 km                               | To increase the overall number of highspeed train and rapid train sets to 120 from 31  |

- Ensuring Safety, Speed, Efficiency, and Effectiveness: The plan underscores the importance of a railway infrastructure that prioritizes safety, speed, efficiency, and effectiveness. By implementing advanced technologies and optimizing operational practices, the objective is to provide a reliable and seamless railway experience for passengers and efficient freight transportation for businesses.
- Promoting Renewable Energy Sources: As part of the government's commitment to sustainability, the plan aims to meet 35% of the railway sector's total energy needs from renewable energy sources.

TCDD has released a comprehensive four-year strategic plan outlining the targets for railway transportation in Türkiye. Within this report, they have also assessed the achievements of their previous plan, which encompassed multiple targets. The success rates for these targets varied significantly. Signalization projects boasted a 95% success rate, while electrification projects achieved a commendable 93% success rate. However, the target relating to the completion of new routes had a lower success rate of 44%. These findings highlight the varying degrees of accomplishment across different targets within TCDD's previous plan (General Directorate of Turkish State Railways, 2019).

In addition to the inherent geographical challenges, the current economic situation in Türkiye introduces potential hurdles for infrastructure investments, particularly in the context of achieving railway infrastructure targets. Türkiye has recently faced significant economic difficulties resulting from a combination of heterodox monetary policies pursued until recently, as well as external factors such as the impact of the COVID-19 pandemic and a major earthquake in the eastern region in 2023 (The World Bank, 2023b). These events have adversely affected the Turkish economy, leading to substantial damage. Consequently, the realization of ambitious railway infrastructure goals may face formidable challenges in light of the prevailing economic circumstances in Türkiye.

Despite the prevailing economic turmoil, Türkiye remains a dynamic country characterized by a youthful population and a growing economy with long-term potential. The government's strategic master plans demonstrate a clear recognition of the railway's crucial role in stimulating economic growth.

Furthermore, Türkiye has the capacity to finance its infrastructure investments with assistance from international organizations, such as the \$350 million loan received from the World Bank in 2020, enabling the country to support key projects, including railway infrastructure (The World Bank, 2020). Thus, once the country's economy stabilizes, it can be anticipated that railway infrastructure development will resume at an accelerated pace. The bilateral trade between the EU and China has witnessed a notable surge, resulting in an increased demand for freight transportation between these regions. In light of the geopolitical challenges and strained relations between the EU and Russia, Türkiye has emerged as a crucial player in ensuring the uninterrupted flow of trade. With its strategic location, Türkiye serves as a pivotal hub for railway transportation, making it the preferred choice for facilitating

the movement of goods. Therefore, it can be argued that recent global developments will exert a significant influence on Türkiye's endeavours to improve and expand its railway infrastructure.

### 5.4 Link to Sectoral Conversation

Inputs from the country partners that were aggregated in the sectoral conversations for freight (held by WP1) were also consulted to inform this work.

### 5.5 Conclusions

In this work, we characterized the current status and issues that hamper a shift from road to rail freight. The driving forces for countries to shift to rail can be categorized as follows:

- Reduce CO<sub>2</sub> emissions and air pollution
- Increasing trade competitiveness reduces oil dependence in countries where rail freight would be economically better than road freight for a significant proportion of freight demand, such as India.

When comparing the regional perspectives, the key constraints to shifting to rail that emerged can be summed up as follows:

- Operational efficiency issues: The operational efficiency of rail through technical solutions such as signaling and digital solutions such as fleet planning, traffic management, warehouse management and tracking are identified and worked on at the country level. Balancing public and private ownership and operational models to improve efficiency and innovation and at the same time ensuring access and equitable growth is a tedious and long-term process often slowed by national politics.
- Infrastructure issues: Expanding and upgrading infrastructure for long distance-high density routes involves high investments. Additionally, difficult terrain, the spatial distribution of freight demand, old infrastructure and high land acquisition issues hamper the development of rail infrastructure. Prioritizing investments in the backdrop of other needs of emerging countries must be considered and requires support by access to international funding opportunities.
- Lack of integration: A rail freight network must be situated in an integrated and multimodal logistic system to be competitive and complementary to road transport. Integration through logistic hubs and terminals and digital platforms needs to occur simultaneously with capacity building. Data-driven, transparent and targeted investment and planning is key to handling many of the constraints listed.
- Politics and institutions: Long-term investments such as railway infrastructure require strong political will and planning. Countries with political instability are unable to push for rail-based freight in a timely manner and need to be supported externally. This can be done through support in access to funds, technology transfer and cross-country rail networks, which can stimulate further rail projects domestically.

### 6 Transport Sector Conclusions and Insights

The study tries to quantify the emission reduction potential in transport and the hurdles in realizing them by focusing on selected mitigation options under the “avoid-shift-improve” framework. The options were compared in selected countries to highlight contrasting mobility, social and infrastructural related constraints that these mitigation options would have to overcome. The major conclusions are as follows.

- **Avoid:** Teleworking leads to an emission reduction potential of 7%-2% of passenger road transport in 2030 in selected representative countries. Car-dependent and developed economies with a higher fraction of teleworkable jobs had a higher potential for reduction. However, this potential is greatly influenced by domestic heating and cooling demands, and building sector transformation must occur in parallel to achieve a substantial impact. Rebound effects such as relocation, increased nonwork-related travel and consumption could diminish the net effects. The infrastructure-related constraints of emerging countries, such as power supply, IT connectivity and infrastructure, were discussed in this work and compared.
- **Shift:** Light Electric Vehicles: Substituting car, two-wheeler and three-wheeler trips with light electric vehicles has a maximum potential of 50-35% emission reduction potential of passenger car, 2 W, 3 W based road transport in 2030 in selected representative countries. The work expands on the constraints and experiences related to vehicle costs, physical road and charging infrastructure provisions for smaller LEVs and safety. The benefits in terms of autonomy and constraints of LEVs relating to harassment across gender is also examined. Satiating increasing car ownership demand per household with LEVs in developing countries such as India with cost, space and charging infrastructure constraints will be a major challenge. Hence, public transport complemented by shared LEVs needs to be pushed for in such dense areas. For car-dependent developed countries such as the USA and European countries, a major shift in industry, policy and mindset is needed to reverse ‘SUVisation’, which is not highlighted enough in international discussions for any tangible change.
- **Shift:** Road freight to rail freight: Rail freight has the potential to reduce GHG emissions per tkm on by 86-92% where it can. In this work, we try to identify the constraints and plans selected countries have to shift freight demand to rail. Given the long-term investments, including tedious land acquisition that entail rail transformation, it has generally taken a seat back despite global acceptance of rail freight as a crucial mitigation option. Data-based strategic investment and planning, intermodality and key turn solutions are necessary to attract freight back to rail.

- **Improve:** Electrification of passenger cars: Electrifying passenger cars is a vital step for reaching net-zero emissions in the transportation sector. While significant progress has been made in adopting electric vehicles (EVs) in key markets such as China, the EU, and the US, there is still much to do. Globally, most ICE passenger car bans are still nonbinding. In the EU, the 2035 ICE ban is binding, but the EU's slow progress toward its 2050 emission reduction target and the Paris Agreement's 1.5°C target show that more action is needed. Our study highlights from a demand-side perspective the importance of addressing customer concerns such as infrastructure, charging speed, range, and cost. From a policy perspective, stricter CO<sub>2</sub> emission standards, zero emission vehicle (ZEV) mandates, and the phase-out of internal combustion engine (ICE) vehicles boost electrification sales and drive innovation in battery electric vehicles. Additionally, implementing policies such as banning older ICE vehicles and introducing scrappage programs can significantly reduce greenhouse gas emissions. Our emissions model suggests that banning vehicles older than 25 years in the EU could almost meet the 2050 GHG reduction goal without extra policies. Removing vehicles older than 25 years in the EU has a CO<sub>2</sub> reduction potential of 14% in 2035. More stringent CO<sub>2</sub> reduction targets in combination with stock turnover policies will be needed in the EU to be able to achieve the Paris Agreement objectives. Additionally, effects such as banning old vehicles will disproportionately affect poorer groups, and thus, compensation programmes will be needed to improve social equity and reduce hardships.

Major issues were found across the mitigation options

- **Data, Sharing, Collaboration:** The overarching role of data and IT tools as an infrastructure and for research, planning and policy is found across all mitigation options. Sharing, open data and collaboration on base models and services across industry partners would help efficiency and thus reduce emissions, especially in freight and urban passenger transport subsectors.
- **Sustainability and Growth:** Emerging countries need to manage economic growth and employment, improve local living conditions and sustainability, and constrain resources and political stability. Mitigation options are thus seen from the lens of job creation, national economy and manufacturing sector improvement, import dependence and local air pollution. Trade dependence also makes them laggards at adopting and preparing for newer technologies.
- **Consumption reduction and lifestyle:** Global consumption trends need to be reduced along with the implementation of these mitigation options to avoid rebound effects. Urbanization, digital tools, and pricing for sustainable consumption and use can propel citizens to take ownership of their lifestyles. Per capita consumption needs to be highlighted to ensure fair shares of responsibilities for climate change actions.

Such work should be a part of a broader collection of research that deep dives into mitigation options not only quantifying the relative potential benefit of mitigation options but also the challenges to realizing them for better global understanding and cooperation to fight against climate change.

## 7 References

- ACEA. (2021a). *2021 Progress Report: Making the transition to zero-emission mobility*.  
[https://www.acea.auto/files/ACEA\\_progress\\_report\\_2021.pdf](https://www.acea.auto/files/ACEA_progress_report_2021.pdf).
- ACEA. (2021b). *New passenger car registrations in the EU*. <https://www.acea.auto/figure/new-passenger-car-registrations-in-eu/>
- ACEA. (2022a). *Passenger car registrations: -4.6% in 2022; +12.8% in December*.  
<https://www.acea.auto/pc-registrations/passenger-car-registrations-4-6-in-2022-12-8-in-december/#:~:text=confirm%20your%20subscription.,Passenger%20car%20registrations%3A%20%2D4.6%25%20in,2022%3B%20%2B12.8%25%20in%20December&text=Brussels%2C%2018%20January%202023%20%E2%80%93%20In,month%20of%20growth%20this%20year>.
- ACEA. (March 2022b). *European EV Charging Infrastructure Masterplan*.  
<https://www.acea.auto/publication/european-electric-vehicle-charging-infrastructure-masterplan/>
- Alarfaj, A. F., Griffin, W. M., & Samaras, C. (2020). Decarbonizing US passenger vehicle transport under electrification and automation uncertainty has a travel budget. *Environmental Research Letters*, 15(9), 0940c2. <https://doi.org/10.1088/1748-9326/ab7c89>
- Aljazeera. (2023, February 21). *China's EV maker Nio eyes 1,000 battery-swap stations this year*.  
<https://www.aljazeera.com/economy/2023/2/21/chinas-ev-maker-nio-eyes-1000-battery-swap-stations-this-year>
- Andrew Hook: Victor Court (2020). A systematic review of the energy and climate impacts of teleworking. *Environmental Research Letters*. Advance online publication.  
<https://doi.org/10.1088/1748-9326/ab8a84>
- Aritua, B., Havenga, J., Simpson, Z., & Chiew, E. (2018). *Unlocking India's Logistics Potential: The Value of Disaggregated Macroscopic Freight Flow Analysis*. <https://doi.org/10.1596/1813-9450-8337>
- Armillei, F., Boeri, T., & Le Barbanchon, T. (2021). *Remote working, Housing Inequality and Social Mobility*. <https://www.t20italy.org/wp-content/uploads/2021/09/TF6-8.pdf>
- Ashcroft, S. (2023, February 20). *Energy prices shunt EU rail freight plans into sidings*. <https://supply-chaindigital.com/logistics/energy-prices-shunt-eu-rail-freight-plans-into-sidings>
- Axsen, J., Hardman, S., & Jenn, A. (2022). What Do We Know about Zero-Emission Vehicle Mandates? *Environmental Science & Technology*, 56(12), 7553–7563.  
<https://doi.org/10.1021/acs.est.1c08581>
- Bai, X., Blanco, H., Lwasa, S., Pan, J., & Seto, K. (2022). *Urban systems and other settlements*. In IPCC, 2022: *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]*. Cambridge University Press. [https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC\\_AR6\\_WGIII\\_Chapter08.pdf](https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_Chapter08.pdf) <https://doi.org/10.1017/9781009157926.010>
- Bajolle, H., Lagadic, M., & Louvet, N. (2022). The future of lithium-ion batteries: Exploring expert conceptions, market trends, and price scenarios. *Energy Research & Social Science*, 93, 102850.  
<https://doi.org/10.1016/j.erss.2022.102850>
- Bänsch, R., & Weidner, M. (2022). *Doubling Rail Freight's Market Share: Re-Railing Freight Rail Business back to Success* (1. Auflage 2022). PMC Media.

- Barrero, J. M., Bloom, N., & Davis, S. J. (2021). *Why Working from Home Will Stick*. Working Paper (Working Paper Series No. 28731). National Bureau of Economic Research. <http://www.nber.org/papers/w28731> <https://doi.org/10.3386/w28731>
- Benjamin Goldstein, Dimitrios Gounaridis, & Joshua P. Newell (2020). The carbon footprint of household energy use in the United States. *Proceedings of the National Academy of Sciences*, 117(32), 19122–19130. <https://doi.org/10.1073/pnas.1922205117>
- Bigazzi, A. Y., & Rouleau, M. (2017). Can traffic management strategies improve urban air quality? A review of the evidence. *Journal of Transport & Health*, 7, 111–124. <https://doi.org/10.1016/j.jth.2017.08.001>
- Bnamericas. (2022, November 23). *FCAB to have its first green hydrogen-powered locomotive in 2024*. <https://www.bnamericas.com/en/news/fcab-to-have-its-first-green-hydrogen-powered-locomotive-in-2024>
- BNSF. (2021). *BNSF and Wabtec commence battery-electric locomotive pilot test in California*. <https://www.bnsf.com/news-media/news-releases/newsrelease.page?relId=bnsf-and-wabtec-commence-battery-electric-locomotive-pilot-test-in-california>
- Cabrera Serrenho, A., & Allwood, J. M. (2016). Material Stock Demographics: Cars in Great Britain. *Environmental Science & Technology*, 50(6), 3002–3009. <https://doi.org/10.1021/acs.est.5b05012>
- CAM. (2021). *Electromobility Report 2021: Update Europa*. <https://auto-institut.de/automotiveinnovations/emobility/elektromobilitaet-in-europa/>
- Campello-Vicente, H., Peral-Orts, R., Campillo-Davo, N., & Velasco-Sanchez, E. (2017). The effect of electric vehicles on urban noise maps. *Applied Acoustics*, 116, 59–64. <https://doi.org/10.1016/j.apacoust.2016.09.018>
- Canadian Pacific. (2020). *CP announces hydrogen-powered locomotive pilot project*. <https://www.cpr.ca/en/media/cp-announces-hydrogen-powered-locomotive-pilot-project>
- Carbon Trust (2021). Homeworking report. [https://www.vodafone-institut.de/wp-content/uploads/2021/06/CT\\_Homeworking-report-June-2021.pdf](https://www.vodafone-institut.de/wp-content/uploads/2021/06/CT_Homeworking-report-June-2021.pdf)
- CEEW (2020). State of electricity access and coverage in India. <https://www.ceew.in/sites/default/files/ceew-research-on-state-of-electricity-access-and-coverage-in-india.pdf>
- Center for Sustainable Systems. (2022). *Residential Buildings Factsheet*. University of Michigan. <https://css.umich.edu/publications/factsheets/built-environment/residential-buildings-factsheet>
- Central Organization for Railway Electrification. (2023). *Central Organization for Railway Electrification*. <https://core.indianrailways.gov.in/>
- Chang-won, L. (2021). *Railway research body embarks on development of locomotive based on liquefied hydrogen*. <https://www.aju-daily.com/view/20210420134232725#:~:text=SEOUL%20%2D%20South%20Korea%27s%20state,trains%20and%20generate%20no%20pollutants>
- Chapuis, R., Delporte, T., Köpke, S., Lotz, C., & Ott, A. (2022, January 21). *Bold moves to boost European rail freight*. <https://www.mckinsey.com/industries/travel-logistics-and-infrastructure/our-insights/bold-moves-to-boost-european-rail-freight#/>
- Choma, E. F., Evans, J. S., Hammitt, J. K., Gómez-Ibáñez, J. A., & Spengler, J. D. (2020). Assessing the health impacts of electric vehicles through air pollution in the United States. *Environment International*, 144, 106015. <https://doi.org/10.1016/j.envint.2020.106015>
- Climate transparency (2020a). A low carbon transport future for South Africa. <https://www.climate-transparency.org/wp-content/uploads/2020/08/CT-Low-Carbon-Transport-SA-DIGITAL.pdf>
- Climate transparency (2020b). A low carbon transport future for South Africa. <https://www.climate-transparency.org/wp-content/uploads/2020/08/CT-Low-Carbon-Transport-SA-DIGITAL.pdf>

- Cohen, P.-Y., Jäger, L., Isermeyer, H., & Grüss, B. (2022). *Study on alternatives to fossil diesel use in railways*. [https://aerri.eu/wp-content/uploads/2023/04/AERRI\\_Report\\_Study-on-alternatives-on-fossil-diesel-use-in-railways\\_final-Version\\_2001232.pdf](https://aerri.eu/wp-content/uploads/2023/04/AERRI_Report_Study-on-alternatives-on-fossil-diesel-use-in-railways_final-Version_2001232.pdf)
- Crespo Cuaresma, J. Income projections for climate change research: A framework based on human capital dynamics. *Global Environmental Change*, 42, pp. 226–236.
- David Williams. (2021). *Why There are So Many Trucks on the Road and so Few Trains on the Tracks*. <https://www.thebrenthurstfoundation.org/downloads/trucks-and-trains-latefinal.pdf>
- DB Cargo. *Strong Rail gets a boost*. <https://www.dbcargo.com/rail-de-en/metanavi/company/strong-rail>
- DECARBONIZATION OF TRANSPORT SECTOR IN INDIA:**
- Dedicated Freight Corridor Corporation of India Limited. (2022). *Annual Report 2021-2022*. [https://dfccil.com/images/uploads/img/DFCCIL\\_Annual-Report-2021-22\\_K0UG.pdf](https://dfccil.com/images/uploads/img/DFCCIL_Annual-Report-2021-22_K0UG.pdf)
- Dedicated Freight Corridor Corporation of India Limited. (2023). *Project Status Tabular View*. <https://dfccil.com/Home/ProgressStatusImage>
- Deloitte. *2022 Global Automotive Consumer Study*. <https://www2.deloitte.com/za/en/pages/consumer-business/articles/2022-global-automotive-consumer-study.html>
- Deloitte. *2023 Global Automotive Consumer Study*. <https://www2.deloitte.com/us/en/pages/consumer-business/articles/global-automotive-consumer-study.html>
- Deloitte. (2023). *The future of automotive mobility to 2035*. <https://www.deloitte.com/content/dam/assets-shared/docs/foms-v2.pdf>
- Demeulenaere, X. (2019). The use of automotive fleets to support the diffusion of Alternative Fuel Vehicles: A Rapid Evidence Assessment of barriers and decision mechanisms. *Research in Transportation Economics*, 76, p. 100738.
- Department Environmental Affairs. (2020). *Passenger transport - increase in vehicle occupancy* [The South Africa 2050 Calculator]. [http://sa2050pathways.environment.gov.za/assets/onepage/za\\_vehicle\\_occupancy.pdf](http://sa2050pathways.environment.gov.za/assets/onepage/za_vehicle_occupancy.pdf)
- Department for Transport South Africa. (2018). *Green Transport Strategy for South Africa: (2018-2050)*. [https://www.transport.gov.za/documents/11623/89294/Green\\_Transport\\_Strategy\\_2018\\_2050\\_onlineversion.pdf/71e19f1d-259e-4c55-9b27-30db418f105a](https://www.transport.gov.za/documents/11623/89294/Green_Transport_Strategy_2018_2050_onlineversion.pdf/71e19f1d-259e-4c55-9b27-30db418f105a)
- Department of Transport. (2008). *NATMAP 2005-2050: Freight Transport in South Africa*. <https://aria.org.za/wp-content/uploads/2021/04/Transport-in-South-Africa.pdf>
- Department of Transport. (2022a). *White paper on National Rail Policy*. [https://www.gov.za/sites/default/files/gcis\\_document/202205/46356gon2077.pdf](https://www.gov.za/sites/default/files/gcis_document/202205/46356gon2077.pdf)
- Department of Transport. (2022b). *White Paper on National Rail Policy*. [https://www.gov.za/sites/default/files/gcis\\_document/201708/draftwhitepapernationalrailpolicy.pdf](https://www.gov.za/sites/default/files/gcis_document/201708/draftwhitepapernationalrailpolicy.pdf)
- DHL. (2023). *The Future of Rail Freight in Europe*. <https://dhl-freight-connections.com/en/trends/the-future-of-rail-freight-in-europe/>
- Dimanchev, E., Fleten, S.-E., MacKenzie, D., & Korpås, M. (2023). Accelerating electric vehicle charging investments: A real options approach to policy design. *Energy Policy*, 181, 113703. <https://doi.org/10.1016/j.enpol.2023.113703>
- Dornoff, J. (2023). *CO2 emission standards for new passenger cars and vans in the European Union*. ICCT. <https://theicct.org/wp-content/uploads/2023/05/eu-co2-standards-cars-vans-may23.pdf>
- Duarte, C. M., & Fernández, M. T. (2017). The Influence of Urban Structure on Commuting: An Analysis for the Main Metropolitan Systems in Spain. *Procedia Engineering*, 198, 52–68. <https://doi.org/10.1016/j.proeng.2017.07.073>
- Dunatchik, A., Gerson, K., Glass, J., Jacobs, J. A., & Stritzel, H. (2021). Gender, Parenting, And The Rise Of Remote Work During The Pandemic: Implications For Domestic Inequality In The United

- States. *Gender & Society : Official Publication of Sociologists for Women in Society*, 35(2), 194–205. <https://doi.org/10.1177/08912432211001301>
- EAFO. *European Green Deal: ambitious new law agreed to deploy sufficient alternative fuels infrastructure*. <https://alternative-fuels-observatory.ec.europa.eu/general-information/news/european-green-deal-ambitious-new-law-agreed-deploy-sufficient-alternative>
- EAFO. (2022). *Road statistics*. <https://alternative-fuels-observatory.ec.europa.eu/transport-mode/road>
- ECM Ventures. (April 2022). *The European Rail Freight Market. Competitive Analysis and Recommendations. Study on behalf of European Rail Freight Association (ERFA). Final Report*. <https://erfarail.eu/uploads/The%20European%20Rail%20Freight%20Market%20-%20Competitive%20Analysis%20and%20Recommendations-1649762289.pdf>
- Ehrenberger, S., Dasgupta, I., Brost, M., Gebhardt, L., & Seiffert, R. (2022). Potentials of Light Electric Vehicles for Climate Protection by Substituting Passenger Car Trips. *World Electric Vehicle Journal*, 13(10). <https://doi.org/10.3390/wevj13100183>
- Enerdata. (2020). *Change in distance travelled by car*. Odyssee-Mure. <https://www.odyssee-mure.eu/publications/efficiency-by-sector/transport/distance-travelled-by-car.html>
- Enerdata. (2022). *Total unit consumption per m2 in residential (at normal climate)*. <https://en-tranze.enerdata.net/total-unit-consumption-per-m2-in-residential-at-normal-climate.html>
- Engelfriet, L., & Koomen, E. (2018). The impact of urban form on commuting in large Chinese cities. *Transportation*, 45(5), 1269–1295. <https://doi.org/10.1007/s11116-017-9762-6>
- Ernst & Young. (2011). *Green house gas emission reduction analysis for dedicated freight corridor*. [https://dfccil.com/upload/Final\\_Report\\_DFCC\\_30\\_06\\_2011.pdf](https://dfccil.com/upload/Final_Report_DFCC_30_06_2011.pdf)
- ETC. (2018). *Mission Possible: Reaching net-zero carbon emissions from harder-to-abate sectors by mid-century*. [https://www.energy-transitions.org/wp-content/uploads/2020/08/ETC-sectoral-focus-HeavyRoadTransport\\_final.pdf](https://www.energy-transitions.org/wp-content/uploads/2020/08/ETC-sectoral-focus-HeavyRoadTransport_final.pdf)
- Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Regulation (EU) 2019/631 as regards strengthening the CO2 emission performance standards for new passenger cars and new light commercial vehicles in line with the Union's increased climate ambition (2021). <https://op.europa.eu/en/publication-detail/-/publication/870b365e-eecc-11eb-a71c-01aa75ed71a1/language-en/format-PDF/source-221684139>
- Directive 2014/94/EU of the European Parliament and of the Council of 22 October 2014 on the deployment of alternative fuels infrastructure Text with EEA relevance, 2014. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32014L0094>
- European Commission. (2022, October 28). *Zero emission vehicles: first 'Fit for 55' deal will end the sale of new CO2 emitting cars in Europe by 2035* [Press release]. Brussels. [https://ec.europa.eu/commission/presscorner/api/files/document/print/en/ip\\_22\\_6462/IP\\_22\\_6462\\_EN.pdf](https://ec.europa.eu/commission/presscorner/api/files/document/print/en/ip_22_6462/IP_22_6462_EN.pdf)
- EUROPEAN COMMISSION. *Mobility and Transport. Infrastructure*. [https://transport.ec.europa.eu/transport-modes/rail/infrastructure\\_en](https://transport.ec.europa.eu/transport-modes/rail/infrastructure_en)
- EUROPEAN COMMISSION. *Railway packages*. [https://transport.ec.europa.eu/transport-modes/rail/railway-packages\\_en](https://transport.ec.europa.eu/transport-modes/rail/railway-packages_en)
- EUROPEAN COMMISSION. (2011, March 28). *Transport 2050: Commission outlines ambitious plan to increase mobility and reduce emissions*. [https://ec.europa.eu/commission/presscorner/detail/en/IP\\_11\\_372](https://ec.europa.eu/commission/presscorner/detail/en/IP_11_372)
- EUROPEAN COMMISSION. (June 2023). *Draft General Budget of the European Union for the Financial Year 2024. Working Document Part XII. 2024 Financial year*. Publications Office of the European Union. <https://commission.europa.eu/system/files/2023-06/DB2024-WD-12-Payment-schedules.pdf>

- European Court of Auditors. (2016). *Rail freight transport in the EU: still not on the right track*. Publications Office of the European Union. [https://www.eca.europa.eu/Lists/ECADocuments/SR16\\_08/SR\\_RAIL\\_FREIGHT\\_EN.pdf](https://www.eca.europa.eu/Lists/ECADocuments/SR16_08/SR_RAIL_FREIGHT_EN.pdf)
- European Union Agency for Railways. (2022). *Cross-border Rail Transport Potential*. Publications Ofce of the European Union. [https://www.era.europa.eu/system/files/2022-12/20225455\\_PDFA2A\\_TR0522377ENA\\_002.pdf](https://www.era.europa.eu/system/files/2022-12/20225455_PDFA2A_TR0522377ENA_002.pdf)
- European Union Agency for Railways. (2023, March 30). *Getting Rail Freight on the Right Track*. <https://www.era.europa.eu/content/getting-rail-freight-right-track>
- Eurostat. (2020). *End-of-life vehicle statistics*. [https://ec.europa.eu/eurostat/statistics-explained/index.php?title=End-of-life\\_vehicle\\_statistics#cite\\_note-1](https://ec.europa.eu/eurostat/statistics-explained/index.php?title=End-of-life_vehicle_statistics#cite_note-1)
- Eurostat. (2022a). *Railway freight transport statistics*. [https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Railway\\_freight\\_transport\\_statistics](https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Railway_freight_transport_statistics)
- Eurostat. (2022b). *Road freight transport statistics*. [https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Road\\_freight\\_transport\\_statistics#The\\_total\\_EU\\_road\\_freight\\_transport\\_performance\\_in\\_2022\\_remained\\_at\\_the\\_2021\\_levels](https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Road_freight_transport_statistics#The_total_EU_road_freight_transport_performance_in_2022_remained_at_the_2021_levels)
- Eurostat. (2023a). *Facts and figures on life in the European Union*. [https://ec.europa.eu/eurostat/data-browser/view/REG\\_AREA3\\_\\_custom\\_5468707/bookmark/table?lang=de&bookmarkId=e9572305-224b-4fa0-bf0f-a039d44e272e](https://ec.europa.eu/eurostat/data-browser/view/REG_AREA3__custom_5468707/bookmark/table?lang=de&bookmarkId=e9572305-224b-4fa0-bf0f-a039d44e272e)
- Eurostat. (2023b). *Freight transport statistics - modal split*. [https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Freight\\_transport\\_statistics\\_-\\_modal\\_split](https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Freight_transport_statistics_-_modal_split)
- Eurostat. (2023c). *Goods transport by road*. <https://ec.europa.eu/eurostat/data-browser/view/ttr00005/default/table?lang=en>
- Eurostat. (2023d). *Modal split of inland freight transport*. [https://ec.europa.eu/eurostat/data-browser/view/tran\\_hv\\_frmod/default/table?lang=en](https://ec.europa.eu/eurostat/data-browser/view/tran_hv_frmod/default/table?lang=en)
- Eurostat. (2023e). *Road traffic by type of vehicle (million Vkm)*. [https://ec.europa.eu/eurostat/data-browser/view/ROAD\\_TF\\_VEH/default/table?lang=en](https://ec.europa.eu/eurostat/data-browser/view/ROAD_TF_VEH/default/table?lang=en)
- Eurostat. (2023f). *Stock of vehicles by category and NUTS 2 regions*. [https://ec.europa.eu/eurostat/databrowser/view/TRAN\\_R\\_VEHST/default/table?lang=en](https://ec.europa.eu/eurostat/databrowser/view/TRAN_R_VEHST/default/table?lang=en)
- Fabienne Wöhner (2022). Work flexibly, travel less? The impact of telework and flextime on mobility behavior in Switzerland. *Journal of Transport Geography*, 102, 103390. <https://doi.org/10.1016/j.jtrangeo.2022.103390>
- Federal Ministry for Digital and Transport. (2021, March 9). *European Railway Policy*. <https://bmdv.bund.de/EN/Topics/EU-Policy/EU-Transport-Policy/European-Rail-Transport-Policy/european-rail-transport-policy.html>
- Federal Ministry for Transport and Digital Infrastructure. (2017). *Rail Freight Masterplan*. [https://bmdv.bund.de/SharedDocs/EN/publications/rail-freight-masterplan.pdf?\\_\\_blob=publicationFile](https://bmdv.bund.de/SharedDocs/EN/publications/rail-freight-masterplan.pdf?__blob=publicationFile)
- Feinauer, M., Senzeybek, M., Herwartz-Polster, S., Dasgupta, I., & Ehrenberger, S. (2023). Analysis of passenger car tailpipe emissions in different world regions up to 2050. Advance online publication. <https://doi.org/10.21203/rs.3.rs-3034542/v1>
- Fleet logistics. (2022, February 15). *EV running costs 50% lower than ICE equivalents*. <https://www.fleetlogistics.com/en/newsroom/ev-running-costs-50-lower-ice-equivalents/>
- Franke, T., & Krems, J. F. (2013). Interacting with limited mobility resources: Psychological range levels in electric vehicle use. *Transportation Research Part a: Policy and Practice*, 48, 109–122. <https://doi.org/10.1016/j.tra.2012.10.010>
- Freeman, C. (1996). The greening of technology and models of innovation. *Technological Forecasting and Social Change*, 53(1), 27–39. [https://doi.org/10.1016/0040-1625\(96\)00060-1](https://doi.org/10.1016/0040-1625(96)00060-1)

- Fucci, A. (2017). NHTS 2017 summary, 60. [https://nhts.ornl.gov/assets/2017\\_nhts\\_summary\\_travel\\_trends.pdf](https://nhts.ornl.gov/assets/2017_nhts_summary_travel_trends.pdf)
- Fyhri, A., & Aasvang, G. M. (2010). Noise, sleep and poor health: Modeling the relationship between road traffic noise and cardiovascular problems. *The Science of the Total Environment*, 408(21), 4935–4942. <https://doi.org/10.1016/j.scitotenv.2010.06.057>
- Gajendran, R. S., & Harrison, D. A. (2007). The good, the bad, and the unknown about telecommuting: Meta-analysis of psychological mediators and individual consequences. *The Journal of Applied Psychology*, 92(6), 1524–1541. <https://doi.org/10.1037/0021-9010.92.6.1524>
- General Directorate of Turkish State Railways. (2019). *2019-2023 Stratejik Plan*. <https://static.tcdd.gov.tr/webfiles/userfiles/files/istrapor/20182022.pdf>
- General Directorate of Turkish State Railways. (2022). *Annual Report 2021*. <http://www.sp.gov.tr/upload/xSPRapor/files/Ds5ia+22021faaliyet.pdf>
- General Directorate of Turkish State Railways. (2023). *2018-2022 Annual Statistics*. <https://static.tcdd.gov.tr/webfiles/userfiles/files/istrapor/20182022.pdf>
- Goel, R. (2018). Distance-decay functions of travel to work trips in India. *Data in Brief*, 21, 50–58. <https://doi.org/10.1016/j.dib.2018.09.096>
- Government of India. (2015). *India's Intended Nationally Determined Contribution*. <https://www4.unfccc.int/sites/submissions/INDC/Published%20Documents/India/1/INDIA%20INDC%20TO%20UNFCCC.pdf>
- Graham, J. D., & Brungard, E. (2021). Consumer Adoption of Plug-In Electric Vehicles in Selected Countries. *Future Transportation*, 1(2), 303–325. <https://doi.org/10.3390/future-transp1020018>
- Green, F. (2018). *Nature Climate Change* 8. <https://www.nature.com/nclimate/volumes/8/issues/8>
- Guihery, L. (2021, October 5). *Rail freight transport in France*. <https://www.internationales-verkehrswesen.de/rail-freight-transport-in-france/>
- Hannah Ritchie, Max Roser and Pablo Rosado (2020). CO<sub>2</sub> and Greenhouse Gas Emissions. *Our World in Data*. <https://ourworldindata.org/co2-and-greenhouse-gas-emissions>
- Hardman, S. (2019). Understanding the impact of reoccurring and non-financial incentives on plug-in electric vehicle adoption – A review. *Transportation Research Part a: Policy and Practice*, 119, 1–14. <https://doi.org/10.1016/j.tra.2018.11.002>
- Hardman, S., Jenn, A., Tal, G., Axsen, J., Beard, G., Daina, N., Figenbaum, E., Jakobsson, N., Jochem, P., Kinnear, N., Plötz, P [Patrick], Pontes, J., Refa, N., Sprei, F., Turrentine, T., & Witkamp, B. (2018). A review of consumer preferences of and interactions with electric vehicle charging infrastructure. *Transportation Research Part D: Transport and Environment*, 62, 508–523. <https://doi.org/10.1016/j.trd.2018.04.002>
- Hasselwander, S., Meyer, M., & Österle, I. (2023). Techno-Economic Analysis of Different Battery Cell Chemistries for the Passenger Vehicle Market. *Batteries*, 9(7), 379. <https://doi.org/10.3390/batteries9070379>
- Havenga, J. H., Simpson, Z.P., King, D. de Bod, A., & Braun, M. (2016). *Logistics Barometer South Africa 2016*. Stellenbosch University. <https://www.sun.ac.za/english/faculty/economy/logistics/Documents/Logistics%20Barometer/Logistics%20Barometer%202016%20Report.pdf>
- Havenga, J. H., & Z Simpson. (2021). *A proposed freight and passenger road-to-rail strategy for South Africa*.
- Havenga, J. H. S. (2014). South Africa's freight rail reform: A demand-driven perspective. *Journal of Transport and Supply Chain Management*.
- Hecht, C., Victor, K., Zurmühlen, S., & Sauer, D. U. (2021). Electric vehicle route planning using real-world charging infrastructure in Germany. *ETransportation*, 10, 100143. <https://doi.org/10.1016/j.etrans.2021.100143>

- Held, M., Rosat, N., Georges, G., Pengg, H., & Boulouchos, K. (2021a). Lifespans of passenger cars in Europe: empirical modelling of fleet turnover dynamics. *European Transport Research Review*, 13(1). <https://doi.org/10.1186/s12544-020-00464-0>
- Held, M., Rosat, N., Georges, G., Pengg, H., & Boulouchos, K. (2021b). Lifespans of passenger cars in Europe: empirical modelling of fleet turnover dynamics. *European Transport Research Review*, 13(1), 9. <https://doi.org/10.1186/s12544-020-00464-0>
- Holman, C., Harrison, R., & Querol, X. (2015). Review of the efficacy of low emission zones to improve urban air quality in European cities. *Atmospheric Environment*, 111, 161–169. <https://doi.org/10.1016/j.atmosenv.2015.04.009>
- Hostettler Macias, L., Ravalet, E., & Rérat, P. (2022). Potential rebound effects of teleworking on residential and daily mobility. *Geography Compass*, 16(9), e12657. <https://doi.org/10.1111/gec3.12657>
- Hütten, F. (2023, June 7). *EU-Kommission will 2024 weniger Geld für Verkehrsprojekte ausgeben*. Deutsche Verkehrszeitung. <https://www.dvz.de/rubriken/politik/detail/news/eu-kommission-will-2024-weniger-geld-fuer-verkehrsprojekte-ausgeben.html#:~:text=Im%20wichtigsten%20EU%2DF%C3%B6rderinstrument%20f%C3%BCr,der%20EU%2DKommission%20pr%C3%A4sidenten%20Haushaltsentwurf>
- IASA. (December 2018). *SSP Database (Shared Socioeconomic Pathways) - Version 2.0*. <https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=10>
- ICT Data and Analytics Division (2022). Global Connectivity Report. <https://www.itu.int/itu-d/reports/statistics/global-connectivity-report-2022/>
- IEA. *The Future of Rail: Opportunities for energy and the environment*. [https://iea.blob.core.windows.net/assets/fb7dc9e4-d5ff-4a22-ac07-ef3ca73ac680/The\\_Future\\_of\\_Rail.pdf](https://iea.blob.core.windows.net/assets/fb7dc9e4-d5ff-4a22-ac07-ef3ca73ac680/The_Future_of_Rail.pdf)
- IEA. (2017). *Energy Technology Perspectives*. [https://iea.blob.core.windows.net/assets/a6587f9f-e56c-4b1d-96e4-5a4da78f12fa/Energy\\_Technology\\_Perspectives\\_2017-PDF.pdf](https://iea.blob.core.windows.net/assets/a6587f9f-e56c-4b1d-96e4-5a4da78f12fa/Energy_Technology_Perspectives_2017-PDF.pdf)
- IEA. (2019a). *The Future of Rail*. Paris. <https://www.iea.org/reports/the-future-of-rail>
- IEA. (2019b). *The Future of Rail: Opportunities for energy and the environment*. [https://iea.blob.core.windows.net/assets/fb7dc9e4-d5ff-4a22-ac07-ef3ca73ac680/The\\_Future\\_of\\_Rail.pdf](https://iea.blob.core.windows.net/assets/fb7dc9e4-d5ff-4a22-ac07-ef3ca73ac680/The_Future_of_Rail.pdf)
- IEA. (2020). *Working from home can save energy and reduce emissions. But how much?* <https://www.iea.org/commentaries/working-from-home-can-save-energy-and-reduce-emissions-but-how-much>
- IEA. (2021). *India Energy Outlook 2021*. Paris. <https://www.iea.org/reports/india-energy-outlook-2021>
- IEA. (2023a). *Global EV Outlook 2023*. <https://www.iea.org/reports/global-ev-outlook-2023>
- IEA. (2023b). *Transitioning India's Road Transport Sector*. <https://iea.blob.core.windows.net/assets/06ad8de6-52c6-4be3-96fc-2bdc3510617d/TransitioningIndiasRoadTransportSector.pdf>
- IFEU. (2014). *Fuel efficiency and emissions of trucks in Germany*. <http://transferproject.org/wp-content/uploads/2014/04/IFEU-2011-HDV-emissions-in-Germany.pdf>
- ILO (2021). Impact of WfH on Women Executives and Managers in PSEs in India. [https://www.ilo.org/wcmsp5/groups/public/---asia/---ro-bangkok/---sro-new\\_delhi/documents/publication/wcms\\_814727.pdf](https://www.ilo.org/wcmsp5/groups/public/---asia/---ro-bangkok/---sro-new_delhi/documents/publication/wcms_814727.pdf)
- India GHG Program. (2015). *India Specific road transport emission factors*. <https://shaktifoundation.in/wp-content/uploads/2017/06/WRI-2015-India-Specific-Road-Transport-Emission-Factors.pdf>
- Infas. (2017). *Mobilität in Deutschland*. Institut für angewandte Sozialwissenschaft GmbH. <https://www.mobilitaet-in-deutschland.de/publikationen2017.html>
- Infras. (2019). *Handbook emission factors for road transport (HBEFA)* (Version 4.1) [Computer software].

- Infras. (2022). *Handbook emission factors for road transport (HBEFA)*. <https://www.hbefa.net/e/index.html>
- International Institute for Population Sciences. (2022). *National Family Health Survey*. Mumbai. <https://dhsprogram.com/pubs/pdf/FR375/FR375.pdf>
- International Labour Office. (2022). *"The Next Normal The changing Workplace in Africa Ten Trends from the COVID-19 Pandemic that are Shaping Workplaces in Africa"*. Geneva. [https://www.ilo.org/wcmsp5/groups/public/---ed\\_dialogue/---act\\_emp/documents/publication/wcms\\_844770.pdf](https://www.ilo.org/wcmsp5/groups/public/---ed_dialogue/---act_emp/documents/publication/wcms_844770.pdf)
- International Labour Organization (2020). Working from Home: Estimating the worldwide potential. [https://www.ilo.org/wcmsp5/groups/public/---ed\\_protect/---protrav/---travail/documents/briefingnote/wcms\\_743447.pdf](https://www.ilo.org/wcmsp5/groups/public/---ed_protect/---protrav/---travail/documents/briefingnote/wcms_743447.pdf)
- Ivasciuc, I. S., Epuran, G., Vuță, D. R., & Tescașiu, B. (2022). Telework Implications on Work-Life Balance, Productivity, and Health of Different Generations of Romanian Employees. *Sustainability*, 14(23). <https://doi.org/10.3390/su142316108>
- IZT, & Greenpeace. (2020). *Arbeiten nach Corona: Warum Homeoffice gut fürs Klima ist*. [https://www.greenpeace.de/publikationen/s03091\\_gp\\_home\\_office\\_studie\\_08\\_2020\\_dt\\_fly\\_fin\\_04.pdf](https://www.greenpeace.de/publikationen/s03091_gp_home_office_studie_08_2020_dt_fly_fin_04.pdf)
- J Rodrigue. (2016). *The Geography of Transport Systems (4th ed.)*. Routledge. <https://doi.org/10.4324/9781315618159>
- Jabben, J., Verheijen, E., & Potma, C. J. M. (Eds.) (2012). *Noise reduction by electric vehicles in the Netherlands*. <https://api.semanticscholar.org/CorpusID:197858917>
- Jan Havenga, & Z Simpson. (2021). *A proposed freight and passenger road-to-rail strategy for South Africa*. <https://sa-tied.wider.unu.edu/sites/default/files/SA-TIED-Havenga-Report.pdf>
- John Jack. *Loadshedding: The death of work-from-home policies*. Engineering News. [https://www.engineeringnews.co.za/article/loadshedding-the-death-of-work-from-home-policies-2022-07-12/rep\\_id:4136](https://www.engineeringnews.co.za/article/loadshedding-the-death-of-work-from-home-policies-2022-07-12/rep_id:4136)
- Keith, D. R., Houston, S., & Naumov, S. (2019). Vehicle fleet turnover and the future of fuel economy. *Environmental Research Letters*, 14(2), 21001. <https://doi.org/10.1088/1748-9326/aaf4d2>
- Kemp, R., & Soete, L. (1992). The greening of technological progress. *Futures*, 24(5), pp. 437–457.
- Khalid, M., Ahmad, F., Panigrahi, B. K., & Al-Fagih, L. (2022). A comprehensive review on advanced charging topologies and methodologies for electric vehicle battery. *Journal of Energy Storage*, 53, 105084. <https://doi.org/10.1016/j.est.2022.105084>
- Khomenko, S., Cirach, M., Barrera-Gómez, J., Pereira-Barboza, E., lungman, T., Mueller, N., Foraster, M., Tonne, C., Thondoo, M., Jephcote, C., Gulliver, J., Woodcock, J., & Nieuwenhuijsen, M. (2022). Impact of road traffic noise on annoyance and preventable mortality in European cities: A health impact assessment. *Environment International*, 162, 107160. <https://doi.org/10.1016/j.envint.2022.107160>
- Kolsut, B. (2020). The import of used cars to Poland after EU accession. *Studies of the Industrial Geography Commission of the Polish Geographical Society*, 34(2). <https://doi.org/10.24917/20801653.342.9>
- Korthauer, R. (2013). *Handbuch Lithium-Ionen-Batterien*. Springer Berlin Heidelberg. <https://doi.org/10.1007/978-3-642-30653-2>
- Kumar, R. R., Chakraborty, A., & Mandal, P. (2021). Promoting electric vehicle adoption: Who should invest in charging infrastructure? *Transportation Research Part E: Logistics and Transportation Review*, 149, 102295. <https://doi.org/10.1016/j.tre.2021.102295>
- Labuschagne, H. (2022). *Eskom hits 100 full days of load-shedding*. MyBroadband. <https://mybroadband.co.za/news/energy/466547-eskom-hits-100-full-days-of-load-shedding.html>
- Lewis, Y., & Cohen, B. (2016). Greenhouse gas emissions from passenger transport in Gauteng.

- Li, Y., Li, J., Xu, A., Feng, Z., Hu, C., & Zhao, G. (2021). Spatial-Temporal Changes and Associated Determinants of Global Heating Degree Days. *International Journal of Environmental Research and Public Health*, 18(12). <https://doi.org/10.3390/ijerph18126186>
- Logistics Division Ministry of Commerce and Industry. (2021). *Draft National Logistics Policy: Integrated Logistics Action Plan*. <https://arunpandit.com/wp-content/uploads/2021/08/Draft-National-Logistics-Policy.pdf>
- M Moselakgomo, Mathetha T Mokonyama, & Felix Ndubisi Okonta. The relationship between urban neighbourhood type and commuting distance in Gauteng city region, South Africa : a preliminary analysis. In *Southern African Transport Conference 2017*. <https://www.semanticscholar.org/paper/The-relationship-between-urban-neighbourhood-type-%3A-Moselakgomo-Mokonyama/bf081c6a6512d26c4c484d236671f7431c6bec56>
- Matli, W. (2020). The changing work landscape as a result of the Covid-19 pandemic: insights from remote workers life situations in South Africa. *International Journal of Sociology and Social Policy*, 40(9/10), 1237–1256. <https://doi.org/10.1108/IJSSP-08-2020-0386>
- Milford, I., Aasebo, S. J., & Strommer, K. (2012). Value for Money in Road Traffic Noise Abatement. *Procedia - Social and Behavioral Sciences*, 48, 1366–1374. <https://doi.org/10.1016/j.sbspro.2012.06.1112>
- Ministry of Environment, Urbanisation and Climate Change. (2023a). *Environmental Indicators: Highway - Railway Network Intensity*. <https://cevreselgostergeler.csb.gov.tr/karayolu--demiryolu-agi-yogunlugu-i-85788>
- Ministry of Environment, Urbanisation and Climate Change. (2023b). *Environmental Indicators: Greenhouse Gas Emissions by Mode of Transport*. <https://cevreselgostergeler.csb.gov.tr/ulastirma-turune-gore-seragazi-emisyonu-i-85790>
- Ministry of Energy and Natural Resources. (2022). *Ulusal Denge Tablolari*. <https://www.eigm.gov.tr/tr-TR/Denge-Tablolari/Denge-Tablolari>
- Ministry of Environment, Urbanisation and Climate Change. (2023). *Amount of Passengers and Cargo Transported by Type of Transport*. Amount of Passengers and Cargo Transported by Type of Transport
- Ministry of Railways. (2020). *National Rail Plan*. <https://indianrailways.gov.in/NRP-%20Draft%20Final%20Report%20with%20annexures.pdf>
- Ministry of Railways. (2022). *Indian Railways Annual Reports and Accounts 2021-2022*. [https://iritm.indianrailways.gov.in/instt/uploads/files/1680252554005-Indian%20Railways%20Annual%20Report%20&%20Accounts%20English%202021-22\\_web\\_Final.pdf](https://iritm.indianrailways.gov.in/instt/uploads/files/1680252554005-Indian%20Railways%20Annual%20Report%20&%20Accounts%20English%202021-22_web_Final.pdf)
- PIB Delhi. (2022). *National Rail Plan Vision – 2030* [Press release]. <https://pib.gov.in/PressReleasePage.aspx?PRID=1806617#:~:text=Indian%20Railways%20have%20prepared%20a,Railways%20in%20freight%20to%2045%25.>
- Ministry of Railways. (2023). *Indian Railways Year book 2021- 2022*. [https://indianrailways.gov.in/railwayboard/uploads/directorate/stat\\_econ/2023/PDF%20Year%20Book%202021-22-English.pdf](https://indianrailways.gov.in/railwayboard/uploads/directorate/stat_econ/2023/PDF%20Year%20Book%202021-22-English.pdf)
- Ministry of Transport and Infrastructure. *2053 Transport and Logistics Master Plan: 2023*. <https://sgb.uab.gov.tr/uploads/pages/yayin-sunum-ve-tablolar/2053-ulastirma-ve-lojistik-ana-plani-rev.pdf>
- Möring Martínez, G., Senzeybek, M., & Jochem, P. (2023). How the European ban of registering combustion vehicles impacts the national car markets until 2035. *Transportation and Research Part D*.
- Münzel, C., Plötz, P [Patrick], Sprei, F., & Gnann, T [Till] (2019). How large is the effect of financial incentives on electric vehicle sales? – A global review and European analysis. *Energy Economics*, 84, 104493. <https://doi.org/10.1016/j.eneco.2019.104493>

- National Planning Commission South Africa. (2020). *The Contribution of SOEs to Vision 2030: Case studies of Eskom, Transnet and PRASA*. [https://static.pmg.org.za/NPC\\_Position\\_Paper.pdf](https://static.pmg.org.za/NPC_Position_Paper.pdf)
- Nayak, S., & Pandit, D. (2021). Potential of telecommuting for different employees in the Indian context beyond COVID-19 lockdown. *Transport Policy*, 111, 98–110. <https://doi.org/10.1016/j.tranpol.2021.07.010>
- Ndrepepa, A., & Twardella, D. (2011). Relationship between noise annoyance from road traffic noise and cardiovascular diseases: A meta-analysis. *Noise & Health*, 13(52), 251–259. <https://doi.org/10.4103/1463-1741.80163>
- Neaimeh, M., Salisbury, S. D., Hill, G. A., Blythe, P. T., Scofield, D. R., & Francfort, J. E. (2017). Analysing the usage and evidencing the importance of fast chargers for the adoption of battery electric vehicles. *Energy Policy*, 108, 474–486. <https://doi.org/10.1016/j.enpol.2017.06.033>
- Netherlands Tax Administration. *BPM*. <https://www.belastingdienst.nl/wps/wcm/connect/bldcontenten/belastingdienst/individuals/cars/bpm/bpm#:~:text=Bpm%20is%20the%20private%20motor,to%20the%20Netherlands%20from%20abroad%3F>
- Netherlands Tax Administration. *Calculate motor vehicle tax*. <https://www.belastingdienst.nl/wps/wcm/connect/nl/auto-en-vervoer/content/hulpmiddel-motor-rijtuigenbelasting-berekenen>
- Nicolas Gomez Parra (2020). Who on Earth can work from home. <https://openknowledge.worldbank.org/bitstream/handle/10986/34277/Who-on-Earth-Can-Work-from-Home.pdf>
- Nivakoski, S., Calò, X., Mencarini, L., & Profeta, P. (2022). *Covid-19 pandemic and the gender divide at work and home. Living conditions and quality of life / Eurofound*. Publications Office of the European Union. <https://www.eurofound.europa.eu/publications/report/2022/covid-19-pandemic-and-the-gender-divide-at-work-and-home> <https://doi.org/10.2806/015588>
- Noll, S. (2021). *Koalitionsvertrag: Das ist für den Güterverkehr wichtig*. <https://www.verkehrsrundschau.de/nachrichten/transport-logistik/koalitionsvertrag-das-ist-fuer-den-gueterverkehr-wichtig-3061747>
- OECD. (2023). *Road traffic in thousand vehicle-km per road motor vehicle*. OECD.Stat. <https://stats.oecd.org/index.aspx?queryid=73641>
- OECD Data. (2023). *Freight transport*. <https://data.oecd.org/transport/freight-transport.htm>
- OECD Stats. (2022). *ICT Access and Usage by Households and Individuals*. [https://stats.oecd.org/Index.aspx?DataSetCode=ICT\\_HH2](https://stats.oecd.org/Index.aspx?DataSetCode=ICT_HH2)
- Oguchi, M., & Fuse, M. (2015). Regional and longitudinal estimation of product lifespan distribution: A case study for automobiles and a simplified estimation method. *Environmental Science & Technology*, 49(3), 1738–1743. <https://doi.org/10.1021/es505245q>
- Ookla LLC. (2022). *Speedtest Global Index*. <https://www.speedtest.net/global-index>
- Paladugula, A. L., Kholod, N., Chaturvedi, V., Ghosh, P. P., Pal, S., Clarke, L., Evans, M., Kyle, P., Koti, P. N., Parikh, K., Qamar, S., & Ann Wilson, S. (2018). A multi-model assessment of energy and emissions for India's transportation sector through 2050. *Energy Policy*, 116, 10–18. <https://doi.org/10.1016/j.enpol.2018.01.037>
- Pearre, N. S., Kempton, W., Guensler, R. L., & Elango, V. V. (2011). Electric vehicles: How much range is required for a day's driving? *Transportation Research Part C: Emerging Technologies*, 19(6), 1171–1184. <https://doi.org/10.1016/j.trc.2010.12.010>
- PESA. (2022). *A Shunting Locomotive Powered by Hydrogen. SM42 6Dn specification*. [https://pesa.pl/content/uploads/2022/09/ulotka\\_SM42\\_ENGpdf.pdf](https://pesa.pl/content/uploads/2022/09/ulotka_SM42_ENGpdf.pdf)
- Plötz, P [P.], Wachsmuth, J [J.], Gnann, T [T.], Neuner, F [F.], Speth, D [D.], & Link, S [S.]. (March 2021). *Net-zero-carbon Transport in Europe until 2050: Targets, technologies and policies for a long-term EU strategy*. Karlsruhe. Fraunhofer. <https://publica-rest.fraunhofer.de/ser->

- ver/api/core/bitstreams/dd314723-974c-48e7-a984-02e87b010ecb/content#:~:text=All%20member%20states%20of%20the,in%20other%20sectors%20are%20assumed.
- Plötz, P [Patrick] (2022). Hydrogen technology is unlikely to play a major role in sustainable road transport. *Nature Electronics*, 5(1), 8–10. <https://doi.org/10.1038/s41928-021-00706-6>
- Plötz, P [Patrick], Axsen, J., Funke, S. A., & Gnann, T [Till] (2019). Designing car bans for sustainable transportation. *Nature Sustainability*, 2(7), 534–536. <https://doi.org/10.1038/s41893-019-0328-9>
- Plötz, P [Patrick], Link, S [Steffen], & Ringelschwender, H. (June 2022). *Real-world usage of plug-in hybrid vehicles in Europe: A 2022 update on fuel consumption, electric driving and CO2 emissions*. ICCT. <https://theicct.org/publication/real-world-phev-use-jun22/#:~:text=These%20values%20correspond%20to%20tailpipe,approval%20fuel%20consumption%20is%20growing.>
- Plötz, P [Patrick], Wachsmuth, J [Jakob], Sprei, F., Gnann, T [Till], Speth, D [Daniel], Neuner, F [Felix], & Link, S [Steffen] (2023). Greenhouse gas emission budgets and policies for zero-Carbon road transport in Europe. *Climate Policy*, 23(3), 343–354. <https://doi.org/10.1080/14693062.2023.2185585>
- Policy Department for Economic, Scientific and Quality of Life Policies. (2021). *The impact of teleworking and digital work on workers and society*. [https://www.europarl.europa.eu/Reg-Data/etudes/STUD/2021/662904/IPOL\\_STU\(2021\)662904\\_EN.pdf](https://www.europarl.europa.eu/Reg-Data/etudes/STUD/2021/662904/IPOL_STU(2021)662904_EN.pdf)
- Railpage.com.au. (2022a). <https://www.railpage.com.au/news/s/france-s-captrain-to-develop-hydrogenpowered-locomotives>. <https://www.railpage.com.au/news/s/france-s-captrain-to-develop-hydrogenpowered-locomotives>
- Railpage.com.au. (2022b, October 13). <https://www.railpage.com.au/news/s/namibia-to-develop-africa-s-first-hydrogendiesel-locomotive>. <https://www.railpage.com.au/news/s/namibia-to-develop-africa-s-first-hydrogendiesel-locomotive>
- RailTech.com. (2020, June 29). *Electrification of cross-border tracks urgent for Germany*. <https://www.railtech.com/infrastructure/2020/06/29/electrification-of-cross-border-tracks-urgent-for-germany/>
- RailTech.com. (2022, September 2). *Deutsche Bahn switches regional trains to biofuel*. <https://www.railtech.com/rolling-stock/2022/09/02/deutsche-bahn-switches-regional-trains-to-biofuel/>
- Railvolution. (2022). *Alstom's H3 Locomotive Powered by Hydrogen*. [https://pesa.pl/content/uploads/2022/09/ulotka\\_SM42\\_ENGpdf.pdf](https://pesa.pl/content/uploads/2022/09/ulotka_SM42_ENGpdf.pdf)
- Railway Gazette International. (2022). *Talgo to begin fuel cell loco trials*. <https://www.railwaygazette.com/traction-and-rolling-stock/talgo-to-begin-fuel-cell-loco-trials/60890.article#:~:text=The%20loco%20and%20five%20standard,to%20begin%20trials%20in%202023.>
- Rietmann, N., Hügler, B., & Lieven, T. (2020). Forecasting the trajectory of electric vehicle sales and the consequences for worldwide CO2 emissions. *Journal of Cleaner Production*, 261, 121038. <https://doi.org/10.1016/j.jclepro.2020.121038>
- RTES. (2020). *National Rail Plan - India*. <https://indianrailways.gov.in/railwayboard/uploads/directorate/planning/downloads/Exe-Summary-241220-NPR.pdf>
- RMI, & NITI Aayog. (2021). *Fast Tracking Freight in India*. <https://www.niti.gov.in/sites/default/files/2021-06/FreightReportNationalLevel.pdf>
- RMI, & NITI Aayog. (2022). *Transforming Trucking in India: Pathways to Zero-Emission Truck Deployment*. <https://www.niti.gov.in/sites/default/files/2022-09/ZETReport09092022.pdf>
- Rollingstockworld.com. (2023). *Progress Rail and Wabtec develop alternative traction locomotive projects*. <https://rollingstockworld.com/locomotives/progress-rail-and-wabtec-develop-alternative-traction-locomotive-projects/>

- Roux, N. (2019). General Household Survey. <https://www.statssa.gov.za/publications/P0318/P03182019.pdf>
- Seum, S., & Eisenmann, C. (Eds.) (2020a). *Projecting global land-based transportation up to 2100*. <https://elib.dlr.de/135079/>
- Seum, S., & Eisenmann, C. (Eds.) (2020b). *Projecting global land-based transportation up to 2100*. <https://elib.dlr.de/135079/>
- Shlomo, A., & Alejandro, B. *Commuting and the Spatial Structure of American Cities*. Marron Institute of Urban Management. [https://marroninstitute.nyu.edu/uploads/content/Commuting\\_and\\_the\\_Spatial\\_Structure\\_of\\_American\\_Cities\\_20\\_December\\_2014\\_Version2.pdf](https://marroninstitute.nyu.edu/uploads/content/Commuting_and_the_Spatial_Structure_of_American_Cities_20_December_2014_Version2.pdf)
- SLOCAT. (2022). *Climate Strategies for Transport: An Analysis of Nationally Determined Contributions and Long-Term Strategies*. [www.slocat.net/ndcs](http://www.slocat.net/ndcs)
- Soman, A., & Kaur, H. (2019). *How Urban India Moves*. CEEW. <https://www.ceew.in/sites/default/files/ceew-study-on-sustainable-transportation-mobility-in-urban-india-2022Oct19.pdf>
- Statistics South Africa. *Electricity: Coal use inches lower as solar, wind and diesel rise*. <https://www.statssa.gov.za/?p=11292>
- Statistics South Africa (2022). Quarterly Labour Force Survey. <https://www.statssa.gov.za/publications/P0211/P02112ndQuarter2022.pdf>
- Sucheran, S., & Olanrewaju, O. (Eds.) (2021). *The Effect of Remote Working on Employees Productivity Levels in South Africa*. <http://ieomsociety.org/proceedings/2021rome/313.pdf>
- Szumaska, E. M. (2023). Electric Vehicle Charging Infrastructure along Highways in the EU. *Energies*, 16(2), 895. <https://doi.org/10.3390/en16020895>
- Tanmay Tathagat, & Piyush Varma. (2020). *Unraveling Urban Household Energy Use Patterns in India*. [https://www.clasp.ngo/wp-content/uploads/2021/04/Unraveling-urban-household-energy-use-patterns-in-India\\_ACEEE-2020.pdf](https://www.clasp.ngo/wp-content/uploads/2021/04/Unraveling-urban-household-energy-use-patterns-in-India_ACEEE-2020.pdf)
- TCDD Taşımacılık. (2018). *2018 İstatistik Yilligi*. <https://www.tcddtasimacilik.gov.tr/uploads/images/Strateji/TCDD-T-2018-istatistik-yilligi.pdf>
- TCDD Taşımacılık. (2023). *2022 Yılı Faaliyet Raporu*. [https://adminapi.tcddtasimacilik.gov.tr/files/pdfs/TCDD-Tasimacilik-2022-Faaliyet-Raporu\[26218\].pdf](https://adminapi.tcddtasimacilik.gov.tr/files/pdfs/TCDD-Tasimacilik-2022-Faaliyet-Raporu[26218].pdf)
- TERI. (2018). *Benefits of Cycling in India: An Economic, Environmental, and Social Assessment*. <https://www.teriin.org/sites/default/files/2020-06/benefits-cycling-report.pdf>
- Teske, S. (Ed.). (2019). *Springer eBook Collection. Achieving the Paris Climate Agreement goals: Global and regional 100% renewable energy scenarios with non-energy GHG pathways for +1.5°C and +2°C*. Springer International Publishing. <https://link.springer.com/book/10.1007/978-3-030-05843-2> <https://doi.org/10.1007/978-3-030-05843-2>
- Transnet. (2021a). *Transnet Freight Rail 2021*. <https://www.transnet.net/InvestorRelations/AR2021/Transnet%20Freight%20Rail.pdf>
- Transnet. (2021b). *Transnet Freight Rail*. <https://www.transnet.net/InvestorRelations/AR2021/Transnet%20Freight%20Rail.pdf>
- Transport & Environment. (January 2021a). *Cars CO2 review: Europe's chance to win the mobility race*. <https://www.transportenvironment.org/discover/car-co2-review-europes-chance-win-mobility-race/>
- Transport & Environment. (2021b). *How to decarbonise long-haul trucking in Germany. An analysis of available vehicle technologies and their associated costs*. [https://www.transportenvironment.org/wp-content/uploads/2021/07/2021\\_04\\_TE\\_how\\_to\\_decarbonise\\_long\\_haul\\_trucking\\_in\\_Germany\\_final.pdf](https://www.transportenvironment.org/wp-content/uploads/2021/07/2021_04_TE_how_to_decarbonise_long_haul_trucking_in_Germany_final.pdf)
- Tschöke, H., Gutzmer, P., & Pfund, T. (2019). *Elektrifizierung des Antriebsstrangs*. Springer Berlin Heidelberg. <https://doi.org/10.1007/978-3-662-60356-7>

- Tsoi, K. H., Loo, B. P. Y., Li, X., & Zhang, K. (2023). The co-benefits of electric mobility in reducing traffic noise and chemical air pollution: Insights from a transit-oriented city. *Environment International*, 178, 108116. <https://doi.org/10.1016/j.envint.2023.108116>
- TUMI. (2019). *Sustainable Urban Transport: Avoid-Shift-Improve (A-S-I)*. [https://www.transformative-mobility.org/wp-content/uploads/2023/03/ASI\\_TUMI\\_SUTP\\_iNUA\\_No-9\\_April-2019-Mykme0.pdf](https://www.transformative-mobility.org/wp-content/uploads/2023/03/ASI_TUMI_SUTP_iNUA_No-9_April-2019-Mykme0.pdf)
- Turgut Mehmet Burak. Regional economic activity in Turkey: A new economic geography approach. *Turkish Economic Association*. <https://www.econstor.eu/bitstream/10419/130140/1/780089650.pdf>
- Turkish Statistical Institute. (2022). *Length of railways, train kilometers, tonne kilometers and freight transport*. <https://data.tuik.gov.tr/Bulten/DownloadIstatistikselTablo?p=3DZt3pteTOASVDvyKvG2OIAS4e0YYfF9utBW/HGPNut6gydY3JuOpiwSwxaTrH6y>
- TurkStat. (2023a). *Data Portal For Statistics: Gross domestic product at current prices by kind of economic activity (A21) (value, share, percentage change), at current prices, 1998-2021* [Press release].
- TurkStat. (2023b). *Data Portal For Statistics: Length of railways, train kilometers, tonne kilometers and freight transport* [Press release]. <https://data.tuik.gov.tr/Kategori/GetKategori?p=Ulastirma-ve-Haberlesme-112>
- U.S. Energy Information Administration. *Today in Energy*. <https://www.eia.gov/todayinenergy/detail.php?id=54639#:~:text=U.S.%20electricity%20customers%20averaged%20seven%20hours%20of%20power%20interruptions%20in%202021>
- UIC. (2017). *Railway Handbook 2017*. [https://uic.org/IMG/pdf/handbook\\_jea-uic\\_2017\\_web3.pdf](https://uic.org/IMG/pdf/handbook_jea-uic_2017_web3.pdf)
- Ulaştırma Etütleri Şubesi Müdürlüğü. (2022). *On Highways Heavy Vehicle Traffic And Load Transportation Features And Trends*. [https://www.kgm.gov.tr/SiteCollectionDocuments/KGMdocuments/Yayinlar/YayinPdf/Karayollar%C4%B1ndaAgirTasitTrafigininveYukTasimac%C4%B1ligininOzellikleriveE%C4%9Filimleri\(2015-2020\).pdf](https://www.kgm.gov.tr/SiteCollectionDocuments/KGMdocuments/Yayinlar/YayinPdf/Karayollar%C4%B1ndaAgirTasitTrafigininveYukTasimac%C4%B1ligininOzellikleriveE%C4%9Filimleri(2015-2020).pdf)
- UNFCCC. *Nationally Determined Contributions (NDCs)*. <https://unfccc.int/process-and-meetings/the-paris-agreement/nationally-determined-contributions-ndcs>
- US Census Bureau. (2019a). *Commuting Characteristics by Sex*. American Community Survey. <https://data.census.gov/table?q=S0801:+COMMUTING+CHARACTERISTICS+BY+SEX&tid=ACST1Y2019.S0801>
- US Census Bureau. (2019b). *Types of computers and internet subscriptions*. American Community Survey. <https://data.census.gov/table?q=internet>
- Utikad. (2022). *UTİKAD Lojistik Sektörü Raporu 2021*. <https://www.utikad.org.tr/images/HizmetRapor/utikadlojistiksektoruraporu2021-1654.pdf>
- Vayre, É., Morin-Messabel, C., Cros, F., Maillot, A.-S., & Odin, N. (2022a). Benefits and Risks of Teleworking from Home: The Teleworkers' Point of View. *Information*, 13(11). <https://doi.org/10.3390/info13110545>
- Vayre, É., Morin-Messabel, C., Cros, F., Maillot, A.-S., & Odin, N. (2022b). Benefits and Risks of Teleworking from Home: The Teleworkers' Point of View. *Information*, 13(11). <https://doi.org/10.3390/info13110545>
- Waldemar Marz, & Suphi Sen. (2021). *Does Telecommuting Reduce Commuting Emissions?* CESifo. <https://www.cesifo.org/en/publications/2021/working-paper/does-telecommuting-reduce-commuting-emissions>
- Wassiliadis, N., Steinsträter, M., Schreiber, M., Rosner, P., Nicoletti, L., Schmid, F., Ank, M., Teichert, O., Wildfeuer, L., Schneider, J., Koch, A., König, A., Glatz, A., Gndlgruber, J., Kröger, T., Lin, X., & Lienkamp, M. (2022). Quantifying the state of the art of electric powertrains in battery electric vehicles: Range, efficiency, and lifetime from component to system level of the Volkswagen ID.3. *ETransportation*, 12, 100167. <https://doi.org/10.1016/j.etrans.2022.100167>

- The World Bank. (2020). *Turkey's Rail Connectivity and Logistics will Improve with World Bank Financing* [Press release]. <https://www.worldbank.org/en/news/press-release/2020/06/30/turkeys-rail-connectivity-and-logistics-will-improve-with-world-bank-financing>
- The World Bank. (2023a). *Countries and Economies*. <https://data.worldbank.org/country/>
- The World Bank. (2023b). *Turkey Overview: Developments news, research, data*. <https://www.worldbank.org/en/country/turkey/overview>
- World Development Indicators database. *Labor force, total*. World Bank. <https://data.worldbank.org/indicator/SL.TLF.TOTL.IN?locations=US>
- Worldometer. (2023). *Largest Countries in the World (by area)*. <https://www.worldometers.info/geography/largest-countries-in-the-world/>
- WRI. (2019). *Enhancing NDCs: Opportunities in Transport*. <https://files.wri.org/d8/s3fs-public/enhancing-ndcs-opportunities-transport.pdf>
- Yang, X., Shao, C., Zhuge, C., Sun, M., Wang, P., & Wang, S. (2021). Deploying battery swap stations for shared electric vehicles using trajectory data. *Transportation Research Part D: Transport and Environment*, 97, 102943. <https://doi.org/10.1016/j.trd.2021.102943>
- Yao Shi, Steve Sorrell, & Timothy Foxon (2023). The impact of teleworking on domestic energy use and carbon emissions: An assessment for England. *Energy and Buildings*, 287, 112996. <https://doi.org/10.1016/j.enbuild.2023.112996>
- Zhang, Y., Zhao, N., Li, M., Xu, Z., Wu, D., Hillmansen, S., Tsolakis, A., Blacktop, K., & Roberts, C. (2023). A techno-economic analysis of ammonia-fuelled powertrain systems for rail freight. *Transportation Research Part D: Transport and Environment*, 119, 103739. <https://doi.org/10.1016/j.trd.2023.103739>

## PARTICIPANTS



NDC ASPECTS project has received funding from the European Union's Horizon 2020 Research and Innovation programme under grant agreement No 101003866



**NDC ASPECTS**

[www.ndc-aspects.eu](http://www.ndc-aspects.eu)

@ndcaspects



@ndcaspects

