Analysis of passenger car tailpipe emissions in different world regions up to 2050

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Abstract

This study presents the carbon dioxide (CO\textsubscript{2}), particulate matter (PM\textsubscript{2.5}) and nitrogen oxides (NO\textsubscript{x}) tailpipe emission analysis of passenger cars in 9 different world regions up to 2050 based on a bottom-up calculation method. A diffusion model which considers current policy electrification targets is used to analyze market entry and development of different drivetrain/fuel technologies in the respective vehicle stocks of each world region. Drivetrain- and country-specific emission factors are weighted according to the modelled stock compositions. The obtained stock-fleet-average emission factors are multiplied with the transport demand in order to obtain total passenger car emissions which are then spatially distributed using proxy raster emission data.

The results of this study reveal that global passenger car CO\textsubscript{2}, NO\textsubscript{x} and PM\textsubscript{2.5} emissions decrease from 2015 until 2050 by approx. 45%, 63% and 54%, respectively. The market analysis indicates that gasoline will continue to be a significant energy carrier in 2050 with a stock share of approx. 25%; however, electric vehicles will take the lead, especially after 2040. Furthermore, China and Europe stay as advancing markets for passenger car fleet electrification, while the majority of developing countries follow up with low shares. It can be obtained that even if the passenger car fleets become cleaner, an increase of the transport demand can dampen or even nullify the total emission reduction effect. As a conclusion, the bottom-up approach enables to quantify passenger car emissions in a transparent way. However, challenges exist regarding the uncertainty caused by lacking data availability.

1 Introduction

Anthropogenic greenhouse gas (GHG) and pollutant emissions need to be reduced in order to mitigate climate change and further environmental issues like air quality in urban areas. Transportation is of particular interest as it is one of the major emissions-causing sectors. According to International Energy Agency (2019), in 2019 transportation accounted for 15% of global GHG emissions. Road transport is largely responsible for this, accounting for two-thirds of transport-related CO\textsubscript{2}-eq emissions. Consequently, passenger cars take on a significant role as they constitute the essential share of road transportation.

In order to analyze energy use, land use and emissions of relevant sectors and their impacts on climate change, the Shared Socioeconomic Pathways (SSPs) scenario framework has been established. The SSPs describe plausible and internally consistent views of society's future in terms of demographic, economic, technological, social political, and environmental factors in 5 narratives which lead in various challenges of climate change mitigation and adaption (O'Neill et al. 2017): SSP1 – Sustainability, SSP2 – Middle of the Road, SSP3 – Regional Rivalry, SSP4 – Inequality, SSP5 – Fossil-fueled Development. Riahi et al. (2017) gives a detailed and comprehensive overview of the SSPs. Based on these pathways, several large scenario studies have been conducted for the IPCC Assessment Reports (Riahi et al. 2017). In this context, Integrated Assessment Models (IAMs) are used to comprehensively assess the global energy, economic, land, climate and environmental systems (van Vuuren et al. 2011). For work with IAMs, the SSP scenarios are coupled with climate targets via Representative Concentration Pathways (RCPs) to provide a unified framework for socioeconomic developments and the level of GHG emissions to be achieved. They support modelers to improve the comparability of results and to account for uncertain state-of-knowledge developments, such as population growth, food preferences, environmental awareness or international cooperation (O’Neill et al. 2014).
IAMS can map a wide range of possible future scenarios and their linkages to technical and socioeconomic developments and policy decisions. However, they barely enable a differentiated analysis of specific subsectors, modes, markets, countries or technologies. For instance, according to van Vuuren et al. (2017) global passenger car travel demand will significantly increase from 2010 till 2050, especially within the SSP2 scenario. But, the impacts of increasing activity levels on passenger car energy demand and emissions vary depending on particularly the degree and pace of the circulation of electrified drivetrain technologies which enable high energy efficiencies and reduced or zero tailpipe emissions. The technological development of passenger car fleets, in turn, varies depending on vehicle market mechanisms and political targets in the various countries or regions. Also, the boundary conditions on the passenger car markets have significantly changed in recent years for instance due to advanced battery technology, increased fossil fuel costs and the government plans or regulations on phasing out fossil fuel vehicles all over the globe.

Given these reasons, this study aims at modelling global passenger car emissions from 2015 to 2050 bottom-up in a country-differentiated manner. The selected focus countries are Australia, Brazil, China, Germany, India, Japan, Russia, South Africa and USA. The country selection both includes countries which cover a relevant geographic area globally and also the main vehicle markets which have a leading role in establishing new technology trends like e.g. electrification of drivetrains. Hereby we analyze relevant drivetrain technologies and their development in these countries’ vehicle stock fleets. This is based on diffusion modelling which considers current policy electrification targets to analyze market entry and development of different drivetrain/fuel technologies in the respective vehicle stocks of each country. Further, drivetrain- and country-specific emission factors are derived and subsequently aggregated according to the modelled stock fleet compositions. The obtained stock-fleet-average emission factors are multiplied with the transport demand in order to obtain total passenger car emissions which are then spatially distributed using proxy raster emission data. For the emissions calculation of the other countries of the world, a cluster approach is considered. Thereby, all countries globally are assigned to one of 9 world regions. It is assumed that each country within one world region has the same stock-fleet-average emission factor, based on the respective focus country analysis. The allocation of countries to world regions is described in Appendix 3. Apart from CO$_2$, NO$_x$ and PM$_{2.5}$ are considered as these pollutant emissions can be relevant not only regarding air quality impact assessment but also for climate modelers in terms of indirect climate effects.

The paper is organized as follows. At first, in the Materials and Methods chapter our bottom-up approach is explained comprehensively (2.1), followed by several sections for the individual inputs going into it, i.e. the drivetrain technology market modelling (2.1.1), the emission factors research (2.1.2 and 2.1.3), the considered transport demand data (2.1.4) as well as the final processing of the emissions data to spatial distributed emission maps (2.2). Next, the results are presented in 4 sections differentiated in passenger car market modelling results (3.1), an overview of the global emissions development per world region (3.2) and the CO$_2$ and pollutant emission analyses per country (3.3 and 3.4). Chapter 4 follows with a Discussion and Conclusion.

2 Materials and Methods

2.1 Bottom-up emission calculation procedure

The annual passenger car emissions for each country were calculated in a bottom up manner at a country level using country specific activity data which is the transport demand as vehicle kilometers for the specified year for
cars and the associated stock-fleet-average emission factors for the country in that year.

\[ E_{t,c,x} = T_{t,c} \times EF_{x,t} \]  \hspace{1cm} (1)

\[ EF_{x,t} = \sum_f m_{t,f} \times ef_{x,f,t} \]  \hspace{1cm} (2)

Where \( E \) is the passenger car emission for pollutant species \( x \) at year \( t \) in country \( c \) which had a composition of \( f \) passenger car drivetrain with market share \( m \) stock fleet shares at that time. This is obtained from the transport demand \( T_{t,c} \), which is the vehicle km and the fleet-average emission factor \( EF_{x,t} \) in grams per km driven. The fleet-average emission factor is the emission factors \( ef \) in the year \( t \) for a given pollutant species and drivetrain (drivetrain specific emission factors) weighted by the market share \( m \) of the stock of drivetrain \( f \) in the country. It is assumed in this method that all cars of all drivetrains have the same activity level and are uniformly distributed spatially within the country imitating the national stock split which may not be true given regional differences which needs to tackled in a future work.

The annual country specific emissions were then spatially distributed across the country grid by using a spatial proxy as further described in 2.2.

### 2.1.1 Market development of drivetrain technologies

In 2021, the electric vehicle market share in new passenger car registration exceeded 15% in Germany and China, two of the world’s biggest automotive markets, according to Marklines (2022). However, the crucial factor for reducing passenger car emissions is the proportion of these vehicles in the overall vehicle stock. Despite widespread attention to electric vehicles (EVs), their share in the global passenger car fleet remains at only approximately 1.4% (International Energy Agency 2022), with a significant concentration of EVs in China, the USA, and EU countries. To achieve a significant reduction in global emissions, it is crucial to extend the EV transformation beyond a few countries and expand it worldwide. As discussed in Section 2.1.4, transportation demand is expected to increase in some developing countries such as India and Brazil, while it will be nearly constant in European countries. However, the number of electric cars in stock is negligible at the moment in those countries, as can be seen in Fig. 1.

In order to effectively assess the emissions of vehicles in the stock, it is crucial to analyze the powertrain distribution of the vehicles in question. Although many different sources are available for the diffusion of alternative powertrains, it is difficult to find a centralized analysis that covers many different regions individually and is updated frequently to cover new industry development, such as the EU internal combustion engine (ICE) ban (European Comission 2022). Therefore, for this study, we used our function to able to cover the recent developments in the industry.

The literature generally suggests that the market penetration of electric vehicles will follow an S-shaped curve, leading to numerous studies that utilize this method to analyze the market development of electric vehicles (Plötz et al. 2014; Collett et al. 2021; Rietmann et al. 2020). Where the data is available, the S-shaped logistic growth
functions are applicable to models of various scales and complexities, ranging from elementary particles to the evolution of starts because of their fractal characteristics (Kucharavy and Guio 2011). As a result, the S-curve logistic growth function has been utilized in previous studies to analyze the growth of alternative powertrain shares across various regions globally (Teske 2019; Rietmann et al. 2020). The function used to estimate the stock share development of alternative powertrains is presented in Eq. 3. \( S_{c,p,t} \) is the share of powertrain \( p \) in country \( c \) at time \( t \). \( S_{0,c,p} \) is the share of related powertrain at the time zero (2015 in our model). \( \Delta_{c,p} \) is the target share of the powertrain in country \( c \). \( \gamma_c \) is the \( y \) is the growth rate parameter of the country based on the target year and \( A \) is a scaling parameter that determines the initial growth rate of the market of the curve. More details about the functions are given in Appendix 1.

\[
S_{c,p,t} (\text{unnormed}) = S_{0,c,p} + \frac{\Delta_{c,p}}{1 + A \cdot e^{\gamma_c(t-t_0)}}
\]

(3)

\[
S_{c,p,t} = \frac{S_{c,p,t} (\text{unnormed})}{\sum_p S_{c,p,t} (\text{unnormed})}
\]

As the development of the vehicle stock depends on many different variables, from prices to infrastructure availability, Eq. 3 will be able to provide limited explanation and flexibility about the electric vehicles’ fleet development. Therefore, later we compared our results with different sources to ensure that our calculations were in parallel with the current literature and to discuss discrepancies. The main input in the current model is the target shares. Those target shares in the model are based on the announced targets from the government of selected countries or analyses from different studies. Table 1 shows the target shares used in the model and the sources those shares are based on.
Table 1
Electrification targets used in the model and the sources the values are based on

<table>
<thead>
<tr>
<th>Region/Country</th>
<th>Target stock BEV share</th>
<th>Target Year</th>
<th>Literature considered</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td>70%</td>
<td>2065</td>
<td>65% sales in 2050</td>
<td>Bureau of Infrastructure, Transport and Regional Economics 2019</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total BEV and PHEV sales share is 30% in 2030</td>
<td>Australian Government Department of Industry, Science, Energy and Resources 2021</td>
</tr>
<tr>
<td>OECD Europe (Germany)</td>
<td>100%</td>
<td>2060</td>
<td>100% BEV in 2035</td>
<td>European Comission 2022</td>
</tr>
<tr>
<td>North America (the USA)</td>
<td>100%</td>
<td>2060</td>
<td>100% government vehicles in 2035</td>
<td>Shepardson and Klayman 2021</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>50% electric vehicle sales share in 2030</td>
<td>The White House 2021</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10 US states are in the ZEV Alliance, where 100% of EV sales were aimed between 2035 and 2050.</td>
<td>ZEV Alliance 2021</td>
</tr>
<tr>
<td>China</td>
<td>100%</td>
<td>2060</td>
<td>Net 0 in 2060</td>
<td>Bloomberg News 2022</td>
</tr>
<tr>
<td>India</td>
<td>75%</td>
<td>2070</td>
<td>30% sales in 2030 and 75% in 2050</td>
<td>Kamboj et al. 2022</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>15–20% sales in 2030</td>
<td>Jain et al. 2022</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>EV stock in 2040, 10% in Stated Policies Scenario and</td>
<td>The International Energy Agency 2022</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>60% in Sustainable Development Scenario</td>
<td></td>
</tr>
<tr>
<td>Japan</td>
<td>60%</td>
<td>2050</td>
<td>100% HEV or EV sales in 2030</td>
<td>Nikkei 2020</td>
</tr>
<tr>
<td>Africa (South Africa)</td>
<td>65%</td>
<td>2070</td>
<td>40% fleet will be EV by 2050</td>
<td>Goosen 2022</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>50% stock share in 2050</td>
<td>Chege 2022</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>80% new sales are EV in 2045</td>
<td>Ahjum et al.</td>
</tr>
<tr>
<td>South America (Brazil)</td>
<td>15%</td>
<td>2050</td>
<td>61% hybrid, 11% BEV fleet in 2050</td>
<td>Feil and Alex Sandro 2020</td>
</tr>
<tr>
<td>Eastern Europe (Russia)</td>
<td>10%</td>
<td>2055</td>
<td>10% sales in 2030</td>
<td>Russia Briefing 2021</td>
</tr>
</tbody>
</table>

2.1.2 CO₂ emission factors

CO₂ emission factors are computed based on the transport scenario model TRAEM (Transport Energy Model) which gives passenger car energy intensity figures from 2015 to 2050 differentiated per drivetrain technology and
world region, assuming that energy efficiency improves over time. The energy intensity data were derived from the German Aerospace Centre (DLR) vehicle databases and the state-of-the-art literature (Teske 2019). According to the considered country clustering, it is assumed that within each world region all countries have the same CO₂ emission factors (cf. Appendix 3). For each country, the emission factors per drivetrain technology are then weighted according to the vehicle stock shares of each drivetrain technology (cf. section 3.1) which results in stock-fleet-average CO₂ emission factors.

Following Eq. 4 is derived based on Economic Commission for Europe of the United Nations (UN/ECE) (2012) to calculate the specific CO₂ emission factors.

\[
 e_{CO2,d,f,t} = e_{c,d,f,t} * (1 - b) * r * \frac{1}{LHV_f} * \frac{\rho_f}{c_f} * \frac{1}{0.273}
\]

(4)

Where \( e_{CO2,d,f,t} \) is the drivetrain (\( d \)), fuel (\( f \)) and time (\( t \)) -specific CO₂ emission factor which is calculated based on fuel consumption. This can be obtained from the drivetrain and fuel -specific energy consumption per year (\( e_{c,d,f,t} \)), from which a biofuel rate \( b \) is subtracted in order to only regard the fossil fuel share; an on-road fuel economy gap factor \( r \) which varies between 1.2 and 1.7 is further applied to consider real-world energy consumption and the term is then divided by the lower heating value of the respective fuel (\( LHV_f \)). Further the density of the fuel \( \rho_f \) and a fuel dependent factor \( c_f \) are required. According to UN/ECE (2012) \( c_f \) is 0.118 for petrol fueled vehicles, 0.116 for diesel vehicles and 0.1336 for CNG vehicles. The applied biofuel rate values in Eq. 4 are also based on TRAEM data for the reference scenario (Teske 2019) and can be found in appendix 2.

The resulting region- and drivetrain-specific CO₂ emission factors for the base years 2015, 2030 and 2050 are presented in Table 2.
<table>
<thead>
<tr>
<th>Region/Country</th>
<th>Year</th>
<th>CO₂ EF [g/km]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>G</td>
</tr>
<tr>
<td>Australia</td>
<td>2015</td>
<td>174.7</td>
</tr>
<tr>
<td></td>
<td>2030</td>
<td>127.9</td>
</tr>
<tr>
<td></td>
<td>2050</td>
<td>96.1</td>
</tr>
<tr>
<td>South America (Brazil)</td>
<td>2015</td>
<td>177.7</td>
</tr>
<tr>
<td></td>
<td>2030</td>
<td>142.0</td>
</tr>
<tr>
<td></td>
<td>2050</td>
<td>120.1</td>
</tr>
<tr>
<td>China</td>
<td>2015</td>
<td>138.2</td>
</tr>
<tr>
<td></td>
<td>2030</td>
<td>109.0</td>
</tr>
<tr>
<td></td>
<td>2050</td>
<td>82.7</td>
</tr>
<tr>
<td>OECD Europe (Germany)</td>
<td>2015</td>
<td>147.6</td>
</tr>
<tr>
<td></td>
<td>2030</td>
<td>136.7</td>
</tr>
<tr>
<td></td>
<td>2050</td>
<td>117.8</td>
</tr>
<tr>
<td>India</td>
<td>2015</td>
<td>223.8</td>
</tr>
<tr>
<td></td>
<td>2030</td>
<td>150.3</td>
</tr>
<tr>
<td></td>
<td>2050</td>
<td>112.8</td>
</tr>
<tr>
<td>Japan</td>
<td>2015</td>
<td>174.7</td>
</tr>
<tr>
<td></td>
<td>2030</td>
<td>127.9</td>
</tr>
<tr>
<td></td>
<td>2050</td>
<td>96.1</td>
</tr>
<tr>
<td>Eastern Europe (Russia)</td>
<td>2015</td>
<td>176.1</td>
</tr>
<tr>
<td></td>
<td>2030</td>
<td>149.3</td>
</tr>
<tr>
<td></td>
<td>2050</td>
<td>117.7</td>
</tr>
<tr>
<td>Africa (South Africa)</td>
<td>2015</td>
<td>200.9</td>
</tr>
<tr>
<td></td>
<td>2030</td>
<td>164.3</td>
</tr>
<tr>
<td></td>
<td>2050</td>
<td>130.8</td>
</tr>
<tr>
<td>North America (USA)</td>
<td>2015</td>
<td>268.1</td>
</tr>
<tr>
<td></td>
<td>2030</td>
<td>165.9</td>
</tr>
<tr>
<td></td>
<td>2050</td>
<td>94.3</td>
</tr>
</tbody>
</table>
2.1.3 Pollutant emission factors

Nine selected countries are analyzed in detail to obtain passenger car drivetrain-specific emission factors for two pollutant species, PM$_{2.5}$ and NO$_x$. It is assumed that each of the countries represent a respective world region. For each country, the emission factors per drivetrain technology are then weighted according to the vehicle stock shares of each drivetrain technology (cf. section 3.1) which results in stock-fleet-average emission factors. Each of the representative countries’ fleet-average emission factors are allocated to the remaining countries of the associated world region according to the country clusters described in Appendix 3. Different approaches and data sources are considered for estimating the drivetrain-specific emission factors of each analyzed country. Table 3 summarizes the studied countries and the methods and references for the derivation of the pollutant emission factors.

Generally, the pollutant emission factors of gasoline and diesel hybrid electric vehicles (G-HEV and D-HEV) are set equal to their conventional gasoline and diesel fueled vehicles for each country. Plug-in hybrid electric vehicles’ (PHEV) emission factors are estimated according to the Germany-based emission factor ratio between conventional gasoline/diesel vehicles and corresponding gasoline/diesel PHEVs. Therefore, PHEV emission factors are derived dependent on the emission factor development of the conventional vehicles in each country. Compressed natural gas (CNG) fueled vehicles’ pollutant emission factors are based on the data sources for Germany, except India for which country-specific data is considered.
Table 3
Overview of the pollutant emission factor estimation methods for the studied countries.

<table>
<thead>
<tr>
<th>Region/Country</th>
<th>Pollutant EF estimation method/model</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td>EF weighting according to Euro class fleet shares; Estimation of the composition of the vehicle fleet by Euro classes based on the time lag of the introduction of the Euro-classes-corresponding Australian standards compared to Europe.</td>
<td>(Infras 2019)</td>
</tr>
<tr>
<td>South America</td>
<td>Based on the São Paulo official vehicular emissions inventory (CETESB) and the stock distribution of vehicles by age of use (VEIN model)</td>
<td>(Environmental Agency of São Paulo State 2019) (Ibarra-Espinosa et al. 2018)</td>
</tr>
<tr>
<td>China</td>
<td>Based on literature and Euro-class based data</td>
<td>(Wu et al. 2017); (Infras 2019)</td>
</tr>
<tr>
<td>OECD Europe</td>
<td>Based on the HBEFA 4.1 database</td>
<td>(Infras 2019)</td>
</tr>
<tr>
<td>India</td>
<td>Based on literature</td>
<td>(Goel and Guttikunda 2015)</td>
</tr>
<tr>
<td>Japan</td>
<td>Based on literature and Euro-class based data</td>
<td>(Kurokawa and Ohara 2020); (Infras 2019);</td>
</tr>
<tr>
<td>Eastern Europe</td>
<td>EF weighting according to Euro class fleet shares; Estimation of the composition of the vehicle fleet by Euro classes based on literature and the time lag of the introduction of the Euro-classes in Russia compared to Europe.</td>
<td>(Infras 2019; Ginzburg et al. 2019)</td>
</tr>
<tr>
<td>Africa</td>
<td>EF weighting according to Euro class fleet shares; Estimation of the composition of the vehicle fleet by Euro classes based on literature and the time lag of the introduction of the Euro-classes in South Africa compared to Europe.</td>
<td>(Infras 2019); (Thambiran and Diab 2011);</td>
</tr>
<tr>
<td>North America</td>
<td>Based on the EMFAC2017 database</td>
<td>(CARB 2017)</td>
</tr>
</tbody>
</table>

Germany

Emission factors for German passenger cars are obtained from the Emission factors for Road Transport Handbook (HBEFA). The emission factor values are differentiated according to the emission species ($NO_x$, $PM_{2.5}$), the calendar years (2015–2050), the drivetrain/fuel types (gasoline, diesel, CNG, G-HEV, D-HEV, G-PHEV, D-PHEV), the Euro classes (Pre-Euro till Euro 6) and the traffic situation/road type (urban, rural, motorway). For the weighting of the emission factors, Euro class stock shares are taken from HBEFA, drivetrain/fuel stock shares
come from our own modelling (cf. section 3.1) and traffic situation/road type shares are obtained from the project *Transport and the Environment* (VEU) (Matthias et al. 2020).

Australia, Russia and South Africa

For the countries Australia, Russia and South Africa, no publicly available country-specific emission factor data sources are available. As in these countries the vehicle pollutant emissions are regulated based on the European standards, the base approach of obtaining stock-fleet average emission factors is the estimation of the composition of the gasoline and diesel vehicle stocks by Euro classes. This is based on information from the literature and/or the time lag of the introduction of the Euro standards in the respective country, considering the Euro-class based passenger car stock composition and emission factors from Germany (Infras 2019) as baseline. Figure 2 presents the resulting gasoline and diesel passenger car stock compositions according to Euro classes from 2015–2050 in Australia, Russia and South Africa.

In Australia, the Euro 5 and Euro 6 stages have been introduced via the Australian Design Rules (ADR) ADR79/03, ADR79/04, and ADR79/05. Full Euro 5 requirements were applied since November 2016, while the introduction of Euro 5 in the EU was in January 2010. Euro 6 came into effect in July 2018 in Australia, which corresponds to a delay of about 3.5 years compared to the original introduction date. Previous Euro stages were also introduced with a delay of approx. 5 years in Australia compared to the EU (DieselNet; Ntziachristos and Samaras 2019). Based on these findings, Australian’s petrol and diesel passenger car fleet compositions are estimated based on Germany’s fleet compositions considering a delay of 5–10 years.

In Russia, the most recent emission standard adopted is Euro 5 which has been implemented between 2014 and 2016. Based on information from literature on the Russian passenger car stock composition in 2015 (Ginzburg et al. 2019) and assuming a delay of 5–10 years between Russia’s and Germany’s fleet compositions, the development showed in Fig. 2 is obtained.

In 2008, South Africa’s petrol and diesel passenger car fleets mainly existed of Pre-Euro (or Euro 0 as displayed in Fig. 2) and Euro 1 vehicles (Thambiran and Diab 2011). Euro 2 is the most recent emission standard that has been introduced between 2006 and 2008 (BorgWarner). Considering this information and additionally assuming a delay of approx. 20 years between the development of the passenger car stock of South Africa and Germany, South Africa’s stock composition between 2015 and 2050 is estimated.

China

Mean PM$_{2.5}$ and NO$_x$ emission factors for gasoline passenger cars in China, which constitute approx. 90% of the stock fleet in 2015 (cf. Figure 5), are obtained from literature (Wu et al. 2017). The values are given for calendar years between 2015 and 2030. Values between 2030 and 2050 are estimated based on the corresponding pollutant emission factor development trends in Germany, assuming similar technological trends between the two countries. Emission factors for diesel and CNG vehicles are taken from Germany’s HBEFA based values. As both drivetrains have negligible stock fleet shares during the whole timeline, no significant bias is to be expected from this assumption.

Japan
Average \( \text{PM}_{2.5} \) and \( \text{NO}_x \) emission factor values for Japanese gasoline and diesel passenger cars in 2015 are taken from Kurokawa and Ohara (2020). The yearly development of the average pollutant emission factors for the Japanese gasoline and diesel passenger car stock fleets is assumed to be similar to the corresponding development in Germany. Therefore, emission factor values for the remaining years are derived by applying Germany’s gasoline and diesel vehicle-fleet-based pollutant emission factor development trends. Average CNG passenger car emission factors for Germany are applied.

India

Mean \( \text{PM}_{2.5} \) and \( \text{NO}_x \) emission factors for gasoline, diesel and CNG passenger cars in the greater Delhi region based on Goel and Guttikunda (2015) are considered as representative data for India. Emission factor values are given for the years 2012 and 2030. By interpolation, values for the years in between are obtained. Then, the emission factor development trend is extrapolated till 2050.

Brazil

Country-specific \( \text{PM}_{2.5} \) and \( \text{NO}_x \) emission factors for passenger cars fueled with gasoline, ethanol or various blending ratios of both fuels, with flex-fuel engines, can be found in the VEIN book as described from Ibarra-Espinosa et al. (2018). The Brazilian emission factors origin from the São Paulo official vehicular emissions inventory from the Environmental Agency of São Paulo State (2019) which basically publish the FTP-75 certification test results as an averaged database by type of vehicle and year. For this study, emission factors for vehicles registered in 1982 or before until registration year 2017 are considered. As the emission factors are available per registration year, the age distribution of the vehicle stock fleet is derived based on data of the estimate of the vehicle stock in 2017, which is also obtained from the Environmental Agency of São Paulo State (2019). Assuming that the oldest vehicles in use are 30 years old, fleet-average emission factors per calendar year and fuel/drivetrain type can therefore be calculated. As a result, average emission factors until calendar year 2017 for

- passenger cars using gasoline blended with 25% of ethanol,
- passenger cars with engines that use pure ethanol,
- passenger car with flex-fuel engines using gasoline blended with 25% of ethanol and
- passenger cars with flex-fuel engines that use pure ethanol

are obtained. In order to yield one average emission factor for passenger cars with gasoline engines, first the flex-fuel emission factors are weighted by assuming a 50–50 share, as no further information on ethanol fuel shares of flex-fuel vehicles are available. Next, ethanol and flex-fuel vehicles are weighted according to their estimated stock fleet shares. Emission factors for two groups of gasoline engine vehicles are obtained, one with ethanol shares of 25% and less and one with higher ethanol shares. According to S&P Global Mobility statistical data on new vehicle registrations in Brazil, between 2016 and 2018, 95% of the new vehicles are flex-fuel or ethanol vehicles, while 5% are (mainly) gasoline fueled passenger cars (S&P Global Mobility 2018). As a simplified approach, these percentages are assumed as weighting factors in order to result in one average gasoline passenger car emission factor. The gasoline vehicle emission factors for the years between 2017 and 2050 are calculated by extrapolating the corresponding emission factor trends of the 2010–2017 timeframe. The mean emission factors for the diesel and CNG based drivetrains are used basing on the data for the German vehicle
As gasoline-based vehicles are predominant in Brazilians’ vehicle stock fleet throughout the considered timeframe, no significant bias is expected form this simplified assumption.

**USA**

Emission factors for gasoline and diesel passenger cars are received from the EMFAC2017 web database (CARB 2017). EMFAC is a model that estimates the official emissions inventories of on-road vehicles in California. Besides total emissions, emission factors (or emission rates, as termed in the database) can be selected as datatype. As region, “statewide” is chosen as the most comprehensive option. 2015, 2020, 2030, 2040 and 2050 are chosen as the base calendar years. Annual values are needed, all fuel types and aggregated values in terms of vehicle model years and speeds. After all selections are completed, the data can be computed and exported via .csv format. EMFAC gives out emission factors for different activities or operating conditions. In this study, running exhaust emissions are considered, expressed in g/mile. The emission factors are then calculated in per km values. For CNG vehicles, which have < 1% stock fleet share (Fig. 5), emission factors from Germany are applied.

Appendix 4 contains the considered PM\(_{2.5}\) and NO\(_x\) emission factors per studied country and per drivetrain technology for the three base years 2015, 2030 and 2050.

### 2.1.4 Transport demand

Emissions from transportation are strongly related to transport demand. Therefore, estimating the emissions until 2050 is not possible without estimating the total km driven until that year. For this analysis, we used the global transport demand estimated for each country (Seum and Eisenmann 2020). Figure 3 illustrates the global passenger car transport demand of the regions used in this analysis (countries in each region can be seen in Appendix 3). The graph shows that currently, most of the travel demand by cars comes from North America and Europe. However, in 2050 role of these regions will be smaller with the increasing demand of India and China. Therefore, an effective strategy to reduce the global emissions from passenger cars is only possible with developing countries involved.

In addition to the transportation demand, the powertrain and fuel types of the vehicles are also critical. Electrified vehicles emit significantly lower amounts of or zero greenhouse gas and pollutant tailpipe emissions. Also, gasoline and diesel vehicles can perform significantly differently depending on their emission class or age of use and the considered emission types. Therefore, to be able to analyze emissions from transportation in 2050, we estimated the shares of the different powertrains in the passenger transport demand in the future (section 3.1).

To estimate the travel demand for passenger cars with different powertrain options, we assume that transport demand shares of powertrains will be based on the stock shares of those vehicles. Therefore, the future development of travel behaviors of car owners from different powertrains is beyond this paper’s scope.

### 2.2 Spatial emission disaggregation

The passenger car emission data are aggregated for each country. To locate the emissions spatially, we designed a geodata model (Fig. 4). The inputs for the model are (i) the approximated emissions per country, (ii) gridded proxy emissions (Janssens-Maenhout et al. 2019), consisting of the same emission species and (iii) vector polygons representing country borders (naturalearthdata). The proxy emissions are based on a combination of road type, road length and population within each pixel.
For each species and year, the following steps are carried out: Country emissions $E$ based on the current paper work are written into the attributes of the respective polygons. Within the coverage of each country, the proxy emissions $PE$, are aggregated building a country sum. A new raster is generated, using the extend and resolution of the proxy data (0.1°x 0.1° arcseconds). For each cell/pixel in the raster set, emissions are calculated in the following manner:

$$E_{t,c,x,pixel} = \frac{\sum E_{t,c,x}}{\sum PE_{c,x}} \times PE_{c,x,pixel}$$

(5)

The subscript $t$ is for a given year, $pixel$ indicates emission per pixel and $c$ indicates country. The result is a gridded emission dataset stacked over all species and years. The data can be found in the appendices 5–7.

While emission species are well represented in the proxy data, it only refers to a certain year, i.e. 2012. There is currently no fitting model dataset to represent the spatial distribution of road emissions in the future. This can influence the disaggregation as road networks and urban agglomerations might develop strongly in the future, especially in emerging economies leading likely to stronger distributed emissions. Further stressing on this problem is that in 2012 emissions were high in dense urban areas throughout the world. While this is likely to be true in many cities in the future, it is also probable, that – in face of a proceeding global warming – many densely populated areas introduce mitigation plans such as sustainable city planning concepts, which could have a strong impact on actual ICE-emissions. However, such aspects are not considered in this study.

Finally, the distribution of emissions in EDGAR v4.3.2 was mainly accomplished by using OSM road networks, weighted by road types. This is problematic as the coverage and quality of road networks differ greatly through world regions and because road types are inconsistently mapped and build. For instance, a road mapped as a highway in the United States is likely to differ strongly from a highway in India, Brazil or South Africa and it is likely that traffic conditions on those roads differ accordingly. Furthermore, road types alone do not determine traffic flows as for instance highways crossing big cities might bear much heavier traffic flows than e.g. highways connecting distant cities.

### 3 Results

#### 3.1 Passenger car market modelling

The results of the model can be seen in Fig. 5. Our findings show that the OECD Europe with China will continue to lead the electric car transformation. However, even in those countries, under the scenario that governments have ambitious EV targets and where the EV uptake is at most, there will still be a small share of ICE vehicles left in 2050. From the other perspective, with the current regulations and announced government targets, South America and Eastern Europe & Middle East, those represented by Brazil and Russia, respectively, will be the laggards. Because these countries are major energy suppliers in terms of ethanol (Brazil) and crude oil (Russia), it can be expected that the development of the passenger car market will depend strongly on the development of the energy supplies of these countries.
The graph illustrates the projected growth of electric cars in various countries and regions up to 2050. The data shows that OECD Europe is expected to have the highest market share for electric vehicles, followed by China and North America. Notably, countries such as India, Japan, South Africa, and Australia are projected to have comparable market shares, despite the differences in their income levels. In contrast, Eastern Europe, the Middle East, and South America are forecasted to have the smallest market shares. This disparity can be attributed to the fact that these regions possess economies that are heavily reliant on fossil fuels or alternate modes of transportation. This finding implies that the adoption of electric vehicles in these regions may be impacted by both economic and cultural factors.

To ensure the accuracy of our model and avoid any potential bias, we conducted a comparison of our results with various analyses from credible sources. As many sources share their results as electric vehicles where plug-in hybrid electric vehicles and battery electric vehicles are counted together, we used EV shares (BEV + G-PHEV) for comparison. We compared our results for China, Germany, India, the USA, and World with Rietmann et al. (2020), where 26 countries are analyzed, and two different scenarios from International Energy Agency projections (International Energy Agency 2022). As our OECD Europe values are based on Germany, we used the IEA’s forecast for Europe to compare. In addition, we compared our results for Germany with the stock shares forecast by Infras for Handbook Emission Factors for Road Transport (HBEFA) (Infras 2019). Finally, we also add the global analysis from BloombergNEF to compare our findings for the World with their calculations (BloombergNEF 2022). Except for India, our values are slightly lower than Rietmann et al. (2020); however, in general, they are consistent with other studies, particularly for China, India, and the World. It is worth noting that the results of Rietmann et al. (2020) diverge from other analyses. It can be explained that the values in Rietmann et al. are estimated by the historical development of EV shares until 2018, while most of the other studies are more recent and mainly focus on a more extended time period in the future. For example, annual EV sales in India increased from 680 to 48,000 between 2019 and 2022 (International Energy Agency 2022). Therefore, the estimated values for India are lower in Rietmann et al. (2020) compared to the rest of the analyses. Additionally, our study found that the percentage of electric vehicles is slightly higher in Europe and the USA compared to the analysis conducted by IEA and HBEFA. Our results aligned with our expectations as we considered the latest developments in the industry, such as the European ICE ban and the ZEV alliance of US states.

3.2 Overview of global emissions

Figure 7 presents the modelled development of global CO₂, NOₓ and PM₂.₅ emissions per world region and year. Global CO₂ emissions decrease from 3.1 x 10⁹ t in 2015 to 1.7 x 10⁹ t in 2050. Interestingly, the global CO₂ emissions increase from 2015 to 2024, reaching a maximum level of approx. 3.4 x 10⁹ t. Compared to the situation in 2015, global CO₂ emissions start to decrease as late as by 2031. According to Fig. 7 this beginning increasing trend is mainly caused by the China region whose CO₂ emissions increase strongly until end of the 2020 years. Also, world regions like India, South America, Africa and Eastern Europe and Middle East present a continuous equal or even increasing CO₂ emission level over the considered time frame from 2015 till 2050. While in 2015 North America is by far the main CO₂ causing world region, in 2050 its CO₂ figure is about the same as for the India, China and South America world regions. More details on how the several CO₂ emission trends occur will follow in the country-based CO₂ emission analysis in section 3.3 as well as in the Discussion and Conclusion (Chap. 4).
Global NO\textsubscript{x} emissions significantly decrease from $4.3 \times 10^6$ t in 2015 to $1.6 \times 10^6$ t in 2050. This trend is highly influenced by the OECD Europe region which is by far the main NO\textsubscript{x} causer in 2015 while in 2050 its impact is barely visible because of the previous continuous and strong decrease. However, other world regions show different trends, like especially India, whose NO\textsubscript{x} levels increase during the considered timeline and which constitutes the main polluting world region in 2050. This statement is both relevant regarding NO\textsubscript{x} and PM\textsubscript{2.5} emissions. For the latter, global emissions are mainly caused by India and China considering all years. The overall global trend looks similar to the case of CO\textsubscript{2}. Worldwide PM\textsubscript{2.5} levels increase from 2015 ($2.0 \times 10^5$ t) until 2026 ($2.14 \times 10^5$ t) and the emissions fall below 2015 level beginning in 2033. In 2050, global PM\textsubscript{2.5} emissions are modelled as $9.2 \times 10^4$ t. The sections 3.4 and 4 further analyze and discuss the mechanisms leading to the different pollutant emission trends in different world regions, especially focusing on India and China.

### 3.3 CO\textsubscript{2} emissions per country

Figure 8 shows on the left side the development of the stock-fleet average CO\textsubscript{2} emission factors and on the right side the total CO\textsubscript{2} emissions from 2015 till 2050 for the analyzed countries. Fleet average CO\textsubscript{2}-emission factors show for all countries a decreasing trend from 2015 to 2050. The USA are expected to have the strongest decline, being the largest emitter per km in 2015 and the sixth biggest emitter per km in 2050, cutting CO\textsubscript{2} emissions almost 6-fold. Countries with emerging economies such as India, Brazil and South Africa show comparably high emission factors in 2015 and a constant but less steep decline than the USA until 2050. Regarding total passenger car CO\textsubscript{2} emissions, in 2015 the USA are by far the highest emitter due to the described high fleet-average emission factor and also due to the high level of transport demand (cf. Figure 3). While transport demand in the US keeps almost constant till 2050 as for most of the other countries or world regions, transport demand in India, China and South America increases significantly between 2015 and 2050. This leads to India being the highest CO\textsubscript{2} emitter in 2050, followed by the USA, Brazil and China as further major causing countries. The example of China shows that a country with one of the lowest average per-vehicle emissions can be a major causer of total emissions driven by high transport demand. Especially the strong increase of Chinese transport demand between 2015 and approx. 2030 directly translates to the shape of the CO\textsubscript{2} emission curve shown in Fig. 8: There is a steep increase in emissions until 2027, while in the following years until 2050, emissions are decreasing as transport demand stays on a constant level and fleet-average emission factors are decreasing sharply.

The spatially disaggregated CO\textsubscript{2} emissions for various countries are shown in Fig. 9. We expect the development of CO\textsubscript{2} emissions being different for various countries or regions. We predict that CO\textsubscript{2} emissions in USA and Europe (here Germany) decline constantly from 2015 to 2050, from 1173 million t CO\textsubscript{2}/y to 238 million t CO\textsubscript{2}/y in 2050 in the USA and from 92 million t CO\textsubscript{2}/y to 11 million t CO\textsubscript{2}/y in Germany. In China our model shows a constant increase until approx. 2030 peaking in 2027 with an overall emission of 627 million t CO\textsubscript{2}/y. Afterwards CO\textsubscript{2} emissions are expected to decline rapidly to 153 t CO\textsubscript{2}/y in 2050. In India our model shows a reversed development, with increasing CO\textsubscript{2} emissions from 2015 (74 million t CO\textsubscript{2}/y) to 2050 (265 million t CO\textsubscript{2}/y). In Brazil, we predict a slight increase from 152 million t CO\textsubscript{2}/y to 169 million t CO\textsubscript{2}/y, however in contrast to changes in other countries, the increase is not visible in the map.
In all countries the highest emissions per pixel (pixel vary in size depending on the latitude) are in densely populated urban areas. In industrial countries (i.e. USA, Germany) the emissions are wider spatially distributed as in developing economies, mainly connected to well-developed middle and small cities with large PC fleets and dense road networks throughout the countries. In developing economies such as India, China and Brazil urbanization trends are much stronger and road networks are characterized by a strong centrality towards big cities resulting in stronger concentrated emissions in the big urban centers.

### 3.4 NO\(_x\) and PM\(_{2.5}\) emissions per country

Figure 10 presents on the left graph the development of the fleet-average NO\(_x\) emission factors from 2015 to 2050 for each analyzed country. The trend shows a stepwise or constant decline of the average passenger car NO\(_x\) emissions for all countries. The highest values especially before 2030 are obtained for South Africa, Russia, Germany and India that have all major diesel and / or old vehicle shares in their passenger car fleets which is the main cause for high per vehicle NO\(_x\) emissions. The development of NO\(_x\) emissions shows for all countries a decrease from 2015 till 2050 due to declining stock-fleet average emission factors – except for India. Even though the stock-fleet average NO\(_x\) emission factor is declining constantly in India, the transport demand increase is too dominant in order to limit emissions. In China, the trend is different to India, where NO\(_x\) emissions are fluctuating between 2015 and 2023 due to strong transport demand increase and at the same time decreasing vehicle-average emissions while afterwards during the time period until 2050, NO\(_x\) emissions continuously decrease due to very low vehicle-average emissions.

Figure 11 shows spatially disaggregated NO\(_x\) emissions for various countries. NO\(_x\) emissions are relatively high in Germany in comparison to USA – considering the land area difference – due mainly to the share of diesel vehicles in the German PC fleet respectively the high share of gasoline powered PC in the United States, which are strictly regulated in terms of NO\(_x\) emissions. The case of Germany shows that in 2015 NO\(_x\) emissions are concentrated mainly in urban agglomerations. Interestingly, the picture changes significantly already in 2030, which demonstrates the impact of the strictly decreasing stock-fleet average emission factors due to increasing BEV and decreasing diesel shares as well as general fleet modernization by Euro 6 vehicles with more effective exhaust aftertreatment systems. Therefore, in both countries a severe decline in NO\(_x\) emissions is modeled. In Germany the emissions decline from 283 thousand t NO\(_x\)/y in 2015 to 4.5 thousand t NO\(_x\)/y in 2050, a 63-fold decrease. In the USA NO\(_x\) emissions decline from 364 thousand t NO\(_x\)/y to 29 thousand t NO\(_x\)/y in the same period. Similar to the USA and Germany we also modeled a constant but less steep decline in NO\(_x\) emissions in China and in Brazil, in China from 301 thousand t NO\(_x\)/y in 2015 to 28 thousand t NO\(_x\)/y in 2050 and in Brazil from 112 thousand t NO\(_x\)/y to 50 thousand t NO\(_x\)/y. In India, the model predicts a constant increase in NO\(_x\) emissions, from 148 thousand t NO\(_x\)/y in 2015 to 590 thousand t NO\(_x\)/y in 2050.

Figure 12 shows the development of the stock-fleet average PM\(_{2.5}\) emission factors as well as of the total PM\(_{2.5}\) emissions from 2015 till 2050 for the analyzed countries. Stock-fleet average PM\(_{2.5}\) emission factors are predominantly high in India. South Africa's and Russia's passenger car stock also present higher emission factors than the rest of the analyzed countries especially in the beginning years. Even though India's stock-fleet average PM\(_{2.5}\) emissions are decreasing 10-fold from 2015 till 2050, there is still one order of magnitude difference to most of the other, foremost the industrialized countries.
PM$_{2.5}$-emissions emerge similar to the development of NO$_x$ emissions, however particularly high emissions occur foremost in India, South-East Asia (i.e. Thailand, Indonesia, Malaysia), central Asia, in the middle east and on the Arabian Peninsula. India is characterized by an early increase caused by the transport demand increment peaking in 2033 at 62 thousand t PM/y and a later decrease down to 39 t PM/y in 2050, which is about the same level as in 2017. A similar development can be observed in China with a peak of 15 thousand t PM/y in 2025 and a decrease to 2655 t PM/y in 2050. Compared to the case of India, China’s transport demand increase slows down after 2030, so that total particulate emissions are significantly reduced from the 2015 level until 2050. Apart from India and China, the deeper investigated countries show relatively low particular matter loads (Fig. 12 and Fig. 13). USA declines from 5000 t PM/y to 825 t PM/y, from 2015 to 2050, Germany from 3895 t PM/y to 133 t PM/y in the same period.

4 Discussion and Conclusion

Using a bottom-up model, this study analyzed CO$_2$, NO$_x$, and PM$_{2.5}$ emissions from passenger cars for different world regions until 2050. The diffusion of alternative powertrains and emission factors of the vehicles on the road in selected countries are examined to explore the emissions effectively. This analysis’ results were later aggregated to estimate the global emissions and disaggregated for estimating the spatial emission developments in selected countries. The created datasets (cf. Data availability statement) giving yearly emission values per country globally can be useful especially for climate and air quality modelers.

The results of this study reveal that global passenger car CO$_2$, NO$_x$ and PM$_{2.5}$ emissions decrease from 2015 until 2050 by approx. 45%, 63% and 54%, respectively. This is partly based on the fact that stock-average passenger car CO$_2$, NO$_x$ and PM$_{2.5}$ emissions per vehicle and kilometer driven decrease significantly in all world regions and analyzed countries. The main reasons for this trend are increasing electrification rates of the stock fleets, energy efficiency improvements and the introduction of stricter emission regulations and accompanying more advanced exhaust gas aftertreatment systems. However, the total passenger car emission trends in these world regions or countries can differ, especially due to increasing transport demand. Further, the study findings indicate that although EVs are at the center of the discussions about the future of passenger cars, the progression of EV adoption varies significantly among different global regions. Our analysis found that while most passenger cars will be electric in China and Europe in 2050, the transformation will be slower in the rest of the world. Especially in the countries like Brazil and Russia, where there is a strong connection between the domestic economy and the fuels of the vehicles, the transformation will be slower under the current policies.

For CO$_2$, total emissions decrease in most of the analyzed countries, especially in the industrialized countries like the US, Germany or Japan. Whereas in India, China and Brazil, there is an increasing CO$_2$ emission trend mainly caused by increasing transport demand in those developing countries. In China, passenger car CO$_2$ emissions in 2015 increase 2.5-fold until 2027 before they decrease and reach the 2015-level again approx. in 2045. Indian passenger car CO$_2$ emissions keep increasing until after 2040 and stay at a high level until 2050 showing only marginally decreasing emissions. Brazil's passenger car CO$_2$ emissions show a flat and constant increase over the considered time frame. Next to the over-time increasing transport demand in South America, Brazil also has relatively low BEV stock shares and therefore stock-fleet-average CO$_2$ emission factors decrease not so drastic compared to other countries with higher electrification rates. On the other hand, our modelling results show that South America’s gasoline passenger car fleet will mainly be replaced by G-HEVs. This is due to the strong
dependence of Brazil (and further Latin-American countries) on Ethanol as an energy carrier so that it can be assumed that such regions aim at hybridization of passenger car powertrains. It should be noted that for the CO\textsubscript{2} emissions calculation, this study only accounts for CO\textsubscript{2} from fossil origin and therefore the biogenic CO\textsubscript{2} from ethanol combustion is not considered in Brazil's CO\textsubscript{2} emission figures. This is a major difference to countries in Eastern Europe and the Middle East, where in 2050 half of the passenger car stock runs on fossil gasoline (Fig. 5). The dependence on fossil gasoline is disadvantageous regarding the stock-average CO\textsubscript{2} emissions, which can be concluded from Russia's high figures (Fig. 8). Due to the persisting relatively low transport demand in this world region, the effect on total CO\textsubscript{2} emissions is only marginally.

Regarding total NO\textsubscript{x} and PM\textsubscript{2.5} emissions, all countries investigated besides of India have a decreasing trend, also China whose pollutant emissions start reducing from approx. 2025 on. In India the results indicate that NO\textsubscript{x} emissions increase until year 2045 and in case of PM\textsubscript{2.5} emissions increase until 2033 and for both species pollutant emissions don't fall below the respective 2015-levels before year 2050. Thus, India seems to represent an exceptional case in terms of passenger car pollutant emission development. First, stock-average emission factors are high compared to most of the other analyzed countries. Even though India's passenger car stock fleet is assumed to have significant BEV shares, also high diesel shares stay persistent during the considered time frame, which can be problematic for NO\textsubscript{x} and PM emissions. According to the literature it can be assumed that before 2020 most of India's passenger car stock consisted of Bharat Stage IV certified vehicles which equals to Euro 4 standard (Gajbhiye et al. 2023; Raparthi et al. 2021). For type approval or first registration, corresponding (diesel) vehicles are allowed to emit approx. 3-times more NO\textsubscript{x} per km and about 5-times more PM/km compared to modern Euro 6 diesel passenger cars. Moreover, petrol and diesel fuel in India contain high sulfur levels which can be problematic also regarding NO\textsubscript{x} and PM emissions, as the high sulfur content affects the proper operation of the exhaust aftertreatment devices like particulate filters or lean NO\textsubscript{x} traps (Goel and Guttikunda 2015). High emission factors can also be related to the existence of old, overloaded and deficiently maintained vehicles in the stock fleet (Raparthi et al. 2021). However, estimating the current average emissions of India's passenger car stock fleet is challenging and especially its future development is highly uncertain. On the one hand, there is no recent national emission factor database covering all traffic situations for all vehicles, but only data from single measurement campaigns covering specific driving situations or cycles and vehicle types / technologies are available. In this study, pollutant emission factors for India between 2015 and 2030 are estimated based on Goel and Guttikunda (2015) and the respective pollutant emissions trends are extrapolated till 2050. However, the authors did not consider the introduction of new vehicle emission and fuel quality standards and the accompanying effects on the fleet-average emission factors. Therefore, the considered extrapolated trends until 2050 might overestimate India's pollutant emissions from passenger cars in future years. Nevertheless, due to the assumed strong increase of transport demand in India, an increment of passenger car NO\textsubscript{x} and PM\textsubscript{2.5} emissions seems likely and policy makers should address this issue and its associated environmental and human health impacts.

Limitations and uncertainties

Although this study can contribute to the literature from many different perspectives, it involves some uncertainties. Therefore, several limitations may have impacted our research outcomes. One of the limitations that may have affected research results is the shares of alternative powertrains on the road in different world regions. Due to the broad scope of the study we covered, we were unable to conduct a detailed analysis of each
aspect of the markets in the countries we studied. While we carefully designed our methodology to minimize the potential biases and tried to validate our findings with the current literature, many variables from politics to infrastructure that were not accounted for can impact the development of alternative powertrains. We encourage future research to address these gaps to build a more robust model.

The considered data for transport demand from Seum and Eisenmann (2020) was calculated based on observed data of average vehicle kilometer travelled per car in a region and estimating car ownership from region-based curves as a function of GDP per capita. Apart from the inherent uncertainties in the development of GDP and population and its effect on car ownership, no input relating to future change in urban structure, congestion and thus change in travel demand per car, increasing investment towards public transport was considered in the model. Though difficult to incorporate and validate in such global models, it is important to compare scenarios related to development of travel demand given the direct impact it has on the total emissions.

One of the main limitations regarding our emission estimations is the lack of specific and country-representative data for most of the considered countries especially regarding emission factors and vehicle stock composition. Also, the limited number of countries which are analyzed in detail and the assumed clustering approach to cover the rest of the world's countries brings further uncertainty into the modelled emission figures. For our calculation of PM$_{2.5}$ emissions, we focus only on tailpipe emissions resulting from fuel combustion. While the results show a strong decline of global PM$_{2.5}$ emissions until 2050, we did not cover the non-exhaust particulate emissions originating from the abrasion of tyres, brakes, roads and resuspension. As these particulate emissions are also caused directly from transportation and will become more significant if ICE vehicles will progressively be replaced by EVs in the future as shown in our model results, these need to be included in future passenger car or land transportation emission inventories.

Regarding the methodology of the spatial disaggregation, this depends on the total emission sums per country and on the data set EDGAR v4.3.2 used as a proxy to spatially distribute emissions. As discussed, there exists gaps in using just road and population densities as inputs to proxy vehicle km since transport through a region depends not only on its inhabitants but also its spatial and utilitarian context and its contribution in connectivity. Densification leads to proximity and higher availability of public transport and shared modes. The effects of these are however neither transparent nor reproducible by what is publicly provided by EDGAR v4.3.2. Validation with real world vehicle counts and other proxy parameters is also missing and has to be continued in future work.

Due to the multiple sources of uncertainties within each input parameter for the bottom-up calculation chain of our emission estimations, an uncertainty assessment combined with a subsequent sensitivity analysis can support checking the robustness of the results. While this goes beyond the scope of this paper, we propose future emission inventory compilers to cover this.

**Declarations**

Data availability statement

The passenger car CO$_2$, PM$_{2.5}$ and NO$_x$ tailpipe emissions datasets generated during this study which include values per country globally and per year from 2015-2050 are available in the [NAME] repository, [PERSISTENT WEB LINK TO DATASETS].
References


15. Gajbhiye, Madhur D.; Lakshmanan, Sandhiya; Aggarwal, Ranjana; Kumar, Naresh; Bhattacharya, Sujit (2023): Evolution and mitigation of vehicular emissions due to India's Bharat Stage Emission Standards – A case


Figures
**Figure 1**

Electric car (BEV + PHEV) stock share of selected countries. Source (International Energy Agency 2022)

<table>
<thead>
<tr>
<th>Country</th>
<th>Gasoline vehicles</th>
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</tbody>
</table>

**Figure 2**

Gasoline and diesel passenger car stock compositions according to Euro classes from 2015 – 2050 in Australia, Russia and South Africa. The x-axis presents the year and the y-axis gives the percentage of the vehicle stock fleet.
Figure 3

Development of the global passenger car transport demand (Seum and Eisenmann 2020)
Figure 4

Geodata model for spatial disaggregation of emission data.
Figure 5

Drivetrain technology stock fleet share development until 2050
Figure 6

Comparison of the model with other EV stock share projections
Figure 7

Development of the global CO$_2$, NO$_x$ and PM$_{2.5}$ emissions per world region and year
Development of the stock-fleet-average CO$_2$ emission factors (left) and the total CO$_2$ emissions (right) by country and year

**Figure 9**

Spatially distributed passenger car CO$_2$ emissions in selected countries for 2015, 2030 and 2050.
Figure 10

Development of the stock-fleet-average NO\textsubscript{x} emission factors (left) and the total NO\textsubscript{x} emissions (right) by country and year
Figure 11

Spatially distributed passenger car NO$_x$ emissions in selected countries for 2015, 2030 and 2050.
Figure 12

Development of the stock-fleet-average PM$_{2.5}$ emission factors (left) and the total PM$_{2.5}$ emissions (right) by country and year.
### Figure 13

Spatially distributed passenger car PM$_{2.5}$ emissions in selected countries for 2015, 2030 and 2050.