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Framework to Quantify the Life Cycle Greenhouse Gas Emissions from the Build-Out and Maintenance of Global Roadway Networks

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Framework to Quantify the Life Cycle Greenhouse Gas Emissions from the Build-Out and Maintenance of Global Roadway Networks

December
2024

A Research Report from the National Center for Sustainable Transportation

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The goal of this study was to develop a framework and first order estimate of the greenhouse gas (GHG) emissions from the build-out and maintenance and rehabilitation of the world’s roadway infrastructure networks from 2020 to 2050. The GHG emissions from road pavement emissions, bridges, and maintenance and rehabilitation were calculated by decade based on the existing road networks and the modelling of their expansion. For comparison, the GHG emissions from vehicle manufacture and operation were estimated. Regional comparisons and sensitivity analyses were then performed. Based on one mid-range scenario, GHG emissions from new road construction account for roughly 0.1 to 4% of regional road transportation GHG emissions depending on the region; existing road maintenance accounts for 0.32 to 3%; vehicle manufacturing for 4 to 13% of regional GHG emissions; vehicle operation accounts for 82% to 93% of regional GHG emissions; and road roughness is responsible for approximately 2% of the total system impacts.</td></tr>
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Framework to Quantify the Life Cycle Greenhouse Gas Emissions from the Build-Out and Maintenance of Global Roadway Networks

A National Center for Sustainable Transportation Research Report

December 2024

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EXECUTIVE SUMMARY

The goal of this study was to develop a framework and first order estimate of the greenhouse gas (GHG) emissions from the build-out and maintenance and rehabilitation of the world's roadway infrastructure networks from 2020 to 2050. The current global road network size was estimated from available data and its future build-out from 2021 to 2050 by decade was modelled using three approaches. The types of pavement structures were estimated and simplified based on available information on a regional basis. Maintenance and rehabilitation practices were also assumed. The same was done for simple reinforced concrete bridges and culverts.

The GHG emissions from road pavement, bridges, and maintenance and rehabilitation were calculated by decade based on the existing road networks and the modelling of their expansion. The report further presents the GHG emissions from road transportation, including the emissions from new road construction (A1 – A5 following ISO 21931 terminology), existing road maintenance and rehabilitation (stages B2 and B3, having their own A1 – A5), and vehicle-related emissions, which include vehicle manufacturing, well-to-wheel (WTW) vehicle operation, and additional fuel due to road roughness (a part of B1 in ISO 21931 terminology). For comparison, the GHG emissions from vehicle manufacturing and operation were estimated using IEA Mobility Model (MoMo) data, presented in Appendix C. Regional comparisons and sensitivity analyses were then performed.

It is important to state this study's limitations, as they provide context for the findings. For example, the study operated under certain assumptions and relied on specific data sources which were at times incomplete. Gross assumptions were made based on available information regarding pavement type and design, and numbers of bridges and culverts and their design. It was assumed that all existing roads in national inventory data are fully paved and adopted the Caltrans maintenance schedule for asphalt pavements with a 20-year design life as a worldwide practice. Vehicle sales data represented the number of vehicles manufactured, and the study assumes linear change of vehicle kilometers traveled across each decade. These limitations should be considered when interpreting the results, which were intended to meet the goal of a first, first-order estimate.

The following conclusions are based on the results of this study:

- The regression analysis shows varying projections of road length increases relative to the estimated 2020 global road network of 40.4 million lane-km. Two models predicted significant growth with approximately a 65% increase in road length by 2050, relative to

2020. A third model projects more moderate growth, approximately a 20% increase by 2050.

- Results from the road network growth models indicate that developing regions and emerging economies will prioritize constructing new roads over the next three decades more than developed regions.
- By 2050, the total cumulative GHG emissions from the pessimistic, moderate, conservative, and optimistic scenarios for the total system (new road construction, existing road maintenance, road roughness, vehicle manufacture, vehicle operations) were estimated to range between 261,812 to 250,171 $MtCO_2e$, respectively. This translates to an annual rate of 8,727 $MtCO_2e$ to 8,339 $MtCO_2e$.
- Approximately 88% of the cumulative global GHG emissions from the conservative scenario will be from vehicle operation, 7% from manufacturing, and 2% from new road construction and existing road maintenance and rehabilitation (M&R).
- Based on the conservative scenario, across each region, new road construction accounts for 0.1 to 4% of the cumulative GHG emissions from road transportation, existing road M&R (0.32 – 3%), vehicle manufacturing (4 – 13%), vehicle operation (82 – 93%), and additional fuel from road roughness (2 – 3%).
- The OECD North America, India, China, Africa, and ASEAN regions have the highest road infrastructure (pavement, bridges, culverts, including pavement M&R) related GHG emissions in each decade. Developing regions, such as India and Africa, have relatively higher new road construction GHG emissions, and developed regions, such as OECD North America, have higher existing road M&R GHG emissions.
- Developed regions such as OECD Europe, EU 5, and Other OECD have the highest vehicle operation impacts, while developing and emerging regions such as Africa, India, and ODA have the highest road project impacts. The maximum regional contribution of new road construction and existing road M&R to total system 30-year cumulative GHG emissions is 6%.
- The GHG emissions from additional fuel due to roughness for gasoline and diesel vehicles are estimated to be approximately 1 – 6% of the GHG emissions from vehicle operation (cars and trucks), depending on the modelling of road network expansion. The GHG emissions from additional fuel due to roughness for electric vehicles is estimated to be 4 to 16% of the GHG emissions from vehicle operation.
- From the sensitivity analysis, across the three decades, road-related emissions reductions range from 2 – 5% reduction in GHG emissions from new road construction (in regions using cement treated base) when portland cement is replaced by portland limestone cement, which includes replacement of 15% of PC with ground limestone.
- From the sensitivity analysis, delayed maintenance in the alternative scenario reduces road project GHG emissions but leads to roads with higher IRI. These rougher roads increase vehicle fuel consumption, resulting in higher vehicle-related emissions and burden shifting, where the environmental impact shifts from road maintenance to vehicle operation.

- The scenario analysis combines the effects from the three models of road network expansion and three sensitivity scenarios for road roughness development, along with fixed estimates of vehicle manufacture and operation, to calculate the GHG emissions for the whole road transportation system. As a fraction of the total system environmental impact, the GHG emissions for the sensitivity analyses scenarios varied by 1 – 4%, depending on the scenario and the decade. The small differences are because of the overwhelming GHG emissions from vehicle operation and the large GHG emissions from vehicle manufacturing in each scenario, which were held fixed.

Vehicle operations and manufacture together have more than 40 times the impact of new road construction and existing road M&R. While road construction and maintenance have relatively low contributions to the global road life cycle GHG emissions, the percentages (1 to 6% of the global road transportation system values) are sufficiently large in terms of percentage and in terms of absolute values to warrant all possible efforts to reduce those contributions to net zero by 2050 or sooner. It is also clear that the primary focus needs to be on finding solutions in emerging economies, where the most growth in road networks will occur as standards of living increase and greater accessibility to locations that increase quality of life is desired and becomes possible.

The three limited scope sensitivity analyses indicate that even simple efforts to reduce embodied emissions of materials and control road roughness (from better initial construction and better maintenance) can begin to provide reductions in GHG emissions, as also the use of pavement preservation instead of only rehabilitation.

It is recommended that regionally appropriate pavement materials, construction, and asset management technologies be developed, communicated, and incentivized throughout the world to reduce the GHG emissions from road infrastructure.

Introduction

Background

Climate change, which is a consequence of increases in the greenhouse effect from human activities, is an existential threat to human civilization and life on the planet.

The transportation sector was responsible for about 15% of global greenhouse gas emissions (GHG, expressed as equivalent carbon dioxide CO_2e) in 2019 (*1*) as shown in Figure 1. Road vehicles comprise 70% of the total global transportation sector GHG emissions. In the United States (U.S), the transportation sector accounts for 28% of the total GHG emissions, out of which 74% come from road vehicles (*2*). In China, India, South Africa and Brazil, transportation contributes 9, 13, 12, and 46% of emissions, respectively (*3*), illustrating that the contribution of transportation to national GHG emissions depends on the geographical and economic development context, per-capita income, and the relative size of the contribution of other end-use sectors to the national GHG totals. Transportation sector emissions are growing world-wide, often at a faster rate than the other sectors. This is particularly true in emerging economies where transportation demand is rapidly increasing, and people are using fossil fuel powered motorized vehicles that they can purchase with increasing wealth to better access jobs, healthcare, education, food, recreation and entertainment, and social connectivity. At the same time, global freight movement growth to 2050 is projected to increase faster, in the range of 7 to 12% tonne-km average annual growth (*4*), than global population growth to 2050 which is approximately 4% per year (*5*). In addition to the ability to purchase vehicles and buy goods, the expansion of vehicle transportation for personal accessibility and freight movement is also dependent on the commensurate building out of road networks.

GHG emissions from vehicle use have been benchmarked and analyzed to develop strategies to reduce transportation sector emissions. Strategies include transitioning to alternative vehicle propulsion systems (e.g., battery electric, fuel cell), less motorized vehicle travel, and changed land use and urban planning to reduce dependence on vehicle travel (e.g., (*6*)).

As has been done with vehicle operation, road construction must be better understood as a component of GHG emissions and benchmarked and analyzed to identify the viability of strategies to reduce emissions from roadway infrastructure and measure progress. The benchmarking of global road transportation infrastructure has not been done, and most national benchmarking has been confined to a few northern European countries. The value of modal shift away from motor vehicle-based personal accessibility and commensurate lowered rates of road building may be more valuable than is currently estimated, even without accounting for contributions from road infrastructure. It must be remembered that while active transportation (walking and bicycling), motorcycles, and electrified micro-mobility devices require good pavement like motor vehicles, they consume less surface area per vehicle than motor vehicles, both when moving and when parked. Some top-down estimates of the growth of road infrastructure, economic activity, and carbon emissions have been done. For example, the work of Churchill et al. indicates that there has been a 0.4% increase in CO_2e emissions from each 1% increase in transportation infrastructure stock[1] over a 150-year period in 17 OECD countries (*6*).

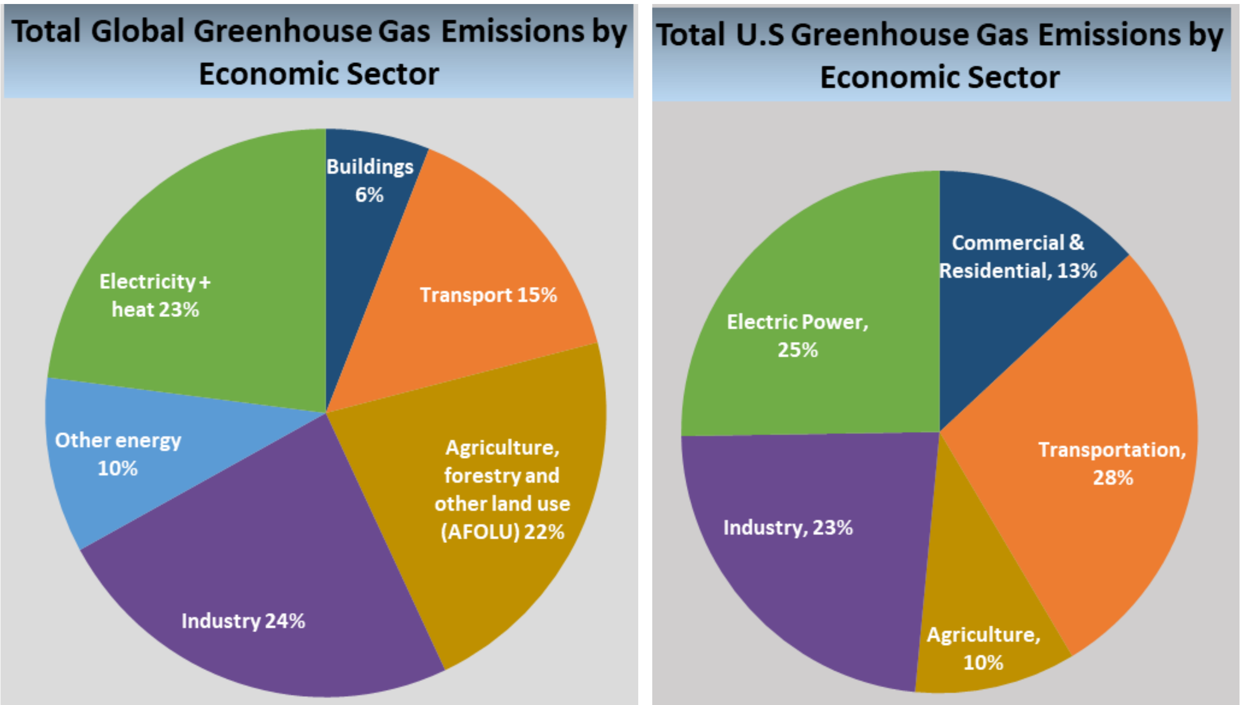

Figure 1. Global GHG emissions by economic sector (*1*) **and U.S GHG emissions by economic sector** (*7*)

Roadway infrastructure in good condition is a requirement for safe and efficient road transportation regardless of vehicle types and propulsion systems. The scale of demand for horizontal capacity (lane-km) of roadway infrastructure is driven by the need for personal access to destinations affecting quality of life (work, education, food, healthcare, etc.) and the need to move freight. The scale of demand for vertical capacity of roadway infrastructure (pavement thickness) is driven by heavy truck axle loads and truck trips. Pavements are primarily made of asphalt, concrete, and crushed stone (sometimes stabilized with cement or asphalt binders). Bridges, culverts, and drainage systems are primarily made of concrete and steel. All these materials have their own supply chains for raw material extraction, material transportation, and material processing, all of which result in GHG emissions. Large quantities of these heavy materials must be transported to roadway, bridge, and drainage construction sites from the gates of the final materials production locations. Construction equipment used to build, maintain, rehabilitate, and reconstruct roadway infrastructure is primarily powered by diesel.

The GHG emissions from the roadway infrastructure life cycle are not well tracked in current emissions inventories, showing up in the industry sector of the economy in Figure 1, and in

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[1] Roads, highways, railways, airports and inland waterways calculated from financial flows.

mining, industry, oil extraction and refining, cement manufacture, and some other sectors in more detailed inventory breakdowns. In addition to benchmarking and identifying effective mitigation strategies, better estimates of roadway construction and maintenance-related GHG emissions can be added to estimates of vehicle-related GHG (production and use), to get a more complete picture of the road-based transportation system. Apart from the direct emissions associated with roadway deployment and upkeep, roadway condition (roughness) plays a critical role in vehicle life (*8*, *9*) and the emissions associated with the vehicle replacement supply chain, as well as in additional fuel use (*10*–*12*) moderated by the influence of roughness on vehicle speeds (*13*). On the other hand, a faster replacement of internal combustion vehicles with alternative fuel vehicles is expected to have potentially important cost equity impacts on those reliant on older vehicles and without the means to frequently replace such older vehicles. The framework for the complete system considering these tradeoffs has also not been well established.

Road infrastructure plays a major role in the economic development of any nation or region; however, their building, maintenance, and rehabilitation (M&R) are resource and energy intensive (*14*, *15*). Thus, road development is a significant contributor and has previously been estimated to contribute about 10% of the transportation sector's global GHG emissions (Ruiz & Guevara, 2020). The specific contribution varies by country, and formal calculations for these are yet to be determined. The UCPRC has previously performed an initial comparison of the GHG emissions from pavements constructed for the same traffic levels in California, China, South Africa, and France considering the pavement structures, energy sources, and other practices unique to each location (*17*). This provided baseline information for considering differences in the practices followed across different regions of the world.

The GHG emissions from transportation infrastructure and the factors that drive them now and into the future have not previously been extensively calculated using life cycle assessment (LCA), particularly for the build-out of road networks in emerging economies (such as India and parts of Africa and Latin America). More work is also needed regarding emissions from the M&R of existing networks in countries with mature road networks such as the USA, western Europe, Mexico), and networks that are in transition from deployment to asset management such as China and parts of Africa. It is expected that the emissions from roadway infrastructure are much smaller than the emissions from vehicles operating on roadways, but are still large enough to warrant attention and development of strategies to reduce them.

Problem Statement

Most of the world's population aspires to have an economy, culture and the supporting infrastructure that provide meaningful employment, a clean environment, access to medical attention, educational opportunity, social connection, and goods provided by trade. There are many types and densities of roadway networks that can be designed, delivered, and maintained to support different transportation systems to achieve these goals. Equity of access to roadway infrastructure is essential to equity of opportunity.

There is a need to develop estimates of the GHG emissions for development of global roadway infrastructure based on region-by-region modeling so that emissions can be benchmarked, strategies can be developed, and progress towards reducing projected emissions can be measured.

Goal and Objectives

Goal

Sustainability of global transportation systems regarding climate change mitigation requires consideration of all important sources of GHG emissions. The goal of this study is to develop a framework and first order estimation of the GHG emissions from the build-out and M&R of the world's roadway infrastructure networks from 2021 to 2050. The calculations include consideration of pavement roughness and the resultant additional vehicle fuel consumption, and emissions. Private pavement and vehicle replacement rate differences due to pavement roughness are not included. Sensitivity analyses considering uncertainties in the most important variables are included in the study.

Objectives

The objectives to achieve the study goal are to:

- Quantify the current and future global road network size
- Characterize typical regional pavement structures
- Assess the contributions of road project construction and M&R and additional vehicle fuel consumption in the use stage from road roughness to global road transportation GHG emissions
- Conduct regional comparison of road transport emission levels (CO_2/km-road and CO_2/km^2 of land) as a benchmarking exercise
- Perform sensitivity analyses
- Draw conclusions and make recommendations

Data and Methods

Figure 2 shows the overall approach used for quantifying the GHG emissions from global roadway networks. The methods involve information gathering on current and projected road network size and designs, vehicle fleet typicality, status of road network deployment, and other factors. Where detailed information was not available, estimations and reasonable assumptions were made and documented. The subsections below present the detailed approach to estimate GHG emissions contributions from global road build-out and M&R, global build-out of bridges and culverts, vehicle manufacturing and operation (computed outside this study and used for comparison with infrastructure emissions), and the additional fuel from road roughness.

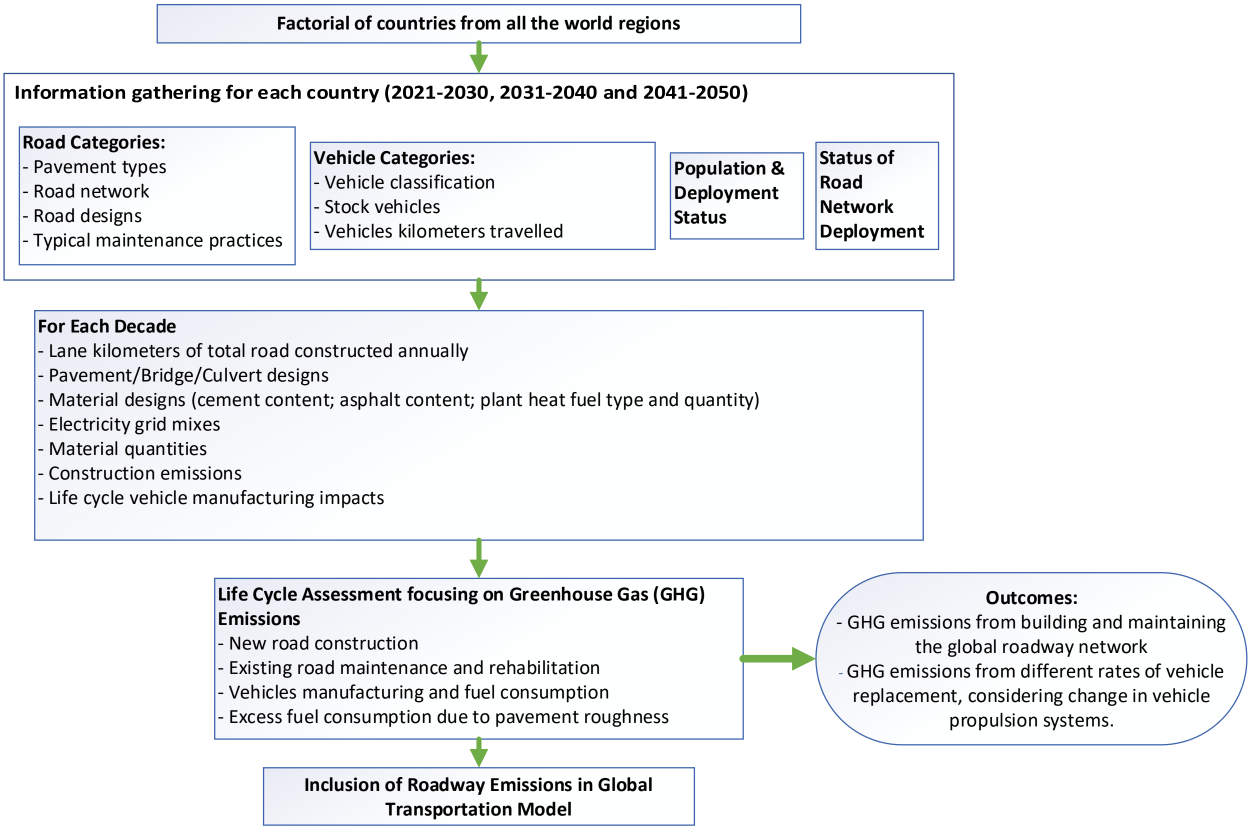

Figure 2. Summary of the framework for calculating road transportation GHG emissions

Approach for estimating GHG emissions from the build-out and M&R of global roads

Summary of steps

The steps taken in estimating the GHG emissions from the build-out and maintenance of global roads are as follows:

1. Collect road network information data for all the countries of the world
2. Adapt the International Energy Agency's regional classification of countries

3. Collect vehicle fleet data, and socio-economic data that influence road growth for all countries
4. Use regression analysis to predict road growth for 2030, 2040, and 2050 for all the countries of the world
5. Select representative countries from each IEA's regional classification of countries for collecting example pavement designs and maintenance activities, electricity mixes, and asphalt mixing fuels data
6. Collect pavement design data for representative countries to determine regional design typicality
7. Collect projected 2030, 2040, and 2050 electricity mix and asphalt mixing fuel data for representative countries
8. Analyze pavement design commonalities among representative countries
9. Develop common materials, transport, and construction emission factors for countries or regions representing the regional classification of the countries.
10. Develop common electricity mix and asphalt mixing fuel emission factors for countries or regions representing the regional classification of countries.
11. Develop common pavement maintenance emission factors for countries or regions representing IEA's regional classification of countries
12. Use LCA to estimate the GHG emissions from the construction of new roads (A1 through A5 following ISO 21931 terminology) and the M&R of existing roads (stages B2 and B3).

Details of each step presented above are explained in the subsections below.

Regional road network size

Current road length data were collected from different sources for 223 countries, including those of small island developing states (see Table 30 in Appendix A). These countries were then categorized into regions using the International Energy Agency's (IEA) Mobility Model (MoMo) zone classification system for countries (*18*). IEA bases its classification system on continental Organisation for Economic Co-operation and Development (OECD) membership, developed regions, transition economies, and developing economies. This study adopts this classification system because vehicle fleet information such as vehicle stock, vehicle kilometers of travel (VKT), and other information collected for the analysis used this same classification.

The classification system was slightly adjusted to include countries that the IEA excludes but which have road length data. Table 1 presents the adapted table with the 'Others' category that was not included in IEA's zonal classification system. Among the 16 regions, four are classified as OECD. India and Russia are individually categorized, while China is categorized with Hong Kong. The 'Others' category comprises 17 of the 223 countries with road length data that do not fall under any of IEA's classification. Since countries in the 'Others' region do not have vehicle fleet information, they are only included in infrastructural life cycle analysis but excluded from the vehicle-related life cycle analysis. Thus, the infrastructural life cycle analysis incorporates data from 223 countries, while only 206 countries were factored into the vehicle-related life cycle analysis.

Table 1. Regional classification for all countries (adapted from IEA's Mobility Model zone classification of world's countries)

Region	Countries
Africa	Algeria, Angola, Benin, Botswana, Burkina Faso, Burundi, Cabo Verde, Cameroon, Central African Republic, Chad, Comoros, Congo, Congo, Dem. Rep., Cote d'Ivoire, Djibouti, Egypt, Arab Rep., Equatorial Guinea, Eritrea, Eswatini, Ethiopia, Gabon, Gambia, The, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Libya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Mozambique, Namibia, Niger, Nigeria, Rwanda, Sao Tome and Principe, Senegal, Sierra Leone, Somalia, South Africa, Sudan, Tanzania, Togo, Tunisia, Uganda, Zambia, Zimbabwe, Seychelles, South Sudan
ASEAN (Association of Southeast Asian Nations)	Brunei Darussalam, Cambodia, Indonesia, Lao PDR, Malaysia, Myanmar, Philippines, Singapore, Thailand, Vietnam
ATE (Asian Transition Economies)	Armenia, Azerbaijan, Georgia, Kazakhstan, Kyrgyz Republic, Tajikistan, Turkmenistan, Uzbekistan
China	China, Hong Kong
EU 5 (European Union 5)	Bulgaria, Croatia, Cyprus, Malta, Romania
India	India
Latin America	Argentina, Aruba, Bahamas, Barbados, Belize, Bolivia, Brazil, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Guatemala, Guyana, Haiti, Honduras, Jamaica, Nicaragua, Panama, Paraguay, Peru, Saint Lucia, Suriname, Uruguay, Venezuela, Antigua and Barbuda, Bermuda, British Virgin Islands, Cayman Islands, Curacao, Dominica, Falkland Islands (Islas Malvinas), Grenada, Saint Kitts and Nevis, Saint Pierre and Miquelon, Sint Maarten, Turks and Caicos Islands
Middle East	Bahrain, Iran, Islamic Rep., Iraq, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, United Arab Emirates, Yemen, Rep.
ODA (Other Developing Asia)	Afghanistan, Bangladesh, Bhutan, China Macao, Fiji, French Polynesia, Maldives, Mongolia, Nepal, New Caledonia, Pakistan, Papua New Guinea, Samoa, Solomon Islands, Sri Lanka, Tonga, Vanuatu, Cook Islands, Kiribati, Korea, Dem. People's Rep., Palau, Svalbard, Timor-Leste
OECD Europe	Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Netherlands, Norway, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom, Monaco, San Marino
OECD North America	Canada, Mexico, United States, American Samoa, Guam, Northern Mariana Islands, Puerto Rico, U.S. Virgin Islands

Region	Countries
OECD Pacific	Australia, Japan, Republic of Korea, New Zealand
OETE (Other European Transition Economies)	Albania, Belarus, Bosnia and Herzegovina, Moldova, Montenegro, North Macedonia, Serbia, Ukraine, Gibraltar
Other OECD	Chile, Israel
Russia	Russia
Others	Andorra, Anguilla, Christmas Island, Cocos (Keeling) Islands, Faroe Islands, Guernsey, Isle of Man, Jersey, Liechtenstein, Marshall Islands, Nauru, Niue, Norfolk Island, Saint Barthelemy, Saint Helena, Tokelau, Tuvalu

Figure 3 presents the current 2020 road length data for the 16 regions above. The total length of roads in these regions is 40.4 million lane-kilometers (lane-km). OECD North America, India, OECD Europe, and China have the highest lane-km, representing 20%, 16%, 14%, and 13% of the entire global road length in 2020. Others, Other OECD, EU 5, and ATE represent only a tiny fraction of the entire global road length.

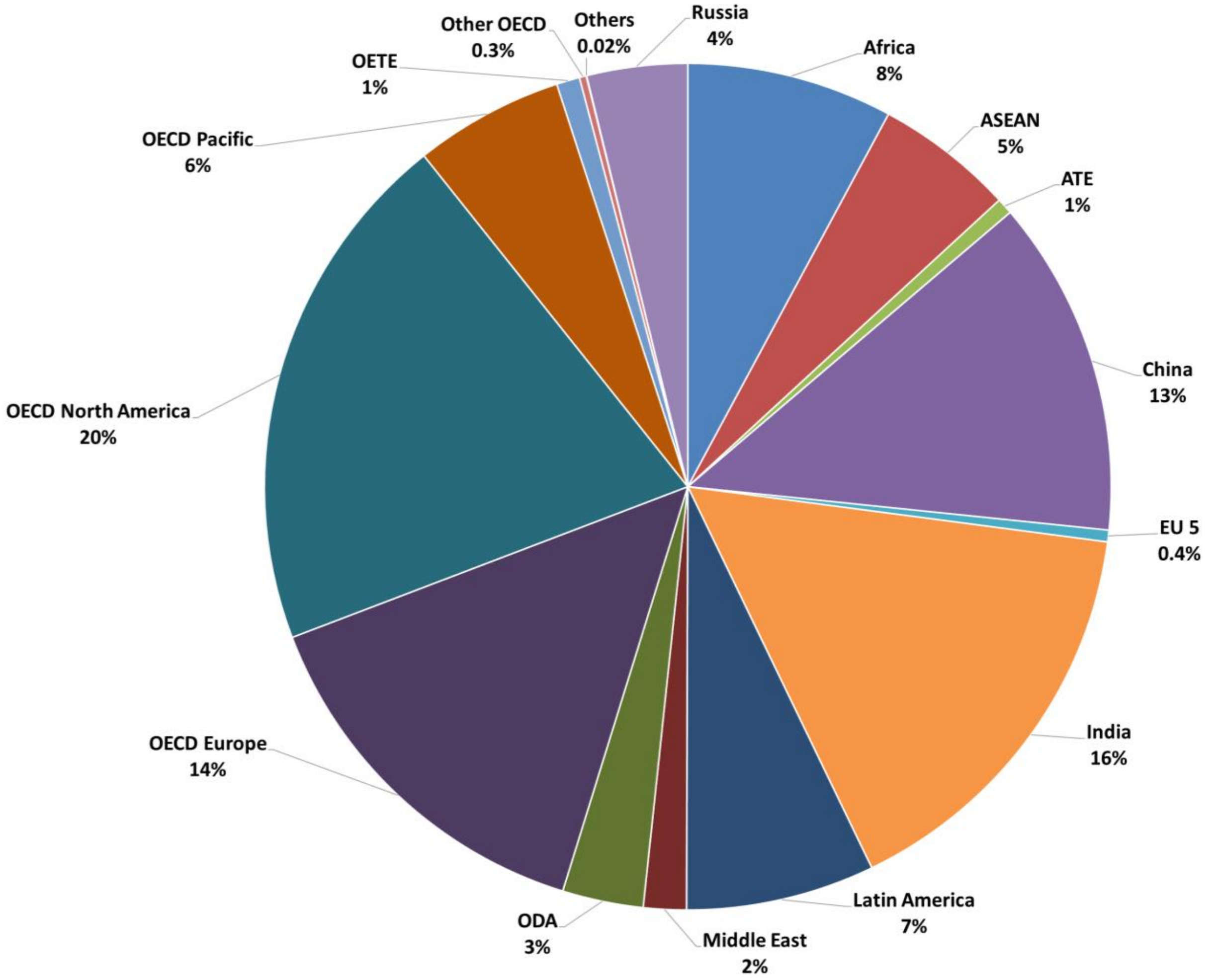

Figure 3. Current regional road network size.

Road network growth projection

Three models were considered to predict future road lengths. A summary list of the models is presented, and the models are briefly described in Table 2. The literature suggests that urbanization, socio-economic growth, vehicle travel, and government policies are some factors that drive road development (*19*–*22*). Multiple linear regression analysis was employed to determine and quantify possible relationships between road network size, socio-economic drivers, and annual vehicle kilometers traveled (VKT). Data were collected for the five explanatory variables: the countries' human population density, total land surface area, gross domestic product (GDP) per capita, purchasing power parity (PPP) (international US$), annual passenger light duty vehicle (PLDV) VKT, and truck VKT. Table 34 in Appendix B shows the socio-economic data collected for predicting road length.

Projected GDP per capita, PPP (current international $) data based on Shared Socioeconomic Pathway 1 (SSP1) was retrieved from the International Institute for Applied Systems Analysis (*23*). The Shared Socioeconomic Pathways (SSPs) provide five distinct socio-economic future scenarios with SSP1 scenario focusing on a gradual and pervasive shift to sustainability (*24*). Current and future data for population density, and land surface area of each country were taken from United Nations[2] and World Bank[3] sources, respectively. The IEA MoMo projections in Appendix C provide the vehicle travel data for PLDV and trucks through 2050. Data from 2020 were adopted as the current data for most of variables. Allocation based on the 2020 GDP, PPP (current international $) was done on the regional VKT data (see Table 35) to determine the VKT of PLDVs and trucks for each country (see Table 36).

Of the 223 countries with road length data, 45 countries did not have population density, GDP per capita, PPP, land surface area, or vehicle kilometer travel data. Thus, the current road lengths of these 45 countries were maintained through to 2050 since there was no way to predict additional road building. Only maintenance is assumed to be carried out for these countries. Future road lengths were predicted for the remaining 178 countries using the explanatory variables. In Model 1, road density is predicted by regressing road densities of countries to the selected explanatory variables and then the predicted road density is multiplied by the land area to estimate projected road length. In Model 2 road length is predicted by regressing road lengths of countries to the selected explanatory variables. Model 3 uses regression coefficients from a previous study (*21*) that used similar explanatory variables.

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[2] https://population.un.org/wpp/Download/Standard/MostUsed/

[3] https://databank.worldbank.org/source/world-development-indicators/Series/AG.LND.TOTL.K2

Table 2. Summary of models for predicting road length

	Model 1	Model 2	Model 3
Model	Uses road density to predict road density	Uses road length to predict road length	Uses model from literature to predict road length
Response variable	Road density (lane-km/km^2)	Road length (lane-km)	Road length (lane-km)
Explanatory variables	Population density, GDP/capita PPP, Land surface area	Land surface area, and Annual truck kilometers travel	Population density, GDP/capita, PPP, Land surface area, OECD Membership
Description	Road lengths for 2030, 2040, and 2050 were determined by multiplying the predicted road density by the country's land area	Road lengths for 2030, 2040, and 2050 were predicted from linear regression model	Road lengths for 2030, 2040, and 2050 were predicted from linear regression coefficients from a previous study
Major assumptions	- Only GDP per capita, PPP, for the most optimistic Model (SS1) from the five Shared Socioeconomic Pathway (SSP) models was used. - No shrinkage of road network, that is, present-year estimate was retained when the model predicts smaller projected road lengths than the present-year estimate - the percentage changes of predicted lengths for each 10-year interval period were used on current data for estimating the final lengths	- Current GDP was used for allocating vehicle kilometers travel (VKT) for most countries with only regional VKT data - No shrinkage of road network, that is, present-year estimate was retained when the model predicts smaller projected road lengths than the present-year estimate	- Only GDP per capita, PPP, for the most optimistic Model (SS1) from the five Shared Socioeconomic Pathway (SSP) models was used. - No shrinkage of road network, that is, present-year estimate was retained when the model predicts smaller projected road lengths than the present-year estimate
Limitation	- Excludes other drivers of road expansion such as urban development patterns, and transportation planning decisions	- Excludes other drivers of road expansion such as urban development patterns, and transportation planning decisions	- Excludes other drivers of road expansion such as and urban development patterns, and transportation planning decisions

Variable Selection Process for Regression

Scatter plot matrix, actual vs predicted scatter plot, residual plots and outlier detection techniques were used to check linear relationships between the response variables (road density and road length) and each explanatory variable. Outlier detection techniques, including the Interquartile Range (IQR) method and robust regression, were employed to identify and handle outliers since outliers distort the true relationship between variables and affect model accuracy. Robust regression identifies outliers in the context of a regression model, considering the influence of all predictors on the response variable. In contrast, the IQR method identifies outliers purely based on the distribution of individual variables without requiring model fitting. A disadvantage of the IQR method is that it does not account for the relationship between variables and might identify points as outliers that are not influential in a regression context.

Figure 4 and Figure 5 show the scatter plot matrix for the full dataset and the dataset without outliers from all variables filtered using IQR, respectively. The plots suggest high collinearity between PLDV and Truck, and less collinearity between other independent variables. There exists a strong correlation between road length and Area, PLDV, and Truck, and between road density and population and GDP. Land surface area appears to be correlated with road density after outliers are removed from the dataset (see Figure 5). Based on the scatter plot matrix, and outlier detection technique, only explanatory variables that had significant impact on the response variable and were not strongly correlated with other explanatory variables were selected for regression. Results from the variable selection analysis show that only three (population density, GDP / capita PPP, and land surface area) of the five explanatory variables significantly influence road density in Model 1. Since the Truck variable showed the highest linear relationship with the dependent variable (road length) based on R value, it was chosen over PLDV. Consequently, only land surface area and Truck were used in Model 2.

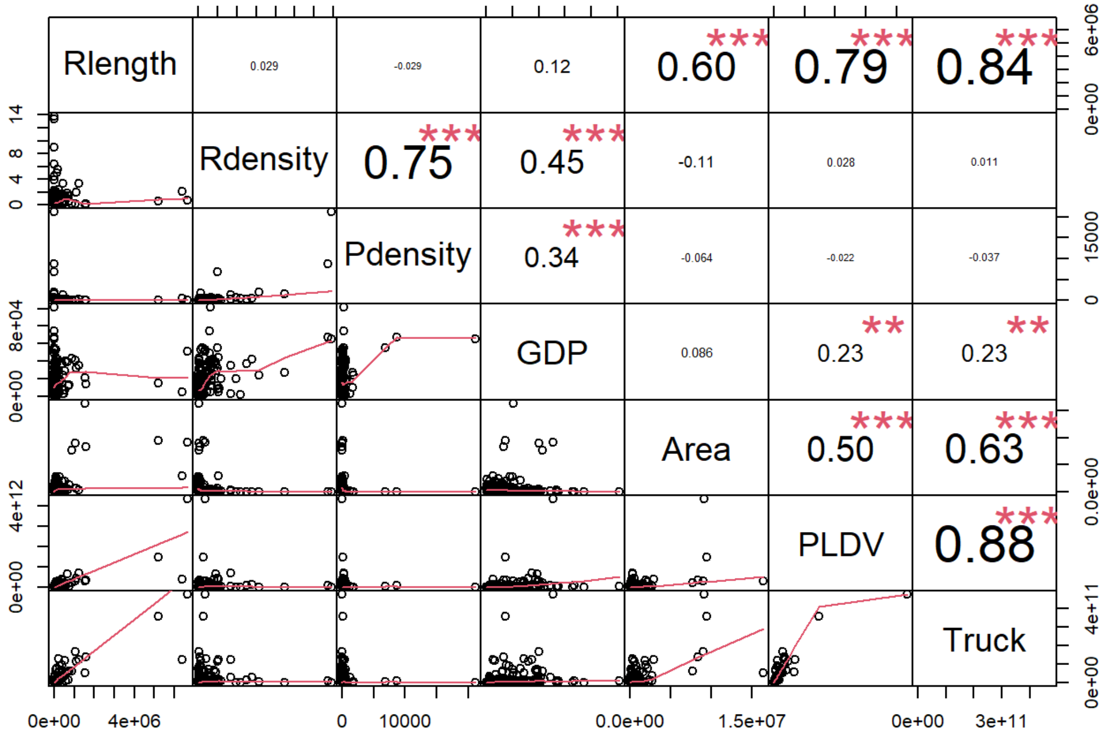


Figure 4. Scatter plot matrix for full dataset

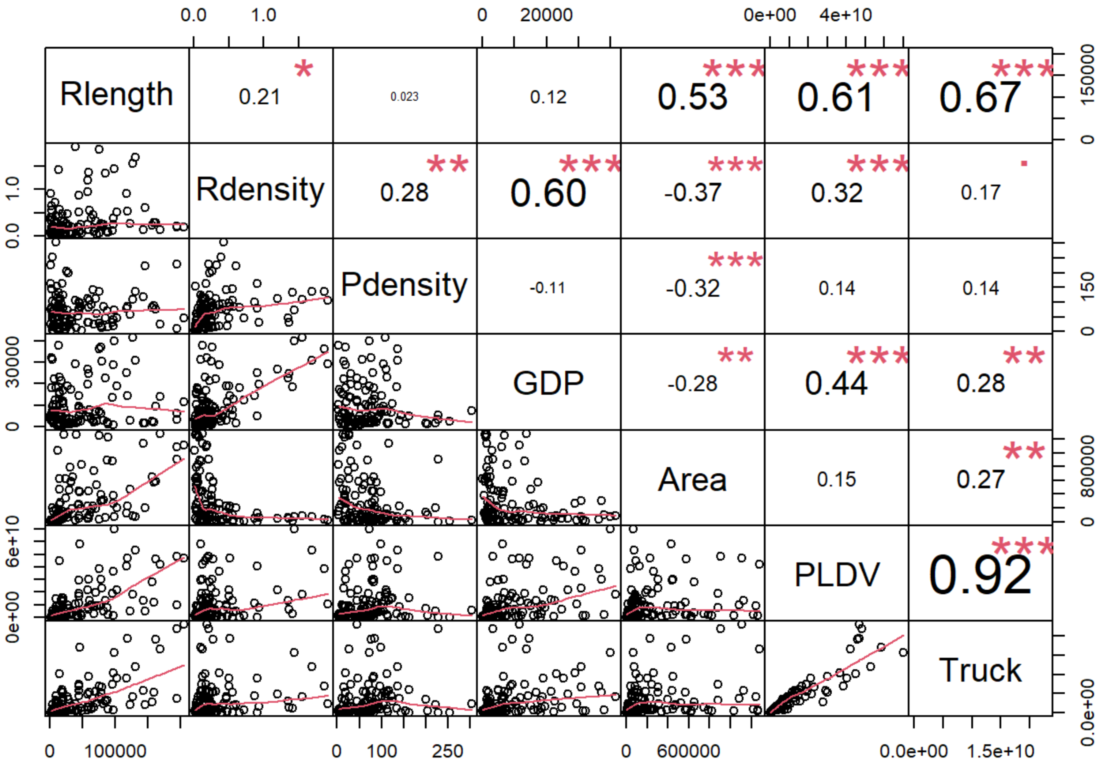


Figure 5. Scatter plot matrix for filtered (non-outlier) dataset

Development of regression models

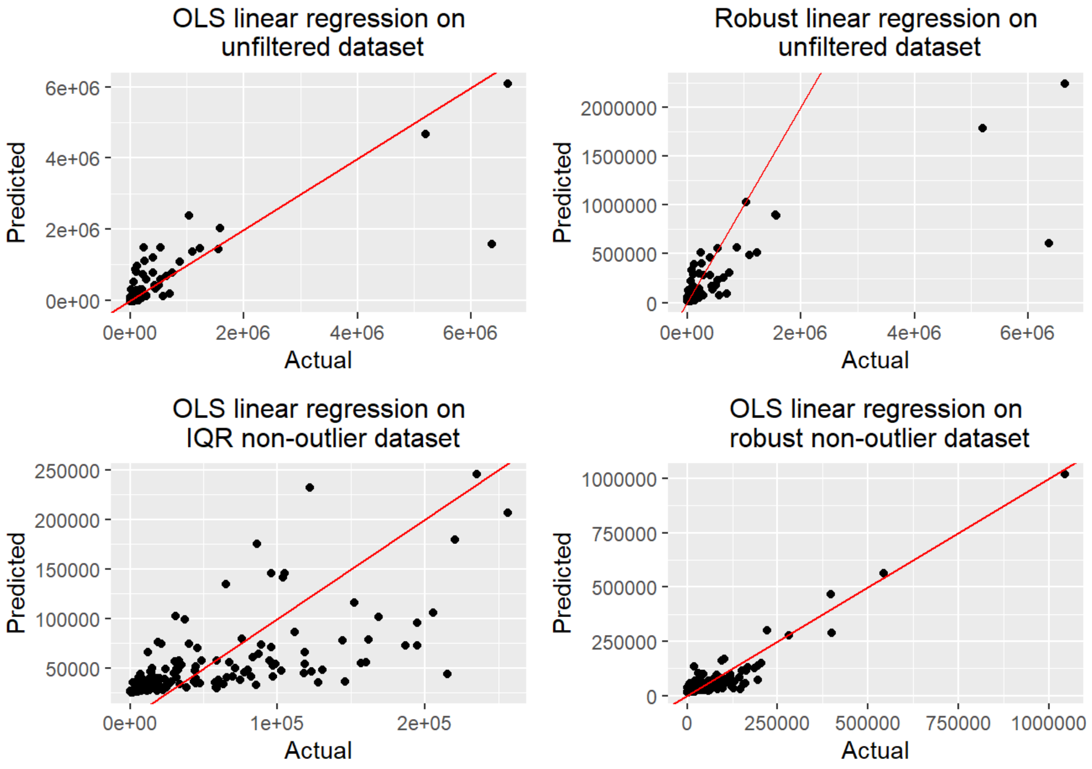
Application of the IQR outlier technique on the road length variable suggests 23 countries with road length outliers, while the road density variable suggests 18 countries with road density outliers. A data point is an outlier if it is more than 1.5 IQR above the third quartile (Q3 + .5 IQR) or 1.5 IQR below the first quartile (Q1 – 1.5 IQR). All the outliers in road length and road density variables are high outliers, that is, 1.5 IQR above the third quartile. On the other hand, the robust regression outlier technique shows that 31 outliers exist when road length is regressed against Area and Truck, and 31 outliers exist when road density is regressed against population density, GDP, and land surface area. Outliers from the IQR technique were also present in the robust regression technique. Road length for China, India, and the US represent the outliers of road length based on the IQR method, while China Macao, and Singapore represent the outliers of outliers for road density. Ordinary least square (OLS) linear regression and robust linear regression, an alternative to OLS regression that is less sensitive to outliers but still defines a linear relationship between the dependent and independent variables, were used to develop models to predict dependent variables. Four regression models were developed for predicting the dependent variables. The models include:

- OLS linear regression on the unfiltered dataset.
- Robust linear regression on the unfiltered dataset.
- OLS linear regression on non-outlier datasets filtered by IQR.
- OLS linear regression on non-outlier datasets filtered by robust regression.

Performance of regression models

Figure 6 and Figure 7 show the performance of the regression models for predicting road length (total lane-km) for the case of Model 2 (using road length to predict road length). The predicted vs actual scatter plot (Figure 6) shows a tight cluster around the diagonal line for all the models, with OLS linear regression on the non-outlier datasets filtered by robust regression having the tightest cluster. The robust linear regression on the unfiltered dataset and OLS on the robust non-outlier dataset appear to have a more even distribution of data points around the diagonal line than the other regression models. Most of the data points are also close to the diagonal line in the two regression models. The spread of data points in the other two plots suggests high variability in the predictions.

Figure 7 shows a random scatter around the horizontal line in each regression model. OLS linear regression on the non-outlier datasets filtered by IQR and OLS linear regression on the non-outlier datasets filtered by robust regression shows a more random scatter of residuals around zero with a few outlier points. The spread of the residuals appears to be moderately constant across all predicted values for OLS linear regression on non-outlier datasets filtered by robust regression, except in the case of outliers. Minimal outliers with large errors are observed across all the models. These outliers represent cases where the model's predictions have significant deviations or inaccuracies from the actual values. However, the robust regression model does better since it is less sensitive to outliers. These diagnostic checks were performed to assess the accuracy, reliability, and performance of the models.

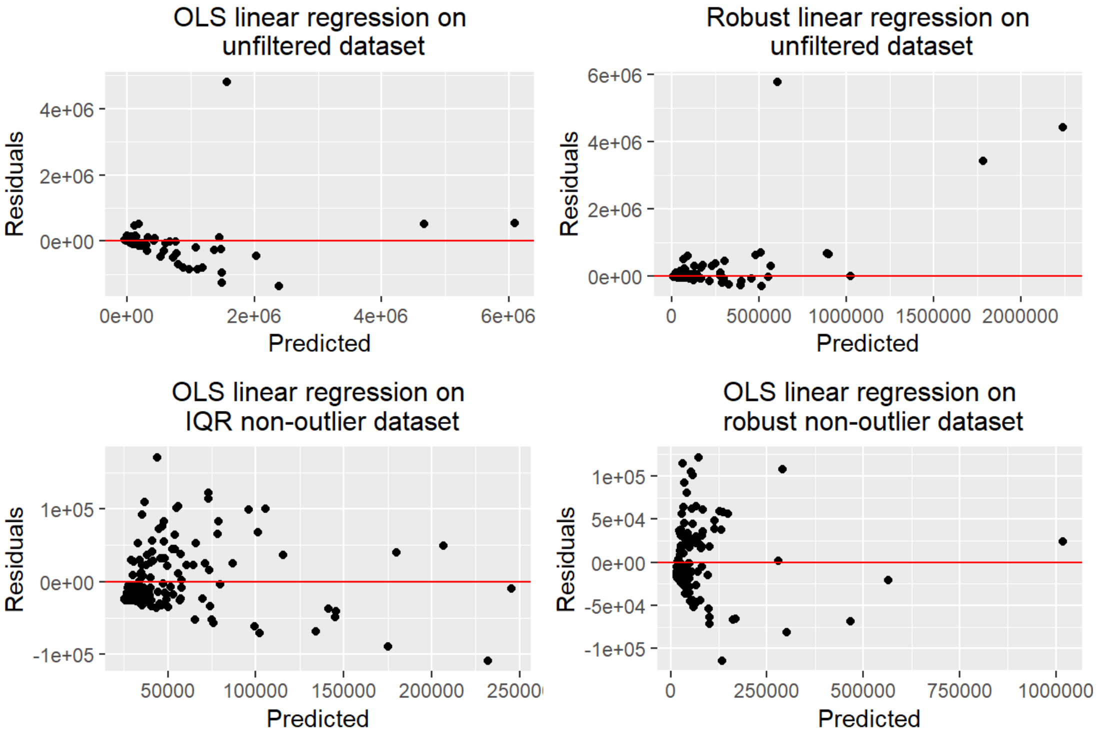

OLS linear regression on unfiltered dataset

Robust linear regression on unfiltered dataset

OLS linear regression on IQR non-outlier dataset

OLS linear regression on robust non-outlier dataset

Figure 6. Predicted vs Actual scatter plots for road length prediction for the regression models


OLS linear regression on unfiltered dataset

Robust linear regression on unfiltered dataset

OLS linear regression on IQR non-outlier dataset

OLS linear regression on robust non-outlier dataset

negative residual means over predicition

Figure 7. Residual plots for road length prediction for the regression models

The root mean square error (RMSE), R^2, and mean absolute error (MAE) of the regression models from predicting the dependent variables are also compared as shown in Table 3. In the case of predicting the road length of unfiltered datasets, the OLS linear regression on the unfiltered dataset model has the lowest RMSE (432,467.89) and a high R^2 (0.71), indicating good performance but potentially influenced by outliers. The robust linear regression model shows a slight decrease in R^2 (0.7) and an increase in RMSE (532,507.0) but better handles outliers, evidenced by a lower MAE (128,792.3). In the case of predicting the road length of non-outlier datasets, the best performance is achieved by OLS linear regression on non-outlier datasets filtered by robust regression model, with the lowest RMSE (37,446.40) and MAE (27,866.90), and the highest R^2 (0.89). Thus, the OLS linear regression on non-outlier datasets filtered by robust regression model was selected for predicting road lengths of the non-outlier datasets, while the robust linear regression on the unfiltered dataset model was used for predicting road lengths of outlier datasets.

Table 3. Performance metrics of regression models for predicting road length (lane-km)

Models used for predicting road length of unfiltered dataset

Metrics	OLS linear regression on unfiltered dataset	Robust linear regression on unfiltered dataset	OLS linear regression on non-outlier datasets filtered by IQR	OLS linear regression on non-outlier datasets filtered by robust regression
RMSE	432,467.89	532,507.0	713,324.40	543,632.1
R^2	0.71	0.7	0.66	0.7
MAE	140,534.69	128,792.3	170,450.08	131,026.4

Models used for predicting road length of non-outlier dataset (filtered by robust regression)

Metrics	OLS linear regression on unfiltered dataset	Robust linear regression on unfiltered dataset	OLS linear regression on non-outlier datasets filtered by IQR	OLS linear regression on non-outlier datasets filtered by robust regression
RMSE	181,664.10	87,533.46	42,996.28	37,446.40
R^2	0.37	0.42	0.44	0.89
MAE	80,818.42	39,809.49	33,166.62	27,866.90

The description provided above focuses specifically on Model 2 (road length), but similar evaluations were conducted for Model 1 (road density). Figure 8 and Figure 9 present the actual vs predicted scatter plots, and residual plots, respectively, from the different regression models. All the models show a tight cluster of data points around the diagonal line, however, the OLS linear regression on the unfiltered dataset shows the tightest cluster, except for the few outliers. It should be noted that the scales for the unfiltered datasets and the non-outlier datasets are different.

Table 4 shows that the OLS Linear Regression on the unfiltered dataset model has the lowest RMSE (1.12) and a high R^2 (0.61), indicating good performance but potentially influenced by outliers. Robust Linear Regression model shows a slight decrease in R^2 (0.58) and an increase in RMSE (1.41), suggesting it better handles outliers as indicated by a slightly lower MAE (0.57) compared to OLS on the unfiltered data. The OLS Linear Regression on the Non-Outlier Dataset filtered by the IQR model appears to be most suitable for non-outlier predictions due to its balance of low RMSE and MAE while maintaining high R^2. For predicting road density, the OLS linear regression on the unfiltered dataset was selected for predicting both the outlier and non-outlier datasets since it had the least error.

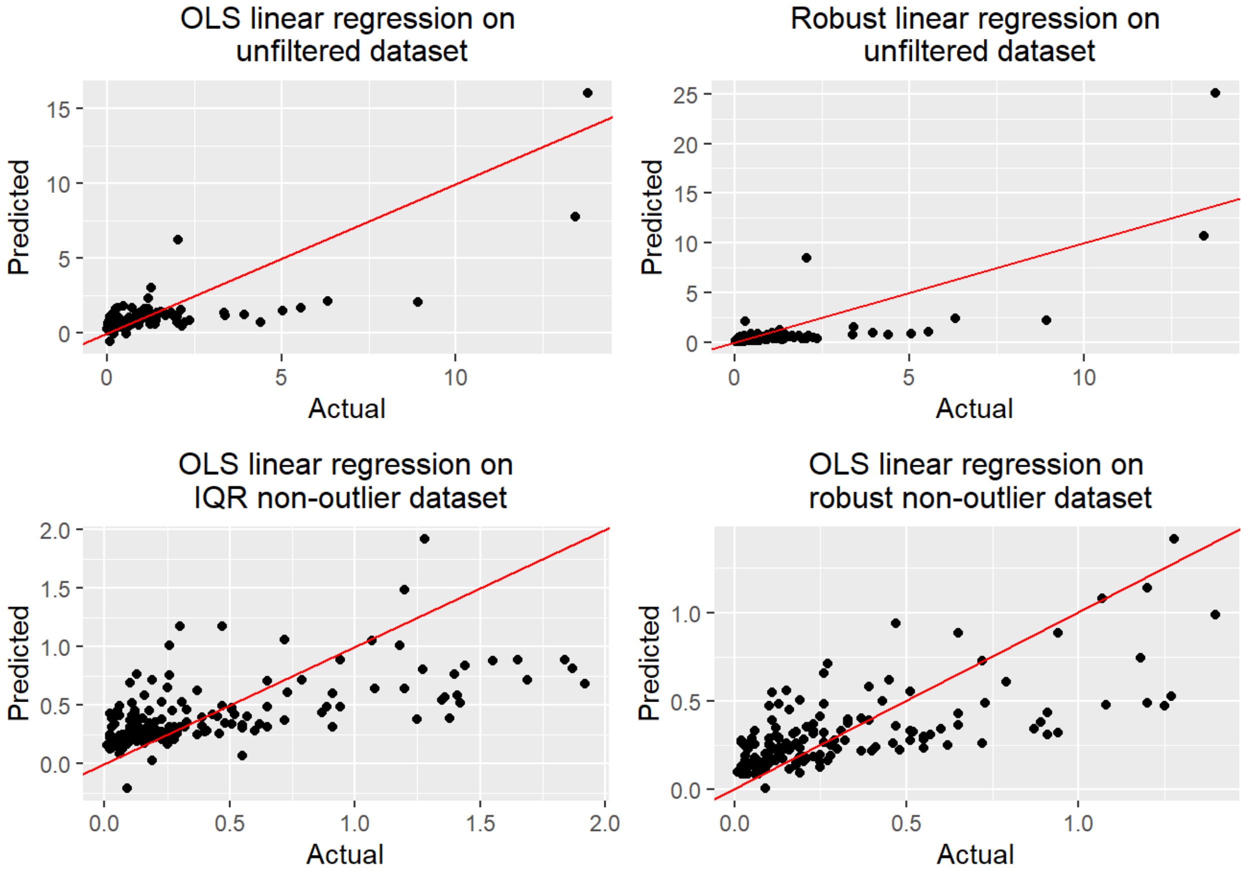
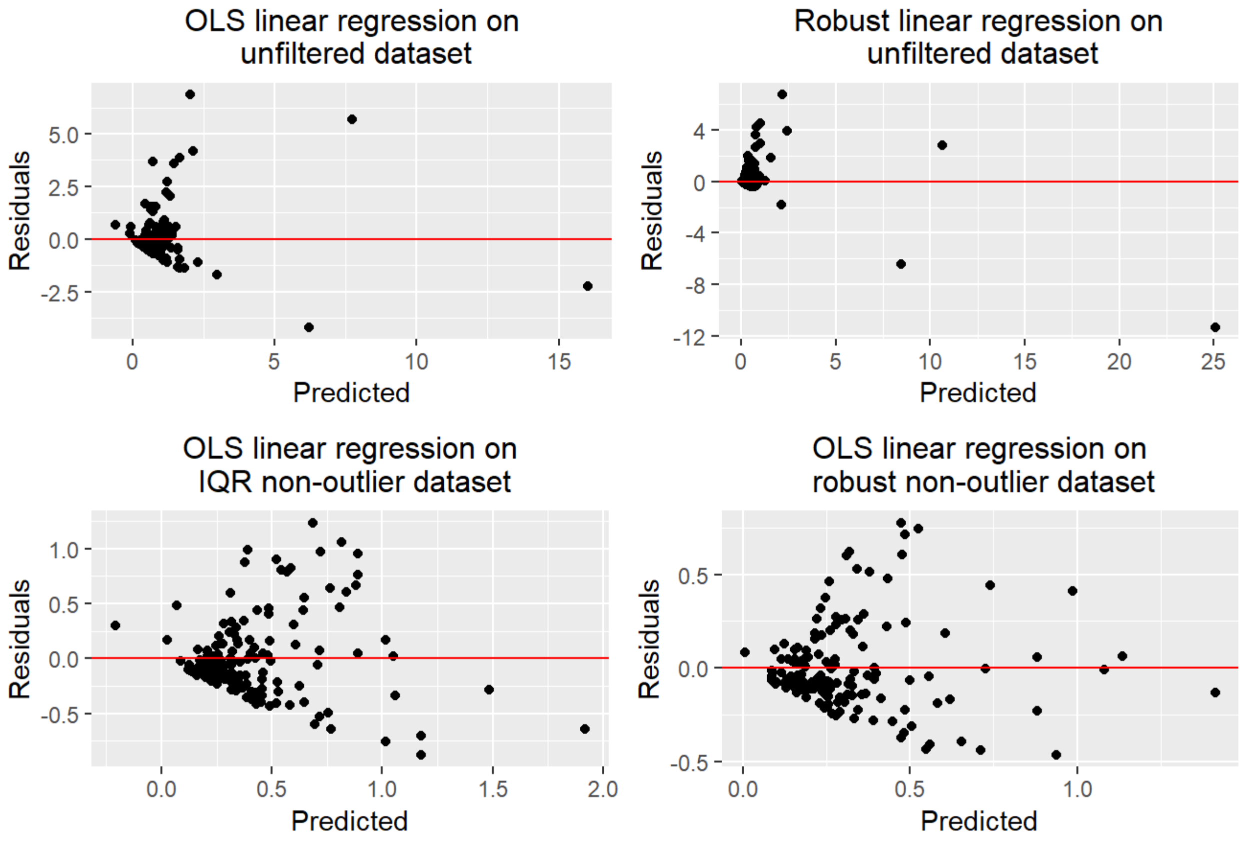


Figure 8. Predicted vs Actual scatter plots for road density prediction for the regression models



negative residual means over predicition

Figure 9. Residual plots for road density prediction for the regression models

Table 4. Performance metrics of regression models for predicting road density (lane-km/km^2)

	Models used for predicting road density of unfiltered dataset			
Metrics	**OLS linear regression on unfiltered dataset**	**Robust linear regression on unfiltered dataset**	**OLS linear regression on non-outlier datasets filtered by IQR**	**OLS linear regression on non-outlier datasets filtered by robust regression**
RMSE	1.12	1.41	1.22	1.38
R^2	0.61	0.58	0.61	0.58
MAE	0.60	0.57	0.55	0.57

Model coefficients

Table 5 presents the regression coefficients and standard error from multiple linear regression for the three models. The response variable for Model 1 is road density (lane-km/km^2), while that of Model 2 and Model 3 is road length (lane-km) but with different explanatory variables. It should be noted that continuous explanatory variables in Model 3 were $\log_{10}$-transformed because of the skewed data distribution (*21*). The regression coefficients of Model 3 from Meijer et al (17) were obtained based on a total road length of approximately 21 million lane-km. In contrast, the regression coefficients of Model 2 were based on different dataset with estimated total road length of 40.4 million lane-km in 2020. The differences in the underlying data and explanatory variables used to establish the regression coefficients are expected to have an impact on all the model's coefficients and predictions.

Table 5. Regression coefficients and standard error of multiple linear regression for the three models

Model 1 (Explanatory variables)	**Road density regression coefficients**	
	Non-outlier dataset	**Outlier dataset**
Intercept	2.72E-01 (1.20E-01)	2.72E-01 (1.20E-01)
Population density	6.67E-04 (5.11E-05)	6.67E-04 (5.11E-05)
GDP/capita PPP	2.53E-05 (5.47E-06)	2.53E-05 (5.47E-06)
Population Density	-8.56E-08 (4.51E-08)	-8.56E-08 (4.51E-08)
Model 2 (Explanatory variables)	**Road length regression coefficients**	
	Non-outlier dataset	**Outlier dataset**
Intercept	4.79E+03 (3.35E+03)	1.27E+03 (2.50E+03)
Land surface area	6.08E-02 (4.39E-03)	6.58E-02 (3.42E-03)
Truck	5.49E-06 (3.66E-07)	5.73E-06 (2.79E-07)
Model 3 (Explanatory variables $\log_{10}$ transformed)	**Road length regression coefficients**	
	Non-outlier dataset	**Outlier dataset**
Intercept	−1.66	−1.66
Population density	0.52 (0.04)	0.52 (0.04)
GDP/capita, PPP	0.13 (0.05)	0.13 (0.05)
Land surface area	0.90 (0.02)	0.90 (0.02)
OECD Membership	0.36 (0.07)	0.36 (0.07)

Regional pavement design information

Table 6 shows the representative countries for pavement design for each region, with the intent of estimating the most likely approaches to pavement design for countries for which pavement design information was not readily available. Pavement design information was not found for any country in the ATE, EU5, OETE, and 'Others' regions; consequently, the pavement design information of a neighboring country from outside the regional group was assumed and adopted for these regions. Pavement design information collected for the representative countries includes pavement structure types, material types, layer thicknesses, mix designs, and specifications, and pavement M&R schedules. The information was sourced from each country's national pavement design standard manuals, reviewed articles, and/or relevant literature. Table 40 presents the pavement structure data collected for the representative countries.

Table 6. Representative countries for pavement design

Region	Representative countries
Africa	South Africa, Nigeria, and Kenya
ASEAN	Vietnam
ATE	Turkey
China	China
EU 5	Germany
India	India
Latin America	Brazil
Middle East	Iran, United Arab Emirates (UAE), Qatar
ODA	Pakistan, Mongolia
OECD Europe	Austria, Spain, Germany, Netherlands, Italy, Sweden, Turkey, United Kingdom
OECD North America	Canada, Mexico, United States
OECD Pacific	Australia, Japan
OETE	Netherlands
Other OECD	Chile, Israel
Others	Australia
Russia	Russia

For most representative countries, the typical material for the surface layer of each road type is hot mix asphalt (HMA), and the base layer is either aggregate base or cement stabilized aggregate base. Table 7 summarizes the materials that are most used as surface and base layers for most road types in the regions. Africa, ASEAN, China, Middle East, ODA, and Others are regions where CTB is mostly used as base layer. The subbase is mainly cement stabilized subbase and granular subbase. Other base materials used in some countries like India, and Brazil include dense bituminous macadam, and wet mix macadam. Pavement LCA was undertaken for only the surface and base layer. Preliminary analysis of the pavement design data shows that representative countries in the same regions had similar pavement designs and maintenance schedules.

Table 7. Regions and their commonly used pavement layer materials

Region	Surface layer	Base layer
Africa	HMA	CTB
ASEAN	HMA	CTB
ATE	HMA	AB
China	HMA	CTB
EU 5	HMA	AB
India	HMA	AB
Latin America	HMA	AB
Middle East	HMA	CTB
ODA	HMA	CTB
OECD Europe	HMA	AB
OECD North America	HMA	AB
OECD Pacific	HMA	AB

Region	Surface layer	Base layer
OETE	HMA	AB
Other OECD	HMA	AB
Others	HMA	CTB
Russia	HMA	AB

Regional electricity and asphalt plant fuel information

The electricity grid mix data was sourced from the US Energy Information Administration (*25*). Collecting this information is crucial to determine electricity and asphalt mixing fuel emission factors for all regions. The U.S. EIA uses a regional classification system for summarizing electricity mix information of countries. Thus, their classification system was mapped to the regional classification system adopted in this study as shown in Table 8. Table 42 shows the projected electricity mix for all regions.

Table 8. Representative countries/regions for electricity mix

Region	Representative countries/EIA regions
Africa	South Africa
ASEAN	Other Non-OECD Asia
ATE	Other Non-OECD Europe & Eurasia
China	China
EU 5	Other Non-OECD Europe & Eurasia
India	India
Latin America	Brazil
Middle East	Total Non-OECD
ODA	Other Non-OECD Asia
OECD Europe	OECD Europe
OECD North America	Mexico & Other OECD North Americas
OECD Pacific	Australia
OETE	Other Non-OECD Europe & Eurasia
Other OECD	Total OECD
Others	Total Non-OECD
Russia	Russia

Asphalt mixing fuel type data were collected for all the representative countries for pavement design from relevant online literature, reports, and national data repositories. Table 9Table 6 shows the asphalt mixing fuel used in the representative countries. Heat energy in asphalt mixing plant is mostly acquired by combustion of diesel, natural gas, residual fuel oil, propane or other fuel types that are common, locally available, and cost-effective to use in the region in consideration. The most used fuel types were fuel oil and natural gas, with some countries also utilizing diesel fuel. Some of the countries such as India, Japan, and the US, use more than one source of asphalt mixing fuel. No mixing fuel information was found for Iran, Qatar, Israel, and Nigeria.

Table 9. Asphalt mixing fuel for pavement design representative countries

Representative Country	Mixing fuel	Reference
China	Heavy oil	(*26*)
India	Heavy oil, natural gas, diesel	(*27*)
Pakistan	Diesel fuel	(*28*)
Vietnam	Diesel oil, fuel oil	(*29*)
Japan	Heavy oil, natural gas, LPG	(*30*)
Mongolia	Natural gas	(*31*)
Austria	Natural gas	(*32*)
Germany	Fuel oil	(*33*)
Sweden	Heating oil, diesel	(*34*)
UK	Natural gas	(*35*)
Netherlands	Natural gas	(*36*)
Spain	Natural gas, fuel oil	(*37*)
Italy	Natural gas	(*38*)
Turkey	Natural gas, fuel oil	(*39*)
Russia	Fuel oil	(*40*)
Canada	Natural gas, diesel, heavy fuel oil	(*41*)
US	Natural gas, fuel oil	(*42*)
Mexico	Diesel fuel	(*43*)
Colombia	Heavy fuel oil	(*44*)
Brazil	Diesel oil	(*45*)
Chile	Natural gas	(*46*)
Australia	Diesel fuel	(*47*)
UAE	Natural gas, diesel fuel	(*48*)
South Africa	Heavy fuel oil	(*17*)

Electricity and HMA mixing fuel emission factors

The electricity emission factors for the current year represent the 2021 carbon intensity of electricity generation for countries and regions as documented by the Statistical Review of World Energy[4]. To estimate the electricity emission factors for other decades, first, the emissions per kilowatt-hour ($kgCO_2e/kWh$) for each electricity source, such as coal, natural gas, and renewables are determined using GaBi[5]. It was assumed that the GHG emissions per kWh of electricity from a given source were similar across all regions. Next, the $kgCO_2e/kWh$ value obtained in the first step was multiplied by the percentage each source contributes to the electricity mix. For instance, coal produces 1.08 $kgCO_2e/kWh$ and accounts for 31% of the 2030 electricity mix in Africa, its contribution would be $1.082 \times 0.311 = 0.337$ $kgCO_2e/kWh$ (0.093 $kgCO_2e/MJ$). Finally, summing up the $kgCO_2e$ /kWh contributions of all electricity sources in a

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[4] https://ourworldindata.org/grapher/carbon-intensity-electricity?tab=table&time=2000.2021

[5] Now called Managed LCA Content (MLC), https://sphera.com/solutions/product-stewardship/life-cycle-assessment-software-and-data/managed-lca-content/

region's electricity mix gives the emission factors for the region's electricity mix. Table 10 presents the electricity emission factors in megajoules (MJ) for the regions.

The expected trend is that as regions transition from fossil fuel electricity sources to renewable sources, the GHG emissions/MJ of electricity will reduce, as observed in regions like Africa, China, OECD North America, etc. However, in regions like ASEAN and ODA, the GHG emissions/MJ of electricity in 2050 are higher than in 2030. The electricity mix data for Other Non-OECD Asia drives this increase, as coal use will rise significantly by 2050 compared to 2030. The significant difference between the current and 2030 emission factors in some regions, such as the Middle East, is likely due to the different data sources and approaches for obtaining current and projected emission factors. The current year uses publicly available data on the carbon intensity of electricity generation for countries and regions. In contrast, emission factors for 2030 to 2050 are estimated based on the future projections of the electricity mix.

Table 10. Electricity emission factors for each region

Region	Representative countries / EIA regions	GHG emission factors ($kgCO_2e/MJ$)			
		Current	2030	2040	2050
Africa	South Africa	0.199	0.111	0.063	0.052
ASEAN	Other Non-OECD Asia	0.151	0.163	0.150	0.164
ATE	Other Non-OECD Europe & Eurasia	0.120	0.107	0.099	0.093
China	China	0.151	0.141	0.122	0.110
Colombia	Colombia	0.050	0.054	0.056	0.042
EU 5	Other Non-OECD Europe & Eurasia	0.120	0.107	0.099	0.093
India	India	0.177	0.128	0.114	0.087
Latin America	Brazil	0.044	0.060	0.053	0.052
Middle East	Total Non-OECD	0.199	0.131	0.114	0.103
ODA	Other Non-OECD Asia	0.151	0.163	0.150	0.164
OECD Europe	OECD Europe	0.102	0.056	0.052	0.048
OECD North America	USA, Mexico, Canada	0.111	0.100	0.087	0.070
OECD Pacific	Australia	0.148	0.056	0.052	0.048
OETE	Other Non-OECD Europe & Eurasia	0.120	0.107	0.099	0.093
Other OECD	Total OECD	0.105	0.087	0.080	0.072
Others	Total Non-OECD	0.199	0.131	0.114	0.103
Russia	Russia	0.100	0.106	0.108	0.106

The UCPRC recently developed a pavement LCA web-based tool called the environmental life cycle assessment for pavements (eLCAP) for the California Department of Transportation (Caltrans) and for teaching and research purposes at the University (*49*). eLCAP includes all the life cycle stages, materials, construction, use and end of life, of a pavement. The data and models were developed to comply with California specific conditions and Caltrans construction practices. HMA surfaced pavements are the most constructed in the world (23) for which HMA is the major construction material needed. After asphalt binder, plant operations are the most energy intensive processes that require electricity and heat to run the operations.

To calculate the GHG emissions impacts of materials produced in different countries, a method that is described below was used:

Step 1: For the list of representative countries (mainly for which the data were available), current and 2030, 2040, 2050 projected electricity GHG emissions were determined.

Step 2: For the same list of countries, fuel types that are most used at asphalt plants to prepare asphalt mixtures were identified. For each fuel type, the energy density (measured as MJ/unit quantity) of the fuel was noted.

Step 3: eLCAP was used to determine the GHG emissions impacts for the HMA mixture that is typically used in California/Caltrans practices. The electric energy (in MJ) and energy from fuel (in MJ) that are used to produce asphalt mixture at a plant were noted.

Step 4: Using the electric and fuel energy required to produce asphalt mixture from Step 3, and data from Step 1 and Step 2, the quantity of fuel and electricity required in each country's asphalt plant were determined.

To demonstrate the steps used to determine fuel quantities and electricity, an example is shown below.

The fuel energy from natural gas needed at an asphalt plant to produce 1 kg of HMA (from eLCAP's database for California), is 0.34 MJ. Fuel oil is commonly used in Germany as the heating fuel at an asphalt plant and the energy density of fuel oil is 38,000 MJ/m^3. Therefore, the quantity of the fuel oil needed at an asphalt plant will be 8.8E-06 m^3 (= 0.34/38,000). The life cycle GHG emissions from the fuel oil using Sphera LCA for Experts is 3,800 kgCO$_2$e/m^3. Hence the GHG emissions from fuel oil to produce 1 kg of HMA will be 0.033 kgCO$_2$e (=b8.8E-06 x 3,800). The electricity needed to produce 1 kg of HMA in California is 1.32E-02 MJ. The life cycle GHG emissions from electricity at grid for Germany is 0.122 kgCO$_2$e/MJ. Thus, the life cycle GHG emissions from electricity in Germany will be 1.6E-03 kgCO$_2$e/kg of HMA, and the total life cycle GHG emissions produced at an asphalt plant in Germany to produce 1 kg of HMA, based on the assumptions and calculation above, is 0.035 kgCO$_2$e (0.033+1.6E-03). The results for other countries are presented in Table 11. Table 43 in the Appendix F summarizes the electricity and asphalt mixing fuel GHG emission factors in KgCO$_2$e/kg of HMA produced at asphalt plants for 2030, 2040, and 2050 across the regions.

Pavement layer emission factors

The design of pavement layers varies considerably around the world. Some countries utilize a two-base layer system with an underlying subbase, while others use a structure with a single base layer. A summary thickness estimate from the pavement data collected resulted in a simplification that cement-treated bases (CTB) of 400 mm thickness or aggregate bases (AB) of 450 mm thickness are used in the representative countries, as shown in Table 40. These thicknesses were assumed for all regions based on whether the base layer is cement-treated or just aggregate base. The thickness of the HMA layer across the representative countries varied but 178 mm was an approximate average (See Appendix D, Table 40). *eLCAP* was run to determine the GHG emissions impacts for a lane-km of a road for each layer type and material type as presented in Table 11. Life cycle inventory data on construction equipment for building pavements and transporting materials were also taken from the *eLCAP* database that can be found in the report by Saboori et al (*29*). The report provides detailed methods of data collection and models' development that are relevant for California-specific conditions and reflect Caltrans construction practices. It is assumed that the asphalt mixtures are transported from an asphalt plant about 40 km away from the construction site for all the regional cases. It is assumed that all the existing roads are fully paved.

Table 11. Common emissions factors for all the regions for HMA, AB, and CTB construction per lane-km

Layer		GHG emissions ($kgCO_2e$)/lane-km
178 mm thick HMA lane-km section of HMA pavement	Asphalt binder	4.07E+04
	Crushed Aggregate	4.01E+03
	HMA transport (cradle-site)	4.12E+04
	Construction	1.48E+03
400 mm thick lane-km section of CTB (5% cement)	CTB (cradle-to-gate)	1.58E+05
	Transport (Gate-to-site)	2.58E+04
	Cement (cradle-to-gate)	1.49E+05
	Construction	4.56E+02
450 mm thick lane-km section of AB	AB (cradle-to-gate)	1.14E+04
	Transport (gate-to-site)	2.97E+04
	Construction	5.26E+02

Table 12. Electricity (2021) and HMA mixing fuel emission factors for pavement design representative countries

	2021 Electricity		Fuel				2021 Electricity + Fuel		
Regions	**Emissions (kgCO$_2$e /MJ)**	**Emissions at Plant from Electricity (kgCO$_2$e)**	**Fuel Type**	**Energy Required for HMA Plant from Fuel (MJ)**	**Energy Density of Fuels (MJ/m^3)**	**Quantity of fuel needed for plant (m^3)**	**Emissions from Fuel (kgCO$_2$e/m^3)**	**Emissions at Plant from Fuel (kgCO$_2$e)**	**Emissions at Plant (kgCO$_2$e) per kg of HMA**
China	0.151	2.0E-03	Fuel Oil	3.4E-01	3.8E+04	8.9E-06	3.8E+03	3.4E-02	3.6E-02
India	0.177	2.3E-03	Fuel Oil	3.4E-01	3.8E+04	8.9E-06	3.8E+03	3.4E-02	3.6E-02
Japan	0.133	1.8E-03	NG	3.4E-01	3.7E+01	9.1E-03	-	2.1E-02	2.3E-02
Germany	0.102	1.3E-03	Fuel Oil	3.4E-01	3.8E+04	8.9E-06	3.8E+03	3.4E-02	3.5E-02
Sweden	0.013	1.7E-04	Fuel Oil	3.4E-01	3.8E+04	8.9E-06	3.8E+03	3.4E-02	3.4E-02
UK	0.075	9.8E-04	NG	3.4E-01	3.7E+01	9.1E-03	-	2.1E-02	2.2E-02
Netherlands	0.108	1.4E-03	NG	3.4E-01	3.7E+01	9.1E-03	-	2.1E-02	2.2E-02
Turkey	0.120	1.6E-03	Fuel Oil	3.4E-01	3.8E+04	8.9E-06	3.8E+03	3.4E-02	3.5E-02
Russia	0.100	1.3E-03	Fuel Oil	3.4E-01	3.8E+04	8.9E-06	3.8E+03	3.4E-02	3.5E-02
Canada	0.036	4.7E-04	Fuel Oil	3.4E-01	3.8E+04	8.9E-06	3.8E+03	3.4E-02	3.4E-02
US	0.105	1.4E-03	Fuel Oil	3.4E-01	3.8E+04	8.9E-06	3.8E+03	3.4E-02	3.5E-02
Mexico	0.111	1.5E-03	Diesel	3.4E-01	3.6E+04	9.4E-06	3.2E+03	3.0E-02	3.1E-02
Colombia	0.050	6.6E-04	Fuel Oil	3.4E-01	3.8E+04	8.9E-06	3.8E+03	3.4E-02	3.4E-02
Brazil	0.044	5.8E-04	Diesel	3.4E-01	3.6E+04	9.4E-06	3.2E+03	3.0E-02	3.1E-02
Australia	0.148	1.9E-03	Diesel	3.4E-01	3.6E+04	9.4E-06	3.2E+03	3.0E-02	3.2E-02
UAE	0.128	1.7E-03	Diesel	3.4E-01	3.6E+04	9.4E-06	3.2E+03	3.0E-02	3.2E-02
South Africa	0.199	2.6E-03	Fuel Oil	3.4E-01	3.8E+04	8.9E-06	3.8E+03	3.4E-02	3.6E-02
Nigeria	0.105	1.4E-03	Diesel	3.4E-01	3.6E+04	9.4E-06	3.2E+03	3.0E-02	3.1E-02
Kenya	0.024	3.2E-04	Diesel	3.4E-01	3.6E+04	9.4E-06	3.2E+03	3.0E-02	3.0E-02

Maintenance schedules and GHG emissions factors

An effort was made to collect the future maintenance schedules for different representative countries however, the team was unable to gather such information. Many countries exclude detailed maintenance information in road design manuals, leading to incomplete or unavailable regional data. Moreover, only a few published sources provide information on pavement maintenance and rehabilitation in certain countries. Differences in data collection methods and reporting standards in published sources lead to inconsistencies, making it harder to conduct reliable and meaningful comparisons across regions or studies. Therefore, it was decided that a maintenance schedule developed by Caltrans for asphalt pavements with 20 years design life and heavy traffic would be used in this study and assumed to be practiced in the world. This maintenance and rehabilitation schedule assumes sufficient available funding is used in a cost-optimized manner. At 7 and 14 years, a thin overlay of 45 mm HMA is applied over roads built after 2021 while a medium overlay of 75 mm HMA is applied every 20 years, and the cycle is then repeated. Caltrans has another schedule that is used for lower volume roads that uses a seal coat in place of the 45 mm HMA overlay and has lower emissions.

Table 13 presents the assumed maintenance schedules for roads existing before 2021 and new roads built after 2021. The maintenance schedule in this study assumes that for roads built before 2021, half receive thin overlay and chip seal maintenance every decade, while the other half receive medium overlay maintenance. Roads built after 2021 receive thin overlay and chip seal in their first 10 years and medium overlay within their first 20 years. This maintenance cycle repeats every 10 years for thin overlay and chip seal and every 20 years for medium overlay. For roads receiving thin overlay and chip seal maintenance, the study assumes that 80% get a chip seal, while 20% get a thin overlay.

Through a sensitivity analysis, the study explores a scenario where maintenance gets delayed due to limited financial resources. In this case, thin overlay and chip seal maintenance gets deferred to the 20th year and medium overlay to the 40th year of a road’s life. This delay represents a situation of low road maintenance, resulting in higher road roughness, which could increase fuel consumption and emissions. The sensitivity analysis highlights the importance of regular maintenance to maintain road quality and minimize its environmental impacts from additional fuel consumption.

Table 13. Maintenance scheduling for global roads

Analysis year	New roads	Existing roads in 2021	Roads built after 2021
2020	All existing		
2030	2021 – 2030	half the roads get thin overlay + chip seal, half are getting medium overlay	built by 2030 (Thin overlay + Chip seal)
2040	2031 – 2040	half the roads get thin overlay + chip seal, half are getting medium overlay	built by 2030 (Medium overlay) + built by 2040 (Thin overlay + Chip seal)
2050	2041 – 2050	half the roads get thin overlay + chip seal, half are getting medium overlay	built by 2030 (Thin overlay + Chip seal) + built by 2040 (Medium Overlay) + built by 2050 (Thin overlay + Chip seal)

The approach adopted to obtain the emission factors of the pavement layers was applied to estimate the emission factors for pavement layers in the maintenance schedules. eLCAP generated GHG emission factors for a lane km of flexible pavement under the assumed maintenance schedule, as shown in Table 14.

Table 14. Emission factors for HMA pavements maintenance schedules

Maintenance Schedules	Maintenance year	GHG Emissions (kgCO$_2$e per lane km)
Medium Overlay (75mm HMA)	20	4.22E+04
Thin Overlay (45 mm HMA)	10	2.55E+04
Chip Seal	10	3.97E+03

Road life cycle assessment

Figure 10 shows the life cycle stages of building/construction works, as presented in EN 15978 and ISO 21931 standards. It shows how embodied and operational carbon occurs at different stages through the life cycle of a building or infrastructure comprised of the product stage (A1 – A3), construction stage (A4 – 45), use stage (B1 – B7), and end-of-life stage (C1 – C4). The standards also cater to future potential for reuse, recovery, and recycling (D1 – D4). The stages range from raw material extraction to product manufacturing, transportation, site installation, building/infrastructure maintenance, and disposal.

In the context of roadway infrastructure, the product stage (A1 – A3), otherwise known as the cradle-to-gate stage, deals with emissions from extraction and manufacturing of raw materials such as portland cement, asphalt binders, aggregates, etc.; transportation of these materials from the point of supply of extraction to manufacturing plant; and manufacturing of infrastructure products such as ready-mix concrete, HMA, etc. The construction stage (A4 – A5) captures emissions from material and component transportation from the factory gate to the construction job or project site and emissions from either off-site or on-site construction and installation.

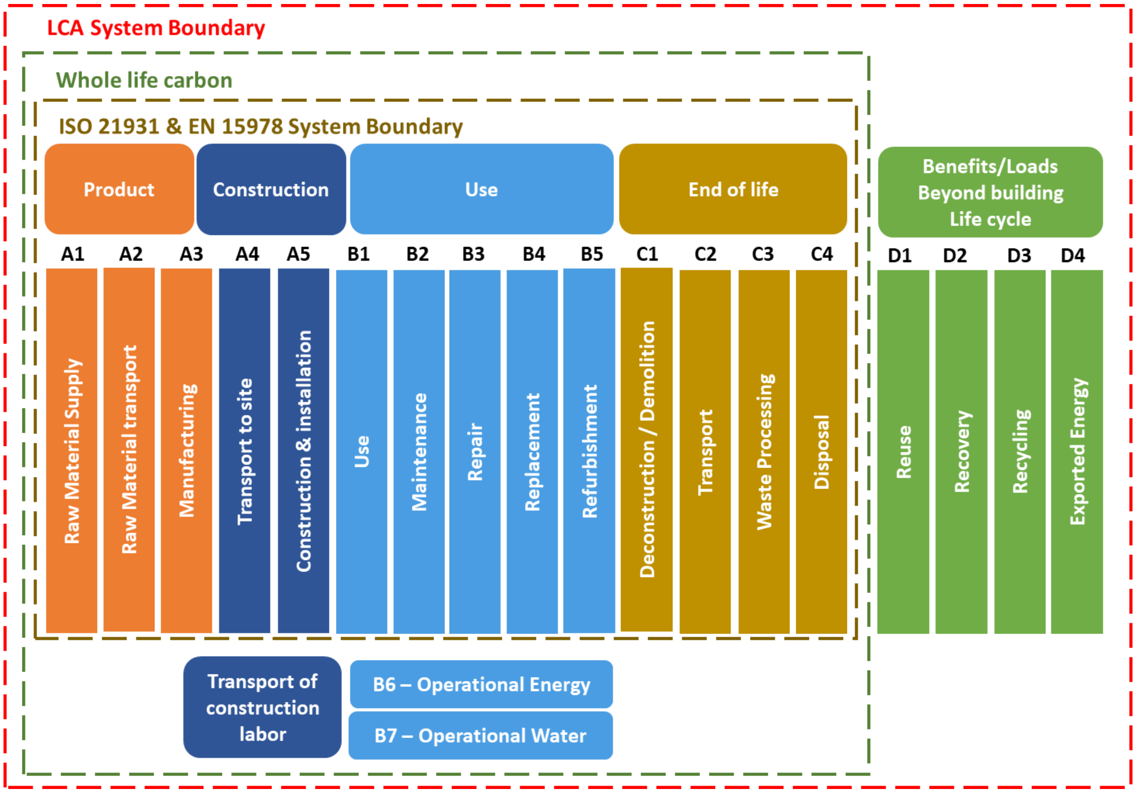

Figure 10. Life cycle stages for road infrastructure (ISO 21931 and EN 15978)

The use stage (B1 – B7) represents carbon emissions from infrastructure usage over its entire life cycle, from completion to the end of its service life. These may include emissions from pavement vehicle interaction, stormwater runoff, cementitious material carbonation, lighting, heat island effect, roadway treatments such as mill and fill, full-depth reclamation (FDR), chip sealing, cold in-place recycling, etc. The end-of-life stage (C1 – C4) accounts for emissions from removing out-of-service roadway features, transporting demolished materials, processing waste materials, landfilling, etc. The benefits/loads beyond the life cycle stage (D1 – D4) could include the impact of material reuse and recycling.

Based on ISO 21931, A1 – A5 in the context of road infrastructure applies to new road construction, while B2 and B3 represent maintenance and rehabilitation of existing roads. The life cycle stages A1 – A5 cover the cradle-to-construction process for new roads, including raw material extraction, transport, manufacturing, and construction activities. For existing roads, B2 (maintenance) and B3 (repair/rehabilitation) represent use-stage impacts but also involve their own A1 – A5 processes, such as raw material supply and construction for repair work. B1 covers the impacts of additional fuel consumption caused by road roughness (pavement-vehicle interaction).

LCA was used to quantify the GHG emissions from roads in each region for the decades 2021 – 2030 (2030), 2031 – 2040 (2040), and 2041 – 2050 (2050). The scope of the LCA covers cradle-to-laid GHG emissions from the initial construction of new roads (A1 through A5 following ISO 21931 terminology), the M&R of existing roads (stages B2 and B3) and additional fuel consumption from road roughness (a part of B1 in ISO 21931 terminology). Although the impact of additional fuel consumption from road roughness typically falls under the B1 use stage of the road, this study presents the impact as part of the vehicle-related GHG emissions for clarity.

The length of new roads to be built for each decade is determined by subtracting the existing road length from the projected length. GHG emissions from maintenance are calculated for existing road lengths and newly constructed roads, focusing on estimating the impact of maintenance activities (thin or medium overlay). Appendix G, Table 48 shows the equations for quantifying GHG emissions.

Approach for estimating GHG emissions from the build-out of global bridges and culverts

Summary steps

This section details the steps taken in estimating the GHG emissions from the build-out of global bridges and culverts. The steps for the bridges are:

1. Select representative countries for each region in IEA's regional classification of countries for collecting bridge density information.
2. Collect the number of bridges data for representative countries
3. Calculate the bridge densities (number of bridges / land area) of countries that represent the regions
4. Estimate the number of bridges in each region (bridge density of representative country / region area)
5. Develop common material (PCC, and reinforcement), transport, and construction emission factors for a typical bridge
6. Determine the GHG emissions from constructing global bridges using the developed emission factors and the estimated number of bridges for each region.
7. Sensitivity analysis for cement replacement in bridge

Similar steps were followed for estimating the GHG emissions from global culverts.

Regional bridge densities

Only very few representative countries used for pavement design had information on the number of bridges. Thus, new representative countries for calculating bridge densities as shown in Table 41 were identified and selected based on availability of data on the number of bridges. Table 15 shows the bridge data information for the regions after using bridge density of representative countries to estimate the number of bridges in each region. The region area was calculated by adding the land area of the countries in a region. The estimation shows that OECD North America, China, and OECD Europe are regions with the highest number of bridges.

Table 15. Bridge data for region

Region	Representative country	Bridge density	Region Area (km^2)	Number of bridges in region
Africa	South Africa	0.008	29,652,434	232,215
ASEAN	Vietnam	0.014	4,394,536	60,290
ATE	Turkey	0.011	4,121,476	46,461
China	China	0.102	9,389,260	961,207
EU 5	Ukraine	0.048	404,160	19,531
India	India	0.013	2,973,190	172,517
Latin America	Brazil	0.014	17,348,398	249,075
Middle East	Saudi Arabia	0.003	5,427,557	15,149
ODA	Mongolia	0.0003	4,089,862	1,137
OECD Europe	UK	0.303	5,108,536	1,545,843
OECD North America	USA	0.068	20,067,380	1,361,608
OECD Pacific	Australia	0.007	8,417,430	57,998
OETE	Ukraine	0.046	1,016,635	47,158
Other OECD	Australia	0.007	765,172	5,272
Other	Fiji	0.066	4,244	279
Russia	Russia	0.003	16,376,870	42,000

Regional culvert distribution

Currently, there is a lack of data regarding the distribution of culverts across countries or regions worldwide. No database or repository provides information on the distribution of culverts by country or for individual countries. An attempt was made to extract the bridge or culvert number or design information using Google Earth; however, this attempt proved unrealistic and was stopped because of the tool's limited resolution, lack of metadata, and the task's scale. As a result, this study adopts the ratio of culverts to road length in California's highway network for all the regions, excluding India. India's Ministry of Road Transport and Highways has cataloged 38,218 bridges and 134,229 culverts within the Indian Bridge Management System (IBMS) (*51*). In India, the number of culverts per kilometer of road ranges from one in flat areas to three in undulating terrain (*52*). California's highway system, spanning 79,894 kilometers, has 205,000 culverts (*53*), translating to roughly 2.6 culverts per centerline kilometer. Table 16 shows the number of bridges for all the regions using 2.6 culverts per centerline kilometer, except for India.

Table 16. Number of culverts by region

Region	Regional road length (km)	Number of culverts
Africa	3,180,446	8,160,678
ASEAN	2,141,458	5,494,747
ATE	250,047	641,593
China	5,200,270	13,343,326
EU 5	181,342	465,304
India	6,371,847	134,229
Latin America	2,912,996	7,474,430
Middle East	661,139	1,696,411
ODA	1,250,183	3,207,833
OECD Europe	5,835,323	14,972,803
OECD North America	8,121,371	20,838,553
OECD Pacific	2,306,127	5,917,271
OETE	358,486	919,836
Other OECD	106,229	272,572
Others	7,035	18,051
Russia	1,553,664	3,986,533

Bridge and culvert emission factors

A bridge engineer at Caltrans was contacted to acquire a box concrete cast in place bridge design. The design shows that for a 30.5 x 23 m^2 bridge span, 183 tonnes of steel reinforcement and 1,117 tonnes of concrete are needed; the bridge width was calculated as width = 4 x 3.65 m (4 lanes) + 2 x 2.4 (2.4 m shoulder) + 2 x 0.6 (0.6 m barrier) + 1.8 (sidewalk) + 0.6 (median barrier).

Design specifications for a typical box concrete cast in place culvert (*54*) were adopted for all the regions for similar reasons shared in the case of the culvert. It is assumed that the culvert span is 3.65 m, and height is 1.8 m, and the portland cement concrete (PCC) thickness is 0.3 m. Using the Caltrans revised standard plan design tables it was determined that the total quantity of concrete needed is 5.37 m^3/m length of culvert and 320 kg/m of steel reinforcement. The materials and construction GHG emissions for a 4-lane culvert and 4-lane bridge are shown in Table 17.

Table 17. Common emissions factor in kgCO$_2$e for 4-lane culvert and 4-lane bridge

Material	Stages	GHG emissions (kgCO$_2$e)
Culvert (3.65 x 3.65 x 0.15 m^3)	PCC production	2.20E+04
	Steel reinforcement	9.40E+03
	Concrete to site transport (Gate-Site)	1.39E+03
	Steel reinforcement to site transport (Gate-Site)	3.46E+01
	Construction	6.42E+02
	Total	3.35E+04
Bridge (30.5 x 23) m^2	PCC production	1.30E+05
	Steel reinforcement	3.67E+05
	Concrete to site transport (Gate-Site)	8.25E+03
	Steel reinforcement to site transport (Gate-Site)	1.35E+03
	Construction	1.61E+02
	Total	5.07E+05

Bridge and culvert life cycle assessment

The scope of the LCA covers the GHG emissions from the build-out of bridges and culvert. The summation of the 4-lane bridge material, transport, and construction emission factors was multiplied by the total number of bridges to be built in the regions to estimate the A1-A5 (cradle-to-laid) GHG emissions of bridges. A1-A5 GHG emissions of culverts followed the same approach. The maintenance and replacement of existing bridges and culverts was not considered, assuming they have long life spans.

Approach for estimating GHG emissions from vehicle manufacturing and operation

Vehicle life cycle assessment (LCA) evaluates a vehicle's impacts throughout its life cycle, from raw material extraction to end-of-life disposal. Stages typically included in vehicle LCA are raw material extraction, manufacturing, distribution, the use stage (operation or driving), maintenance, and end-of-life. The production and disposal of a vehicle and its components, along with the associated upstream material and energy inputs, is termed the vehicle cycle (VC) (*55*). Vehicle operation impacts can be analyzed as Tank-to-Wheel (TTW) or Well-to-Wheel (WTW). TTW focuses on emissions from combusting or using fuel during vehicle operation, specifically the pollutants from a vehicle's exhaust (tailpipe emissions). On the other hand, WTW emissions cover the entire life cycle of fuel, including upstream emissions from fuel extraction, production, and distribution and downstream tailpipe emissions. In the use stage, tailpipe emissions significantly contribute to a vehicle's total environmental impact, especially for fossil fuel vehicles.

This study investigates the impact of vehicle manufacturing (including raw material extraction) and vehicle operation (WTW). It excludes the impact of distribution and end-of-life.

Summary steps

This section details the steps taken in estimating the GHG emissions from vehicle manufacturing and driving vehicles. The steps for vehicle manufacturing and driving are:

1. Collect the 2020, 2030, 2040, and 2050 decadal vehicle kilometers travelled (VKT) and vehicle sales data for each region
2. Determine single vehicle manufacture (kgCO_2e), vehicle operation emission factors (kgCO_2e/liter) for gasoline, diesel, and electric passenger cars and trucks for the regions
3. Determine the regions' cumulative number of manufactured vehicles for the vehicle classes for each decade (2021 – 2030, 2031 – 2040, 2041 – 2050) using decadal sales data
4. Determine the regions' cumulative VKT and the corresponding liters of fuel consumed for the vehicle classes for each decade (2021 – 2030, 2031 – 2040, 2041 – 2050) using the decadal VKT data
5. Estimate the GHG emissions from vehicle manufacturing and operation

Vehicle manufacturing and driving emission factors

Manufacturing and WTW emission factors for gasoline, diesel, and electric cars and trucks were sourced from academic articles and online reports as shown in Table 18 for the different vehicle classes. These factors were used for all the regions. Table 46 and Table 47 in Appendix F show the manufacturing and WTW emission factors for passenger cars and trucks, respectively, for all the regions.

Table 18. Vehicle manufacturing and WTW emission factors

Lifecycle stage	Emission factors	Reference
Vehicle manufacturing per car (kgCO_2e)	4.60E+03	(*56*)
Vehicle manufacturing per truck (kgCO_2e)	1.60E+04	(*57*)
Vehicle operation for gas vehicles (kgCO_2e/liter)	2.77E+00	(*12*)
Vehicle operation for diesel vehicles (kgCO_2e/liter)	3.17E+00	(*12*)

Vehicle life cycle assessment

LCA is adopted to estimate the GHG emissions from vehicle manufacturing and the GHG emissions from driving on a smooth surface (without considering the impact of pavement roughness), also known as WTW GHG emissions. It is assumed that all vehicles sold in each projection year are newly manufactured vehicles, suggesting that vehicle owners change their vehicle every 10 years. Since there are no annual VKT and vehicle sales data, the cumulative VKT and vehicle sales for each decade were estimated by multiplying the VKT and vehicle sales in each projection year by ten. The cumulative number of manufactured vehicles for each decade is determined by multiplying the decadal vehicle sales data of the previous upper-bound year by ten. For example, the cumulative VKT between 2021 – 2030 is calculated by multiplying VKT in 2020 by ten, and the cumulative vehicle sales between 2021 – 2030 by multiplying vehicle sales in 2020 by 10. The GHG emissions from vehicle manufacturing and driving on a smooth surface is estimated using Equation 1 and Equation 2. It is assumed that each region manufactures their own vehicles. According to Chatti & Zaabar (*58*), fuel consumption for a typical car and truck moving at an average speed of 88 km/hr (55 mph) is 83.4 mL/km and 447.3 mL/km, respectively (see Table 16).

Equation 1

$$GWP_{vehicle\ manufacturing} = cumulative\ vehicle\ sales \times GWP_{single\ vehicle\ construction} (kgCO_2e)$$

Equation 2

$$\begin{aligned} GWP_{driving\ on\ smooth\ surface} &= cumulative\ decade\ fuel\ consumption\ (liters) \\ &\times WTW_{emission\ factor} (KgCO_2e/liters) \end{aligned}$$

Approach for estimating GHG emissions due to pavement roughness

Summary steps

1. Collect data on the relationship between International Roughness Index (IRI) and fuel consumption for different vehicle classes.
2. Determine the average speed of cars and trucks on a typical road network
3. Determine the average fuel consumption per vehicle distance travelled (L/km) for cars and trucks as IRI increases from 1m/km to 4m/km in twenty years
4. Determine the additional fuel consumption per vehicle distance travelled (L/km) for cars and trucks on rough roads. This is calculated by subtracting the base fuel consumption per vehicle distance travelled (L/km) at IRI of 1m/km from the average fuel consumption per vehicle distance travelled (L/km) after increased IRI.
5. Determine the cumulative additional fuel for each vehicle class across all decades. This is calculated by multiplying each region's decadal VKT by the additional fuel consumption per vehicle distance travelled (L/km)
6. Determine the WTW emission factor (kgCO_2e/liter of fuel consumed) for gas and diesel vehicles and (kgCO_2e/MJ of electricity consumed) for electric vehicles.
7. Estimate the GHG emissions from additional fuel consumption from roughness (a part of B1 in ISO 21931 terminology for infrastructure LCA)

Pavement roughness life cycle assessment

The additional GHG emissions due to roughness are from the increased fuel consumption caused by increased rolling resistance of the vehicles moving on a rough surface. Data relating roughness and fuel consumption of cars and trucks were collected from Chatti & Zaabar (32) Table 19 summarizes the relationship between pavement roughness and fuel consumption. A road with an IRI of 1 m/km is smooth, while fuel consumption increases with increasing IRI. The average speed of vehicles on road networks is assumed to be 88 km/hr (55 mph). Another assumption is that the road network periodically worsens by 1 m/km (roughness) and reaches a peak IRI of 4 m/km every 20 years. In other words, new roads roughen by 1 – 2 m/km within 10 years and by 3 – 4 m/km after 20 years. For instance, new roads require 83.38 mL/km of fuel for a car (from Table 19). After ten years, this amount increases to 84.63 mL/km, the average of 83.38 and 85.88 mL/km. Thus, the additional fuel due to pavement roughness after 10 years is 1.25 mL/km (84.63 – 83.38 mL/km). By the 20th year, the requirement rises to 88.80 mL/km, the average of 87.55 and 90.55 mL/km. In this case, the additional fuel due to pavement roughness becomes 5.42 mL/km (88.80 – 83.38 mL/km) after 20 years. After 20 years, roads are maintained and restored to an IRI of 1 m/km, restarting the roughening cycle. WTW emission factors for fossil fuel vehicles (kgCO_2e/liter) and electric vehicles (kgCO_2e/MJ) are assumed to be constant for all decades. The additional GHG emissions due to pavement roughness are estimated using Equation 3.

Table 19. Fuel consumption (mL/km) for cars and trucks (Chatti & Zaabar, 2012)

		IRI (m/km)					
Speed (km/hr)	**Type**	**1**	**2**	**3**	**4**	**5**	**6**
88	Car	83.38	85.88	87.55	90.05	91.72	94.22
88	Truck	447.31	456.26	460.73	469.68	474.15	483.09

Equation 3

$$Additional\ GWP_{due\ to\ pavement\ roughness} = additional\ fuel\ consumption\ (liters)\ \times WTW_{emission\ factor}(KgCO_2e/litre)$$

The additional fuel consumption due to roughness for electric vehicles was first estimated in liters and converted to MJ. This was done using fuel conversion factors of gasoline gallon equivalent (GGE) by the US Department of Energy (*59*). One gallon of gasoline is equal to 121 MJ of electricity, and one liter of gasoline is equal to 32 MJ of electricity. Table 20 shows the fuel consumption of electric vehicles after applying the fuel conversion factor to values provided in Table 19. The additional fuel in MJ was then multiplied by the decadal electricity emission factors in Table 10 to estimate the GHG emissions from the additional fuel consumed due to pavement roughness for electric vehicles. This process factors in the environmental impact of the electricity grid mix powering the electric vehicles.

Table 20. Fuel consumption (MJ/km) for electric cars and trucks

		IRI (m/km)					
Speed (km/hr)	**Type**	**1**	**2**	**3**	**4**	**5**	**6**
88	car	2.67	2.75	2.80	2.88	2.93	3.01
88	HHDT	14.30	14.58	14.73	15.01	15.16	15.44

Results and Discussion

Road Length Projection

Global road network growth

Table 21 shows the predicted road lengths and percentage increases for 2030, 2040, and 2050. Based on the available data, the global road length for 2020 is estimated to be 40.4 million lane-km. The results obtained from the regression analysis for Model 1 indicate an increase in 2020's road length by 18.5%, 41.8%, and 67.0% for 2030, 2040, and 2050, respectively. Model 2 shows that road lengths in 2030, 2040, and 2050 will increase by 29.1%, 47.3%, and 66.7%, respectively, relative to 2020. On the other hand, Model 3 suggests a more moderate increase relative to 2020 of 8.1%, 15.5%, and 21.2%, respectively, for 2030, 2040, and 2050. Model 1 and Model 2 both suggest substantial growth in road length. However, Model 2 indicates a higher initial growth (by 2030) than Model 1, though their long-term projections (by 2050) are similar. Model 3 suggests a more conservative or slower rate of growth in road length across all projected years, significantly lower than both Model 1 and Model 2. While economic factors and land area largely influence Model 1, commercial transportation needs significantly impact road growth in Model 2. The regression coefficients of the socioeconomic predictor variables in Model 3 suggest that GDP and population density increases could lead to higher use of existing roads, resulting in moderate road length growth (*21*).

Various studies have estimated future road length projections. Dulac (34) projects a roughly 60% increase in paved road lane-kilometers or approximately 25 million kilometers by 2050, based on a 4°C global average temperature outcome scenario, from the 2010 estimates. Meijer et al. (17) estimates a 14 to 23% increase by 2050 compared to the 2018 estimates of road length, although their study focuses solely on paved lanes and not the entire road length. Wu & Hou (*22*) calculate that under the SSP1 scenario, the global road growth scale by 2030 and 2050 is projected to be 3.02 and 5.48, respectively. These projections are smaller compared to those predicted by the models in this study and the estimates from previous studies. This can be attributed to the fact Wu & Hou (*22*) only considered 10 countries with the longest total road mileage in the world in 2010 for global road network projection. The countries are India, China, USA, Brazil, Japan, Russia, France, Canada, Australia, and Spain. By limiting their analysis to these specific countries, their results do not capture the full extent of road length changes globally, particularly in emerging economies in Africa and Latin America. It is important to note that comparing estimates from different studies is challenging due to variations in methodologies and data sets used for modeling.

Table 21. Predicted Road lengths and percentage increases relative to 2020 road length

	Road length (2020)	Road length (2030)	Road length (2040)	Road length (2050)
Model 1	40,437,963	47,925,862 (18.5%)	57,334,827 (41.8%)	67,537,137 (67.0%)
Model 2	40,437,963	52,191,365 (29.1%)	59,548,557 (47.3%)	67,400,924 (66.7%)
Model 3	40,437,963	43,724,804 (8.1%)	46,706,771 (15.5%)	49,017,384 (21.2%)

Regional road network growth

Figure 11, Figure 12, and Figure 13 show the road length projections from 2020 to 2050 for different regions for Model 1, Model 2, and Model 3, respectively. Among the three 10-year periods (2021 – 2030, 2031 – 2040, 2041 – 2050), ASEAN exhibits the highest mean increase in road length in Model 1, India in Model 2, and Africa in Model 3. The regions with the most substantial growth in roadways across the three models are India, ASEAN, Africa, ATE, and ODA. Conversely, developed regions like OECD Europe, OECD North America, and OECD Pacific show moderate growth change in road lengths. By the year 2050, Model 1 forecasts that OECD North America will have the highest lane-kilometers of roads, while Model 2 indicates that India will take the lead. Model 3 also suggests that OECD North America will have the highest lane-kilometers.

According to Model 1, by 2030 and 2040, OECD North America, India, OECD Europe, and China are projected to have the highest road lengths. However, by 2050, Africa overtakes China as the fourth region with the highest road length. ATE, ASEAN, and India have the highest increase in road length between 2021 – 2030, and 2031 – 2040. This suggests that economic growth and rising population density are driving road development in these regions during these periods. The highest road growth rate is observed between 2021 – 2030 and 2031 – 2040 for all the regions. The growth rate declines between 2040–2050 for all the regions, except for Africa, compared to the previous decade. EU 5, OECD North America, and OECD Pacific show significant reductions in road growth rate by 2050. Russia's road length for 2020 is retained for 2031 to 2050 as the models predict smaller projected road lengths than the actual 2020 road length.

Model 2 suggests that a significant rise in annual truck VKT from 2020 is expected to increase road expansion in China and India. OECD North America will have minimal construction of new roads, thus, GHG emissions from existing road maintenance is expected to be higher than new road construction. India, ASEAN, and China have the highest increase in road length for 2030, 2040, and 2050 relative to road lengths in 2020. China will invest more in constructing more roads between 2020 and 2030 than between 2030 and 2040. This indicates that the GHG emissions from constructing new roads between 2020 and 2030 will be significantly higher than GHG emissions from constructing new roads between 2030 and 2040. India, China, and ASEAN have the highest new road construction between 2020 and 2030. India, Africa, and ASEAN also have the highest new road construction in the next two decades, that is, between 2030 and 2040, and 2040 and 2050. The regions with the lowest increase in road length between 2030 and 2040, and 2040 and 2050 are Other OECD, OECD Pacific, and OECD North America.

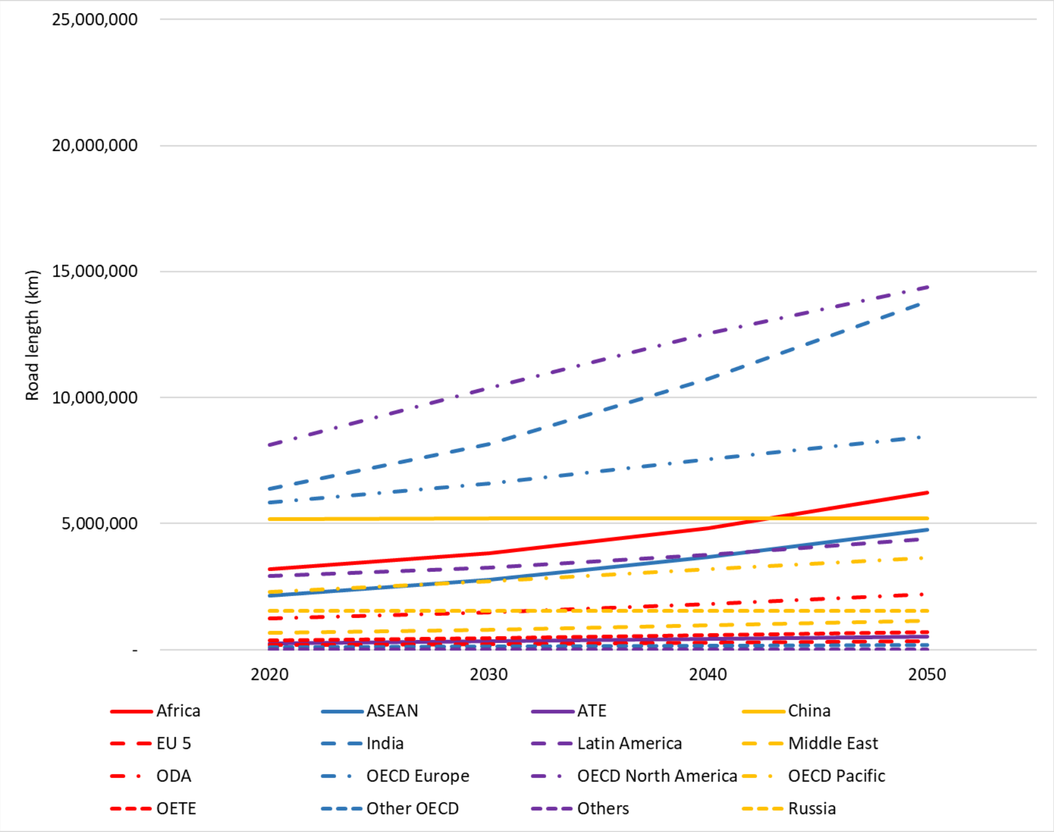

Figure 11. Road length projection from 2020 to 2050 for Model 1

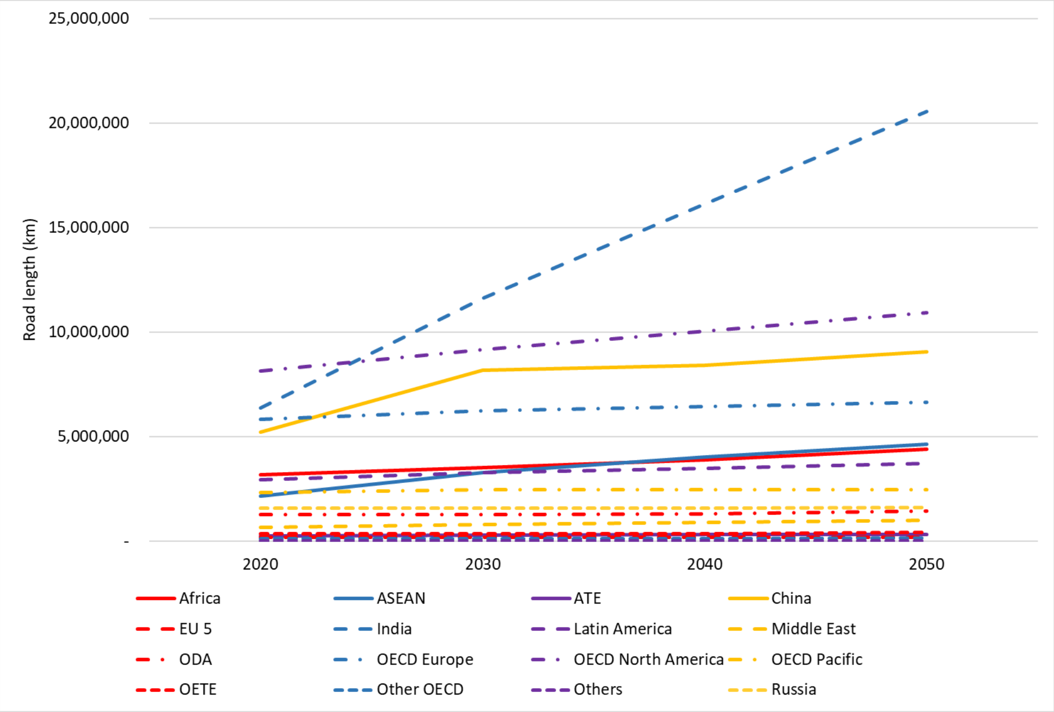

Figure 12. Road length projection from 2020 to 2050 for Model 2

Results from Model 3 show that Other European Transition Economies (OETE) has the lowest mean increase across the 10-year periods, while Africa has the highest. Thus, it is expected that OETE will have less notable change in total GHG emissions across the 10-year periods, while Africa will experience the highest GHG emissions change in this same timeframe. The modelling assumptions used in the regression analysis indicate that these projections serve only as first-order estimates of future road expansion at regional and/or country levels. For instance, in Model 1, Russia does not show any road growth because the projected road lengths are smaller than the current estimate, so the existing road network size is retained from 2020 to 2050. In general, the percentage change in road lengths is larger in emerging and developing countries compared to developed regions, as observed across all three models.

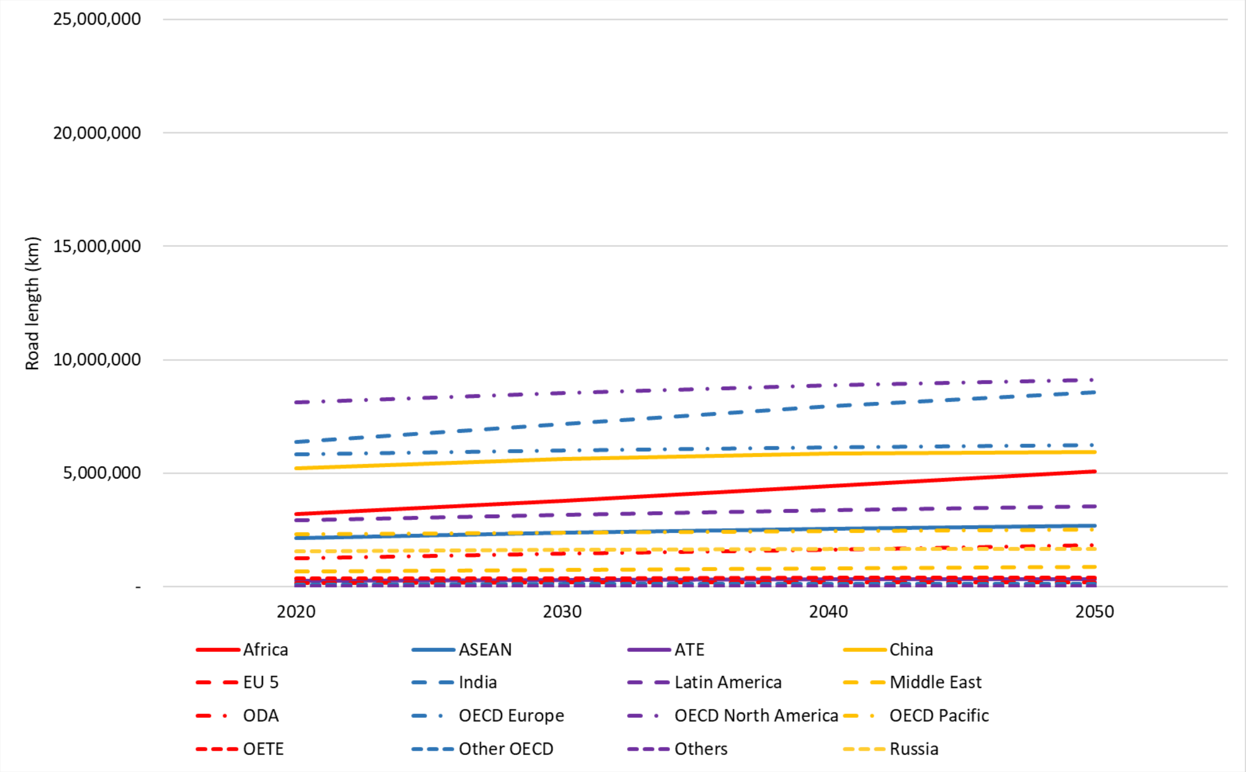

Figure 13. Road length projection from 2020 to 2050 for Model 3

GHG emissions from the Build-out and Maintenance of Global Roads

HMA Quantity

The estimated quantity of hot mix asphalt (HMA) required for new road construction between 2021 and 2030 was compared with the annual HMA quantities reported for specific countries in Table 22. This comparison aims to determine if the estimates from this study align with the published data and are within a reasonable range. The annual quantities in Table 22 include HMA used for construction, maintenance, and base courses, while the estimates as shown in Table 23 are HMA for only new road construction and surface/binder courses. Based on an assumed thickness of 178 mm, 1,538,112 kg of HMA are needed per lane-kilometer. To estimate the annual quantity, the total HMA required for new road construction over the decade was divided by 10. The estimated values are comparable to the reported quantities in literature, as they have similar magnitude. However, Model 1 predicts a very low quantity of HMA for China due to the small projected increase in road length for the 2021 – 2030 decade.

Table 22. Annual quantity of asphalt concrete (HMA) from literature

	HMA quantity (tonnes)	Reference
Australia	10,000,000	(*61*)
China	410,000,000	(*62*)
Europe	279,400,000	(*63*)
United States	381,017,574	(*64*)

Table 23. Estimated annual quantity of HMA for all models

	Model 1	Model 2	Model 3
China	14,107	458,482,165	65,401,574
Europe (EU 5, OECD Europe, OETE)	138,784,705	62,165,421	28,524,172
OECD North America	348,815,801	157,787,816	61,938,170
OECD Pacific (Australia, Japan, Republic of Korea, New Zealand)	62,238,730	21,738,670	11,224,223

GHG emissions from build-out of global roads, culverts and bridges up to 2020

This section shows the total contribution from road, bridge, and culvert construction (road infrastructure construction) up to 2020. The estimates exclude the GHG emissions from constructing drainage, concrete roads, road barriers, and other elements. The total GHG emissions from building roads, culverts, and bridges up to 2020 is approximately 14,433 mega tonnes CO_2e ($MtCO_2e$). As shown in Figure 14, OECD America, China, and Europe contribute the most to GHG emissions from road infrastructure construction, representing 20%, 18%, and 16% of the total. Figure 15 presents the regional contributions to global GHG emissions from the construction of roadway infrastructure up to 2020. China, OECD North America, India, OECD Europe, and Africa are the major contributors to road construction GHG emissions. Except for India, these regions also have the highest GHG emissions from bridge and culvert construction. OECD Europe has the highest impact from bridge construction (33%) and OECD North America in culvert construction (24%). In the total build-out, 63% of the GHG emissions are from road construction, while 17% and 20% are from bridge and culvert buildout, respectively.

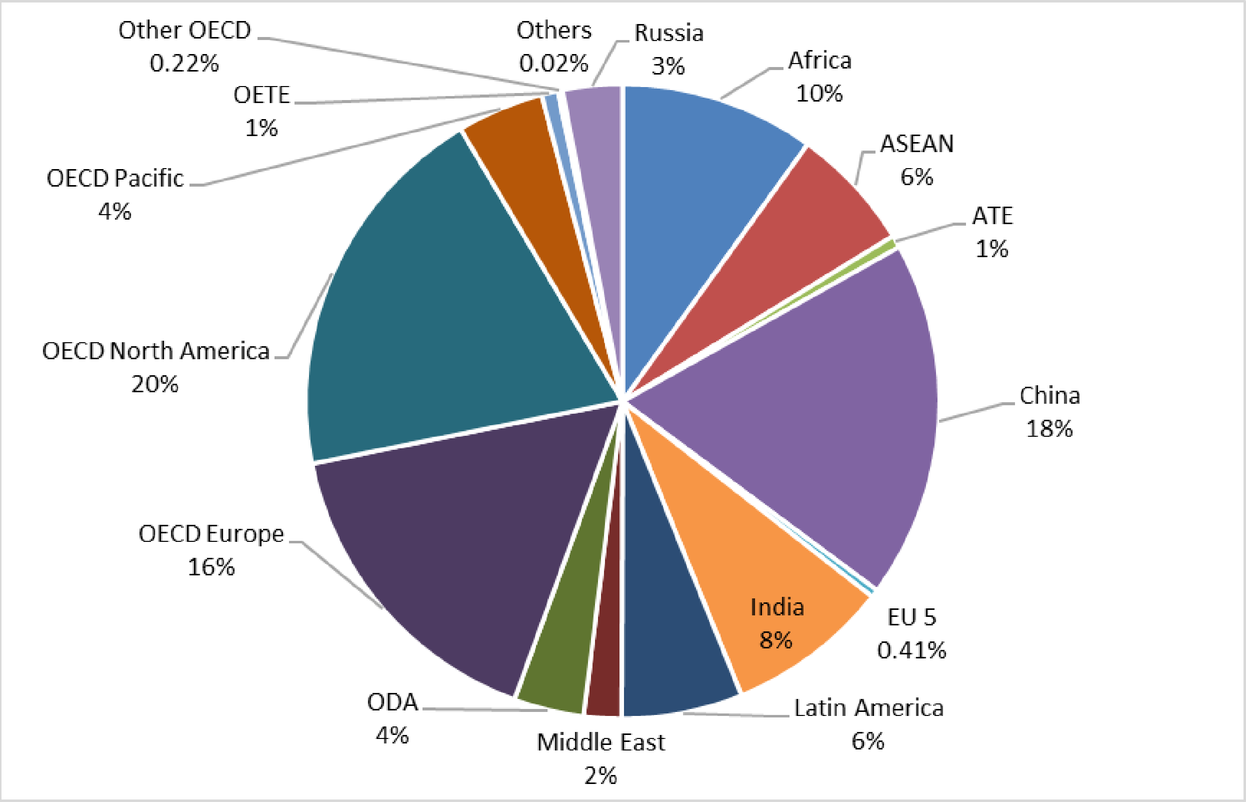

Figure 14. Regional contributions to global road construction GHG emissions up to 2020

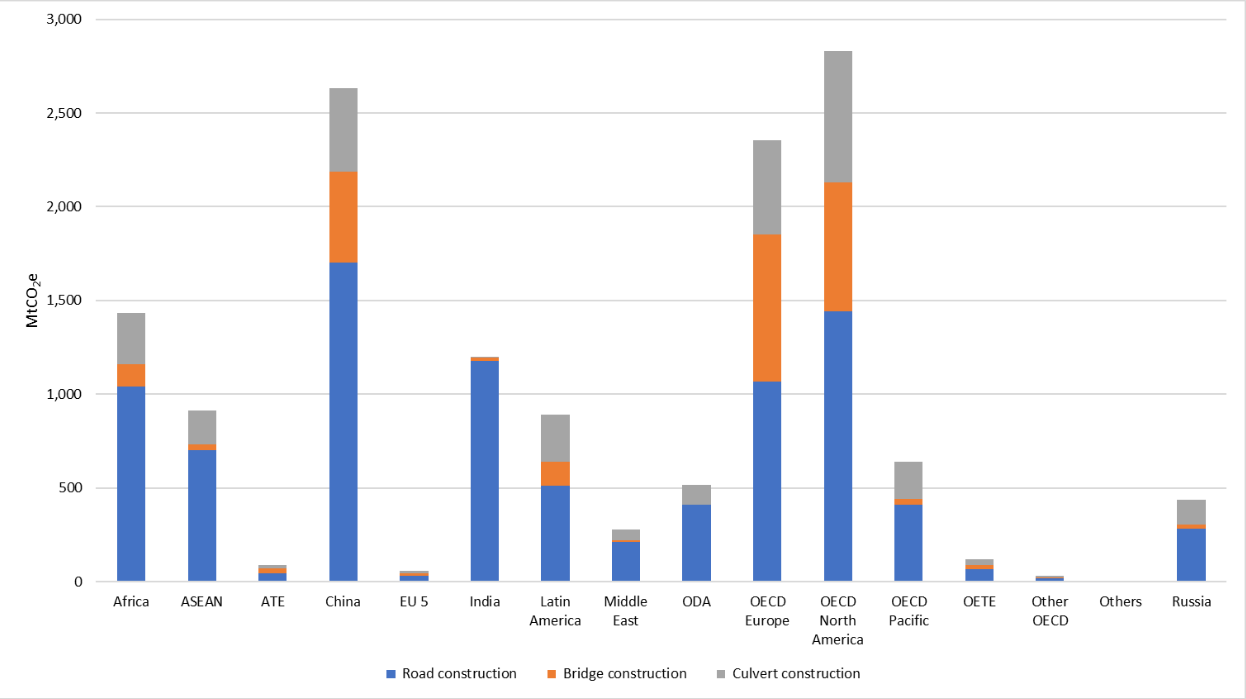

Figure 15. Regional GHG emissions from the construction of road infrastructure up to 2020

Across all regions, excluding OECD Europe, more than 50% of GHG emissions from road infrastructure are from pavement construction. For example, road construction accounts for 65% of GHG emissions from pavement infrastructure construction in China, bridge construction accounts for 18%, and culvert construction accounts for 17%. In OECD North America, pavement construction accounts for 51%, bridge construction accounts for 24%, and culverts account for 25%. In Africa, 73% of the total construction GHG emissions from roadway infrastructure are from pavement, 8% from bridges, and 19% from culverts. In India, over 90% of construction GHG emissions of roadway infrastructure is from pavement, while 2% is from bridges. Regions with more pavement and bridges have the highest A1-A5 GHG emissions from pavement and bridge construction. Humans have already built roadways and bridges to connect destinations of interest and road infrastructure has already contributed significantly to the development and economy of the countries. It is essential now to keep the system functional through more sustainable practices, using minimal virgin resources, so that the road transport infrastructure continues contributing to regional development and economies.

Global GHG emissions for different road length predictions

Figure 16 presents the total global GHG emissions for all three models, showing the impact of new road construction and existing road M&R for the three timelines. The contributions of new road construction and existing road maintenance and rehabilitation (M&R) to global GHG emissions vary across models and decades. In Model 1, new road construction contributes about 60% of the total GHG emissions across the three decades. New road construction remains the dominant GHG emission driver in Model 2, especially in the decade (2021 – 2030). In Model 3, existing road M&R contributes the largest share of GHG emissions, with the emissions becoming more significant in later decades.

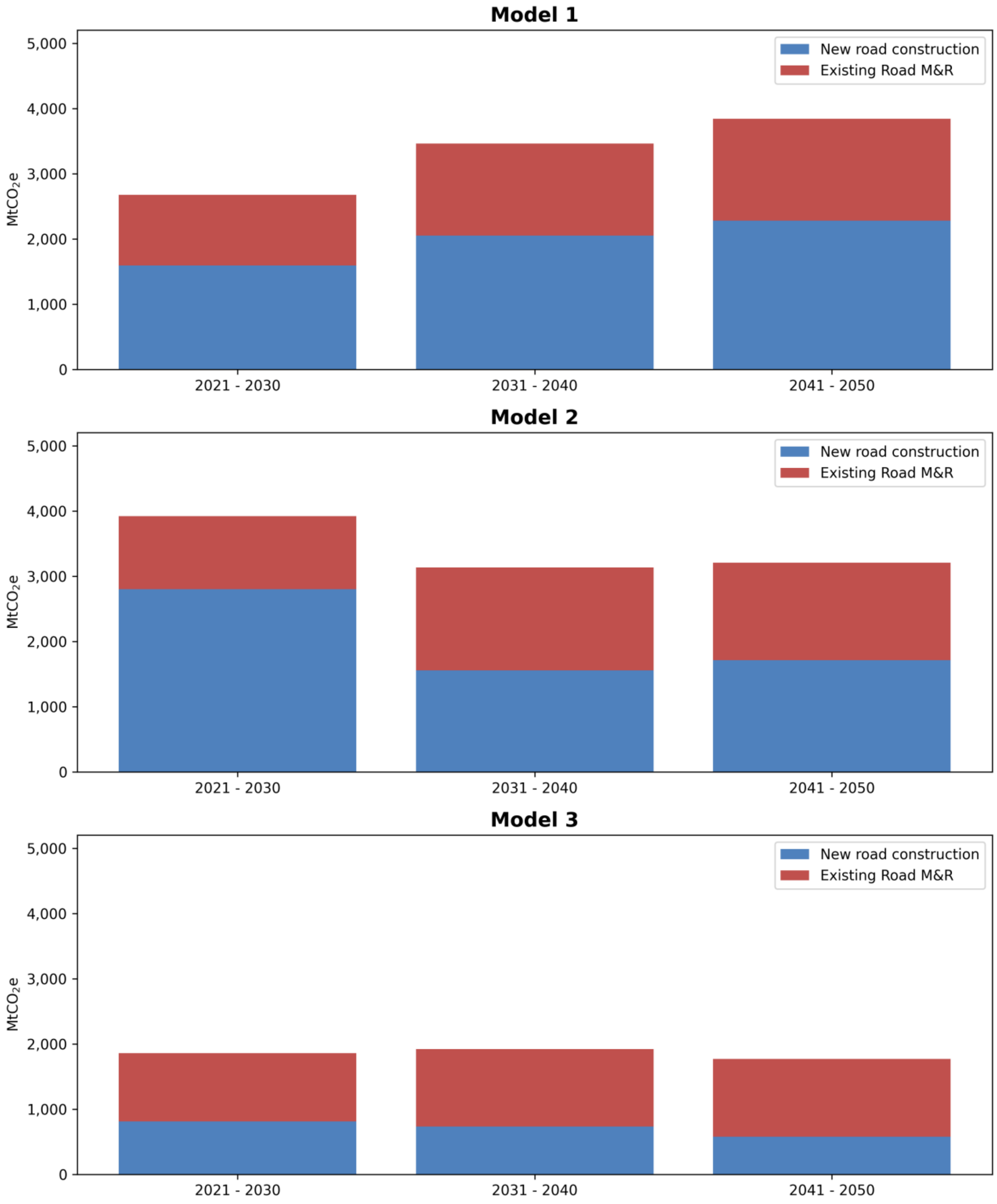

Figure 16. Total GHG emissions from new road construction and existing road M&R

Figure 17 shows the cumulative GHG emissions from the build-out and maintenance of global roads for the three models. Model 3 has the lowest cumulative GHG emissions by 2050, while Model 1 has the highest. Model 1 shows a 19%, 43%, and 69% increase in cumulative global

GHG emissions in 2030, 2040, and 2050, respectively, relative to 2020's emissions from constructing global roads, bridges, and culverts (14,433 $MtCO_2e$). Model 2 shows a similar trend, with a 27%, 49%, and 71% increase in cumulative GHG emissions in 2030, 2040, and 2050, respectively, relative to emissions from 2020. In Model 3, the cumulative emissions by 2030, 2040, and 2050 are 13%, 26%, and 38% higher than the emissions from 2020. The results obtained for the different models (Figure 17) align with the assumptions on increases in global road length for these models. The cumulative GHG emissions by 2050 for Model 1 are 22% higher than those of Model 3, and emissions of Model 2 are 24% higher than those of Model 3.

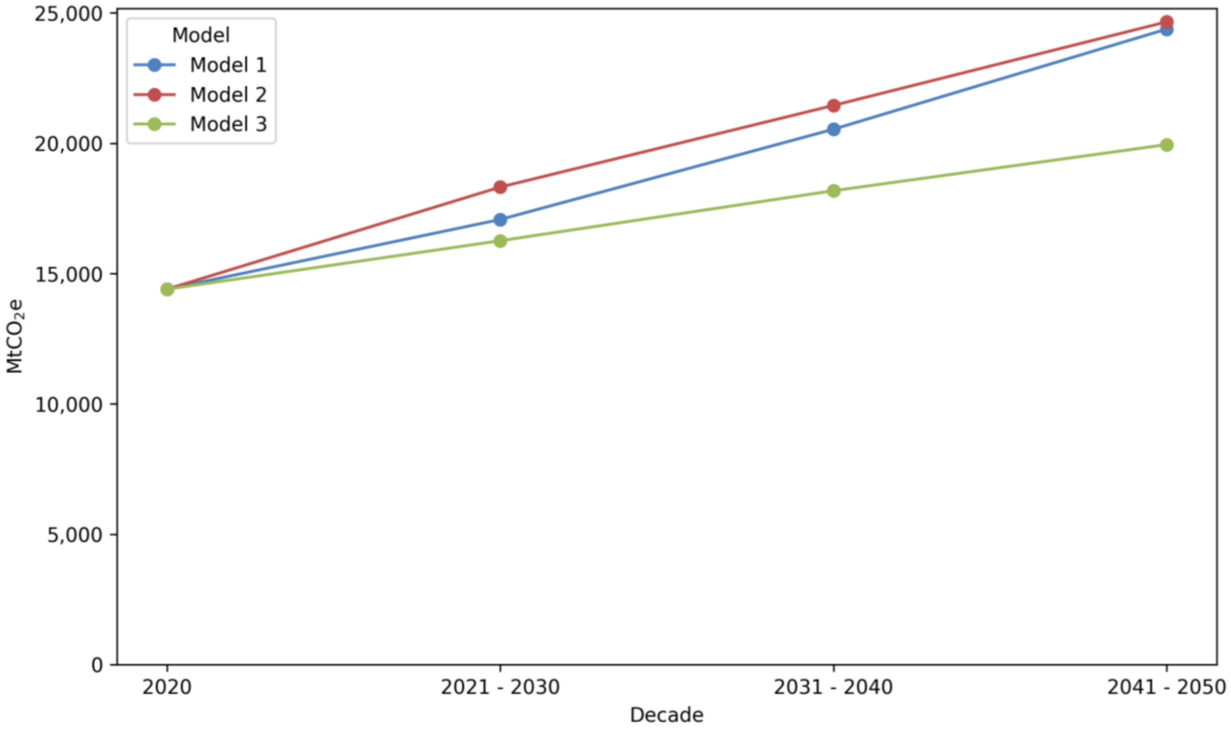

Figure 17. Cumulative road construction and maintenance for all models

Regional GHG emissions from Model 1 road length prediction

Figure 18 presents the GHG emissions attributed to new road construction and existing road M&R of regional roads from 2030 to 2050 using the predicted road lengths from Model 1. In this study, emissions from new road construction and existing road M&R of global roads are termed road project emissions. In this model, OECD North America, India, Africa, and ASEAN are the regions with the highest road project emissions across all decades. Regions such as ATE, EU5, Other OECD, and Others contribute relatively low GHG emissions to the total GHG from global road projects. The trends in GHG emissions for road construction and M&R vary by region. New road construction is the dominant source of road project emissions in developing regions such as Africa, India, and the Middle East, accounting for most GHG emissions across all the decades. For example, in 2021 – 2030, new road construction accounts for approximately 72% of the road project emissions in Africa and 65% in India, while it accounts for 76% and 64% in 2041 – 2050. In 2021 – 2030, new road construction and existing road M&R are projected to significantly contribute to road project GHG emissions in developed regions such as OECD Europe, OECD North America, and OECD Pacific. However, as road networks in these regions mature, the GHG emissions from the M&R of existing roads also increase. For instance, existing road M&R in OECD Europe, OECD North America, and OECD Pacific increased from 52%, 36%, and 38% in 2021 – 2030, respectively, to 55%, 51%, and 51% in 2041 – 2050. GHG emissions from existing road M&R are projected to rise steadily in other developing and developed regions, such as ATE, EU5, and Other OECD. Over 90% of road project emissions in China, Others, and Russia are from existing road M&R.

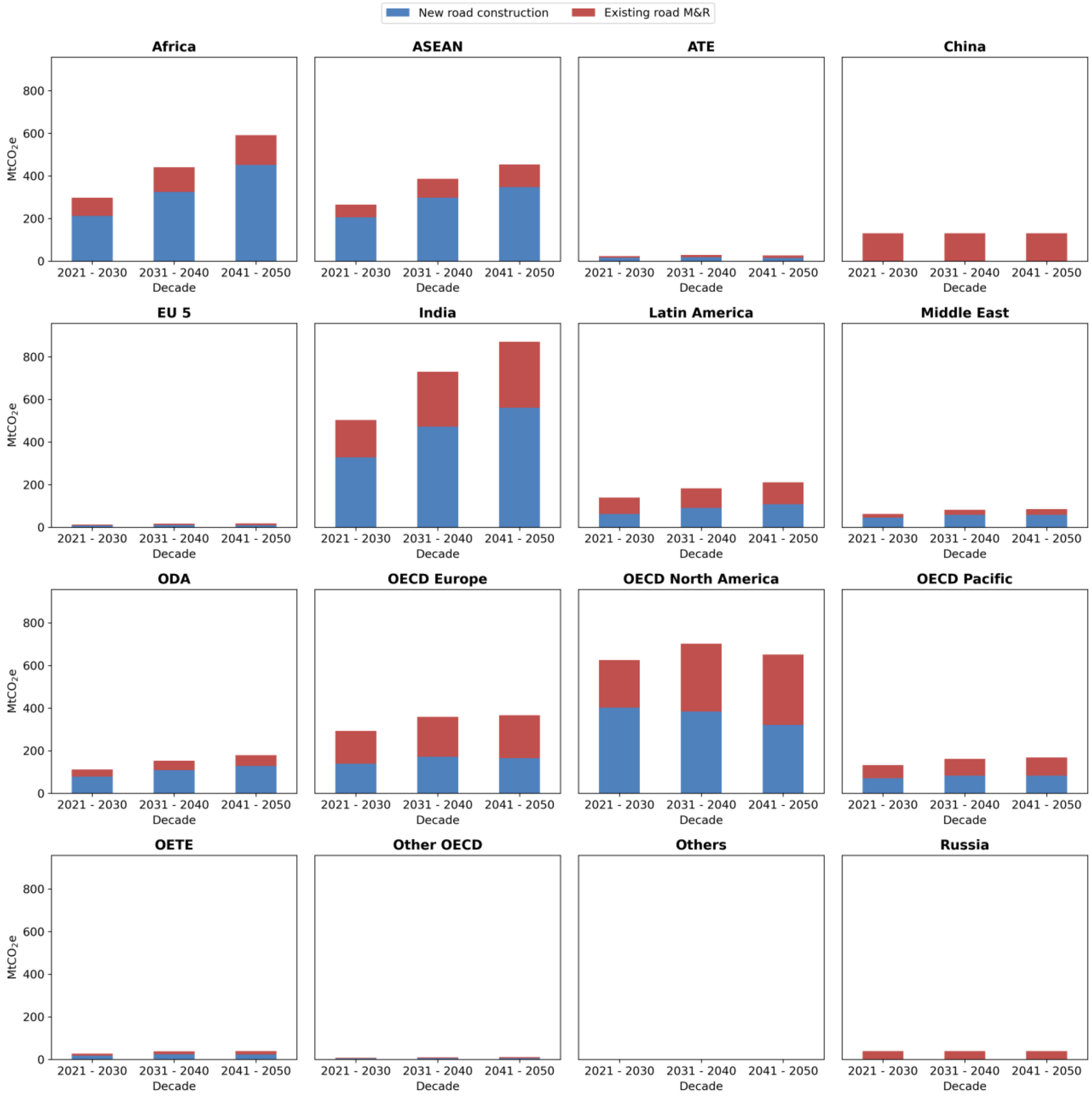

Figure 18. Variation over time in GHG emissions by region for Model 1

Regional GHG emissions from Model 2 road length prediction

Figure 19 shows the GHG emissions from new road construction and existing road M&R for each region using the predicted road lengths from Model 2. India, OECD America, China, and ASEAN are the largest contributors to GHG emissions from road projects.

In India, new road construction contributes around 83% of emissions in 2021 – 2030, decreasing to 65% by 2041 – 2050. In China, new road construction initially makes up 86% of emissions in 2021 – 2030 but dropping sharply to 22% by 2031-2040 before rebounding to account for 55% in 2041 – 2050. This suggests large-scale infrastructure renewal efforts in the decade. In Africa, new road construction is also the primary source of emissions, accounting for about 56 – 61% of total GHG emissions across the decades, reflecting a sustained focus on road expansion. ASEAN follows a similar pattern with new road construction, contributing a large share of 86% of emissions in 2021 – 2030, decreasing to 68% by 2041-2050. Thus, new road construction remains a significant emission driver in developing regions.

For OECD Europe and OECD North America, the GHG emissions trends indicate a gradual shift towards road maintenance, though new road construction continues to play a notable role. In OECD Europe, existing road M&R accounts for the largest share of emissions in 2021 – 2030, contributing approximately 67% to road project emissions. The trend continues in the following decades, with maintenance emissions reaching 83% by 2031-2040 and 80% by 2041-2050. This steady rise in existing road M&R emissions reflects the region's mature infrastructure as new road construction slows down. In OECD North America, new road construction will account for 46% of road project emissions in 2021 – 2030. Over the next two decades, the focus shifts towards maintenance, with road M&R contributing about 62% of the emissions in the final two-decade periods. The result suggests that developed regions will prioritize road maintenance. GHG emissions from road projects in EU5, Others, and OETE are relatively small throughout the decades and are entirely or almost entirely from the M&R of existing roads.

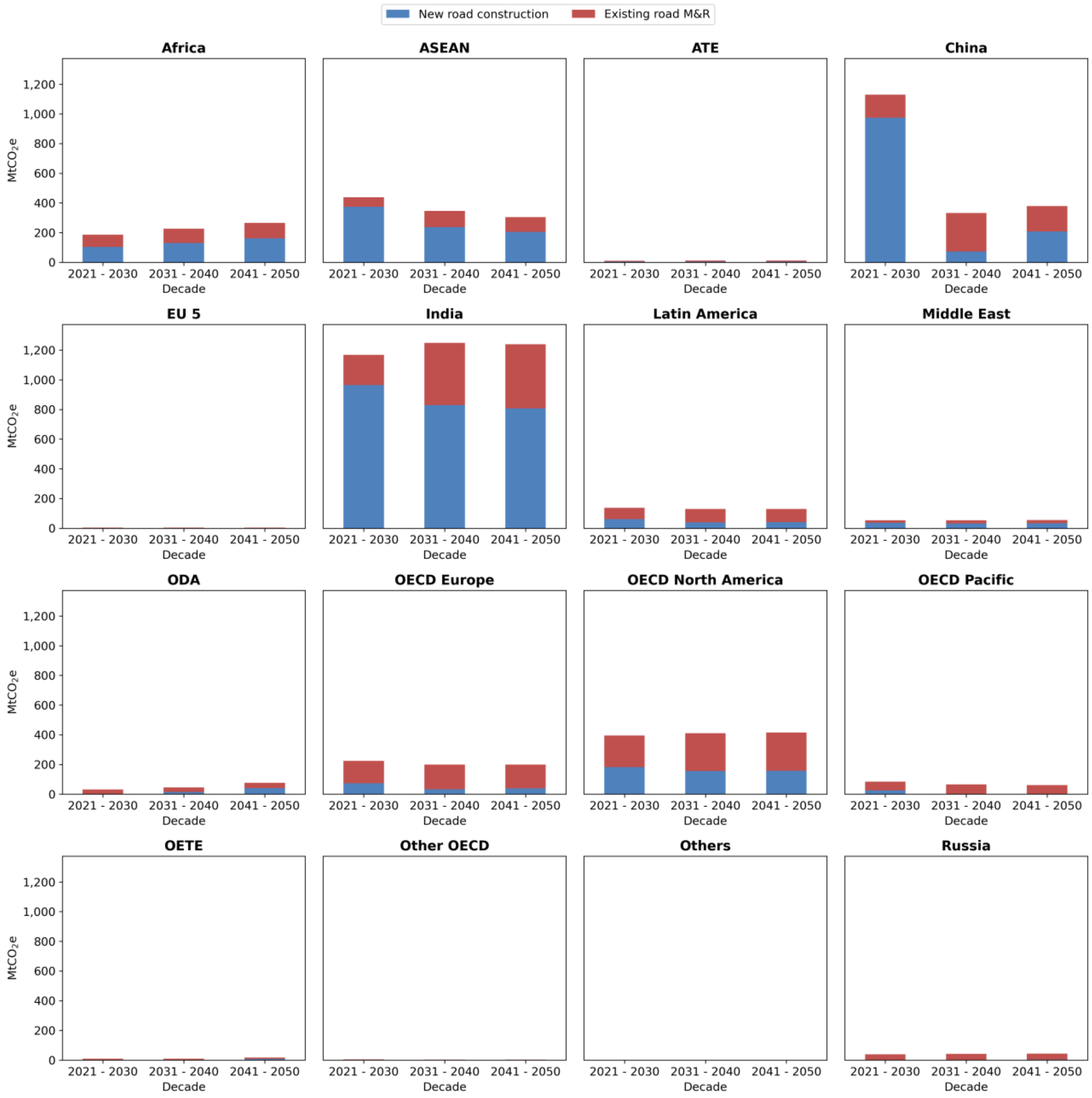

Figure 19. Variation over time in GHG emissions by region for Model 2

Regional GHG emissions from Model 3 road length prediction

Figure 20 shows the GHG emissions from constructing new roads and maintaining existing roads from 2030 to 2050 using the predicted road lengths from Model 3. In this model, India, Africa, China, OECD America, and OECD Europe account for most global GHG emissions from road projects across the decades.

New road construction leads road project GHG emissions in Africa, ASEAN, China, the Middle East, and ODA, contributing over 50% of total road project emissions in 2021 – 2030. However, as these regions develop, the share of emissions from construction declines slightly, indicating a growing focus on infrastructure maintenance. Developed regions like OECD Europe, OECD North America, and OECD Pacific focus predominantly on road maintenance. In OECD Europe, existing road M&R accounts for over 80% of emissions in 2021 – 2030 and is projected to be about 90% by 2041-2050. Similarly, in OECD North America, maintenance rises from 75% to 84%, while OECD Pacific shows a similar increase from 82% to 87%. This shift reflects the developed regions' emphasis on maintaining already built roads rather than expanding them further. Like Model 1 and Model 2, the road project GHG emissions from ATE, EU5, Other OECD, and Others are small compared to other regions and account for only a fraction of the global GHG emissions.

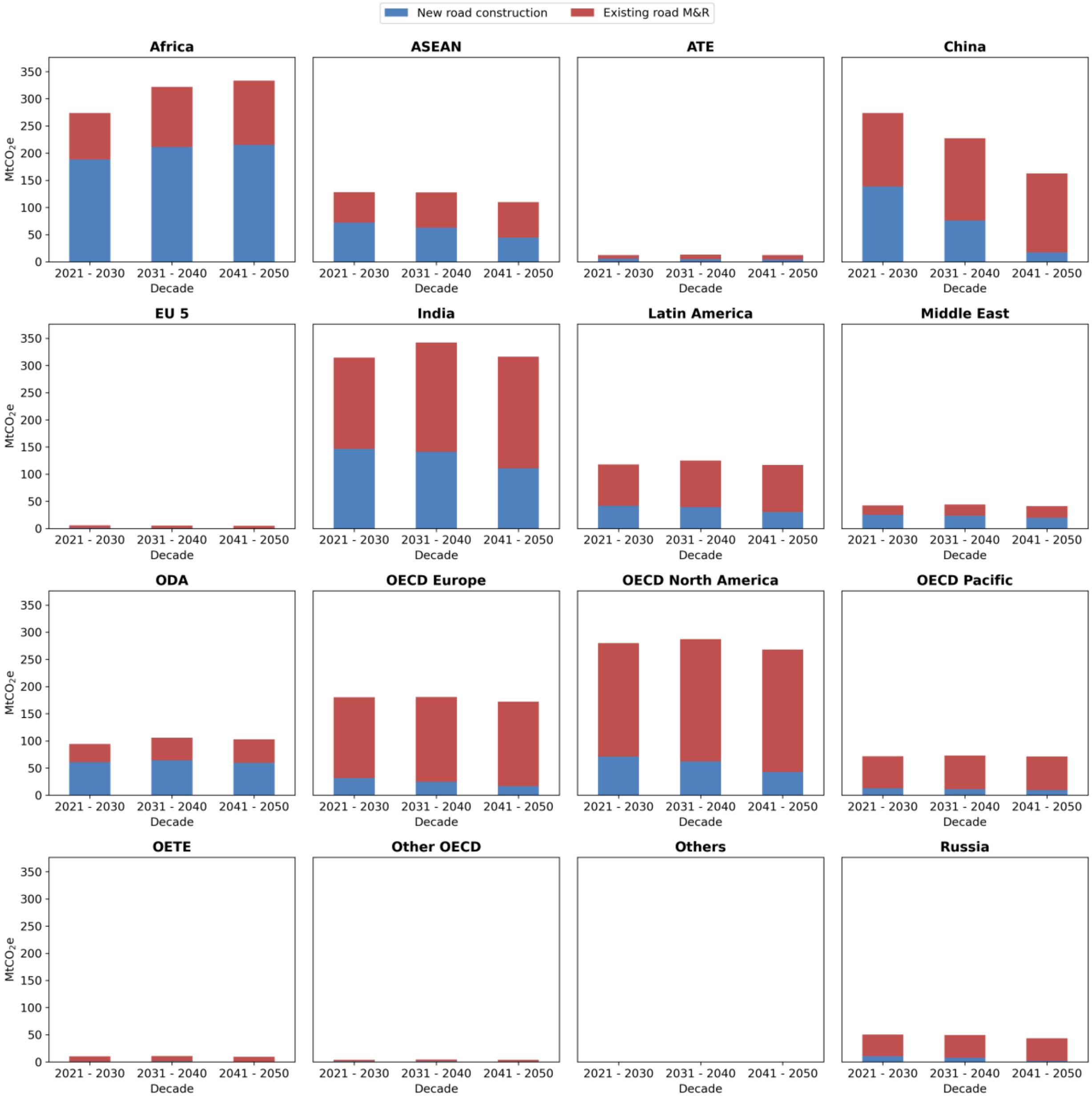

Figure 20. Variation over time in GHG emissions by region for Model 3

Vehicle-related GHG emissions

Global GHG emissions by vehicle fuel class

This section summarizes the results from vehicle-related GHG emissions drivers, including vehicle manufacturing (PLDV and trucks), vehicle operation (WTW), and the additional fuel due to road roughness. As earlier mentioned, additional fuel consumption from road roughness, which typically falls under the B1 use stage of the road, is presented in this study as part of vehicle-related GHG emissions for clarity.

Figure 21, built using VKT data from Table 37 – Table 39, presents the GHG emissions for all vehicle types. Across each decade, vehicle operation is the predominant contributor to vehicle-related emissions, contributing over 89%. Vehicle manufacturing contributes about 7 – 8% of total vehicle-related emissions across the decades. Meanwhile, the emissions from additional fuel consumption due to road roughness account for 1% in 2021 – 2030 and 2041 – 2050, and 5% in 2031 – 2040. This increase is attributed to road maintenance schedules, as roads deteriorate by 1 – 2 m/km IRI in the first decade after construction and worsen to 3 – 4 m/km IRI in the subsequent decade, leading to higher fuel consumption. The reduction in emissions from road roughness in 2041 – 2050 is linked to road maintenance efforts that improve surface quality and reduce fuel consumption in the simplistic scenario modeled.

The results show that 79,430 $MtCO_2e$, 79,088 $MtCO_2e$, and 64,711 $MtCO_2e$ will be emitted from vehicle operation in the decades 2021 – 2030, 2031 – 2040, and 2041 – 2050, respectively, representing an average annual GHG emissions of 7,943 $MtCO_2e$, 7,909 $MtCO_2e$, and 6,471 $MtCO_2e$ for each of the three respective decades. For a rough comparison with the values for vehicle use calculated above, the Announced Pledged Scenario (APS) by the IEA suggests that annual emissions from the operation of light-duty vehicles and trucks will reach 5,200 $MtCO_2e$ by 2030 (IEA, 2021). The IEA's Net Zero Emissions Scenario (NZE) presents a more ambitious target: much lower emissions (3,544 $MtCO_2e$ per year) from light-duty vehicles and trucks by 2030. This scenario implies a significant shift towards cleaner technologies or reduced reliance on these vehicles. The GHG emissions estimated for vehicle driving of all classes of vehicles in this study appear to be reasonable compared with those from IEA.

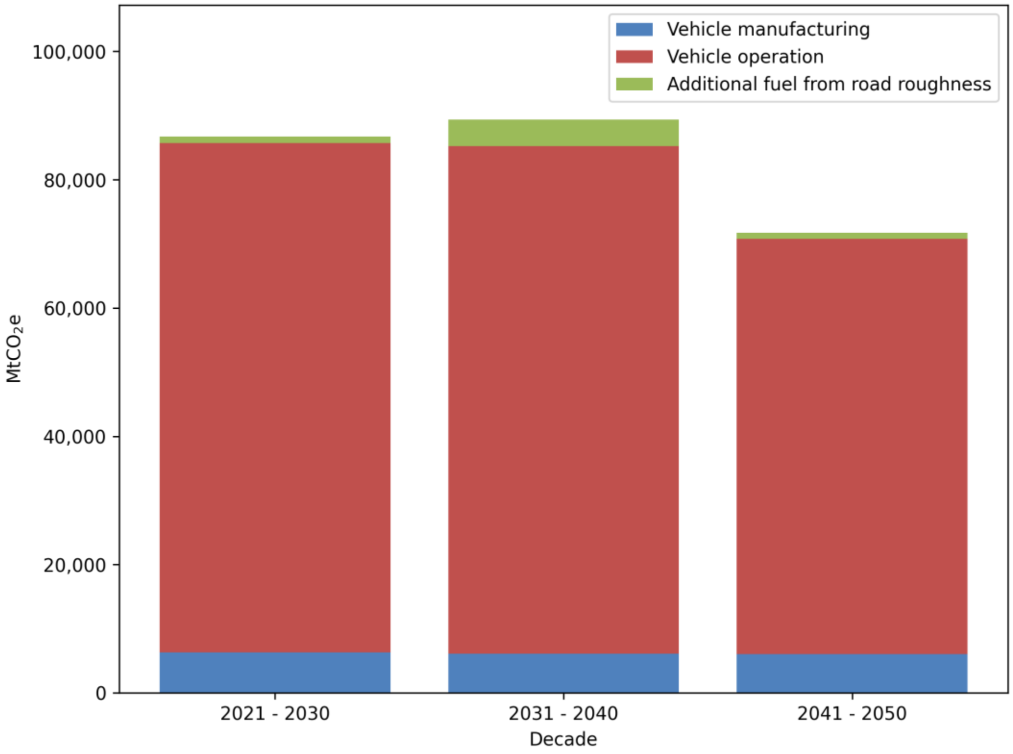

Figure 21. GHG emissions for all vehicle fuel class by vehicle emission drivers

Figure 22 shows the global trend of GHG emissions from the emission drivers for each vehicle fuel class. The vehicle related GHG emissions from diesel vehicles significantly exceed those from gasoline and electric vehicles in each decade.

Across the decades, manufacturing contributes 5 – 10% of the vehicle-related GHG emissions for gasoline vehicles, vehicle operation contributes 88 – 94%, and additional fuel from road roughness accounts for 1 – 5%, peaking during 2031 – 2040. Diesel vehicles' manufacturing emissions decline from 5% in 2021 – 2030 to 3% in 2041 – 2050, with vehicle operation accounting for 93 – 96% of the vehicle-related emissions across the decades and additional fuel from road roughness accounting for 1 – 4%, also peaking during 2031 – 2040. On the other hand, electric vehicles are more manufacturing intensive. Vehicle manufacturing contributes 60% of the vehicle-related GHG emissions in 2021 – 2030, declining to 36% by 2041 – 2050. Vehicle operation accounts for approximately 38 – 62% of the electric vehicle emissions across the decades, while additional fuel from road roughness contributes roughly 2 – 8%.

During 2021 – 2030, high manufacturing GHG emissions are driven by increasing EV demand and the energy-intensive processes of producing vehicles and their components. However, as technology advances and industry gains experience, manufacturing processes are expected to become more efficient, reducing their environmental impact in the subsequent decades. From 2031 – 2040 and 2041 – 2050, vehicle operation GHG emissions for EVs rise significantly due to their widespread adoption and increased usage. As more regions transition from internal combustion engine vehicles to EVs, operational emissions contribute more to the overall environmental impact of the vehicles. Factors that could increase EV vehicle operation emissions may include the carbon intensity of the electricity grid mix and charging efficiencies in the different regions. This trend emphasizes the need to focus on making manufacturing processes more sustainable and address the energy sources used during the use stage to ensure a significant reduction in the GHG emissions from EVs.

Pavement roughness results in a small increase (1 – 6%) in gasoline and diesel vehicle GHG emissions due to higher fuel consumption during vehicle operation. For electric vehicles, pavement roughness causes a higher increase in GHG emissions (4 – 16%), with the extent of the increase determined by the composition of the electric grid mix.

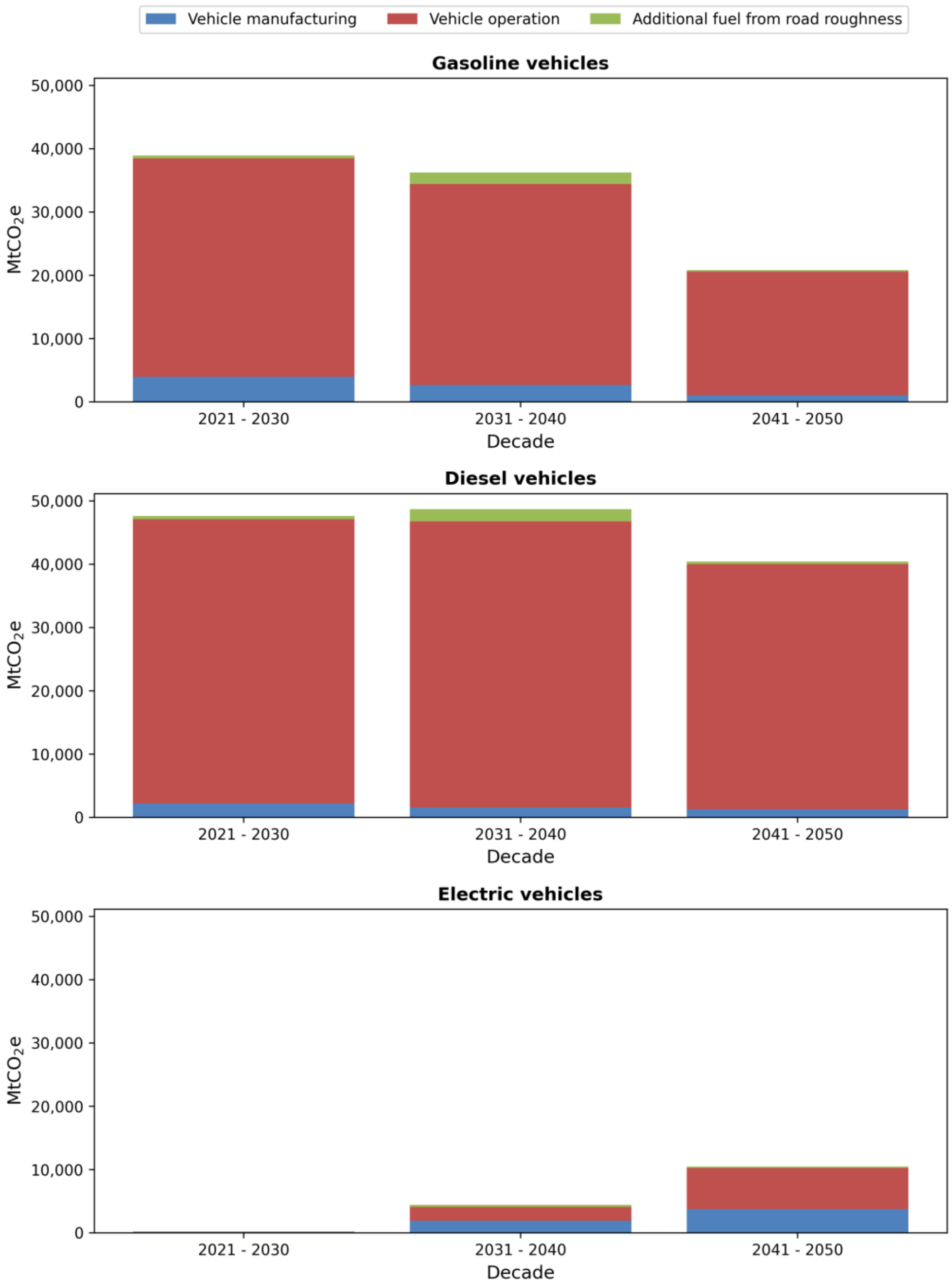

Figure 22. GHG emissions from each vehicle fuel class by vehicle emission drivers

Global GHG emissions by vehicle type

Figure 23 presents the trend of global GHG emissions by vehicle type (PLDVs and trucks) by vehicle emission drivers across the three decades. Across the decades, GHG emissions from PLDVs are dominated by vehicle operation (83 – 90%), with manufacturing contributing 9 – 15% and road roughness accounting for 1–6%. For trucks, operation accounts for 91 – 94% of emissions, manufacturing for 5 – 6%, and roughness for 1 – 4%. Trucks consistently emit more GHGs than PLDVs, with emissions exceeding those of PLDVs by 42% in 2021 – 2030, 59% in

2031 – 2040, and 127% in 2041 – 2050, highlighting their significantly larger environmental impact. This is due to a significant rise in the global VKT of diesel trucks from 2031 – 2040 (see Table 38 in Appendix C) driven by increased freight movement and relatively slow transition to electric trucks.

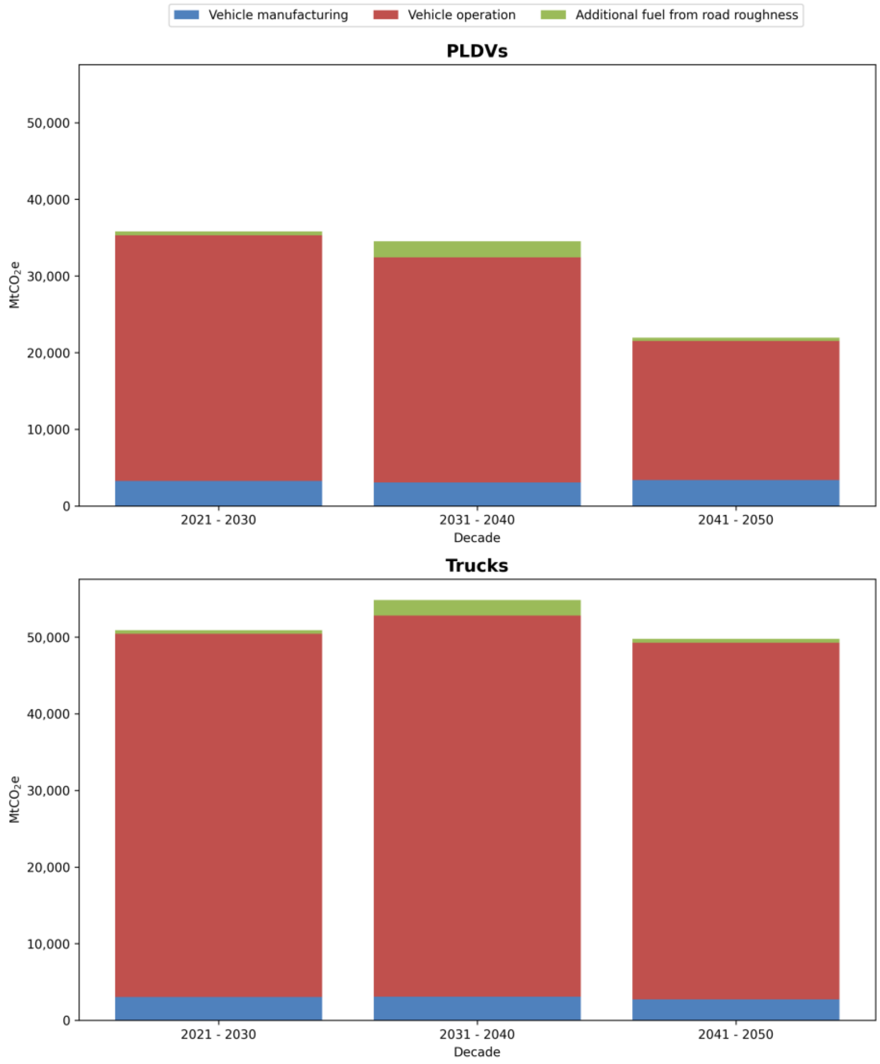

Figure 23. GHG emissions of PLDVs and trucks by vehicle emission drivers

Regional GHG emissions from all vehicles

Figure 24 presents the vehicle related GHG emissions for each region in the decades. OECD North America, OECD Europe, and China have the highest vehicle related emissions, while EU5, ATE, OETE, and Other OECD have the lowest. Emissions from developed regions such as OECD Europe, OECD North America, OECD Pacific, Other OECD, Russia, and EU5 decrease over decades, driven by increased adoption of electric vehicles, cleaner electricity production, and efficient charging infrastructure. In OECD Europe, vehicle related GHG emissions decrease by 24% in 2031 – 2040 and 44% in 2041 – 2050. In OECD America, emissions decline by 10% in

2031 – 2040 and by 34% in 2041 – 2050, while in OECD Pacific, emissions drop by 23% in 2031 – 2040 and by 39% in 2041 – 2050.

Conversely, emissions from developing regions like Africa, and India show an upward trend, primarily due to rising vehicle kilometers traveled (VKT) and infrastructure expansion. GHG emissions increase by 28% and 98% in these regions during 2031 – 2040, followed by a further increase of 6% and 27% in 2041 – 2050. In regions like ASEAN, China, and the Middle East, emissions increase in 2031 – 2040 but decrease in 2041 – 2050, indicating a peak period in 2031 – 2040. This trend aligns with the regional VKT patterns, where VKT peaks in 2030 and significantly declines from 2040 (see Table 37 and Table 38 in Appendix C). As earlier noted, the cumulative VKT for 2031 – 2040 was derived by multiplying the VKT in 2030 by ten, and the VKT for 2041 – 2050 was derived by multiplying the VKT in 2040 by ten.

In all the regions, vehicle operation contributes the largest emissions amongst the vehicle-related emission drivers, accounting for more than 80% of the total emissions in each decade. Manufacturing accounts for 2 – 19% and additional fuel from roughness contributes 1 – 5%. For example, operation accounts for 89 – 94% of emissions in OECD North America and OECD Europe, while manufacturing contributes 5 – 10%. In China, vehicle operation accounts for 80 – 95% of the total emissions, and vehicle manufacture accounts for 10 – 19%.

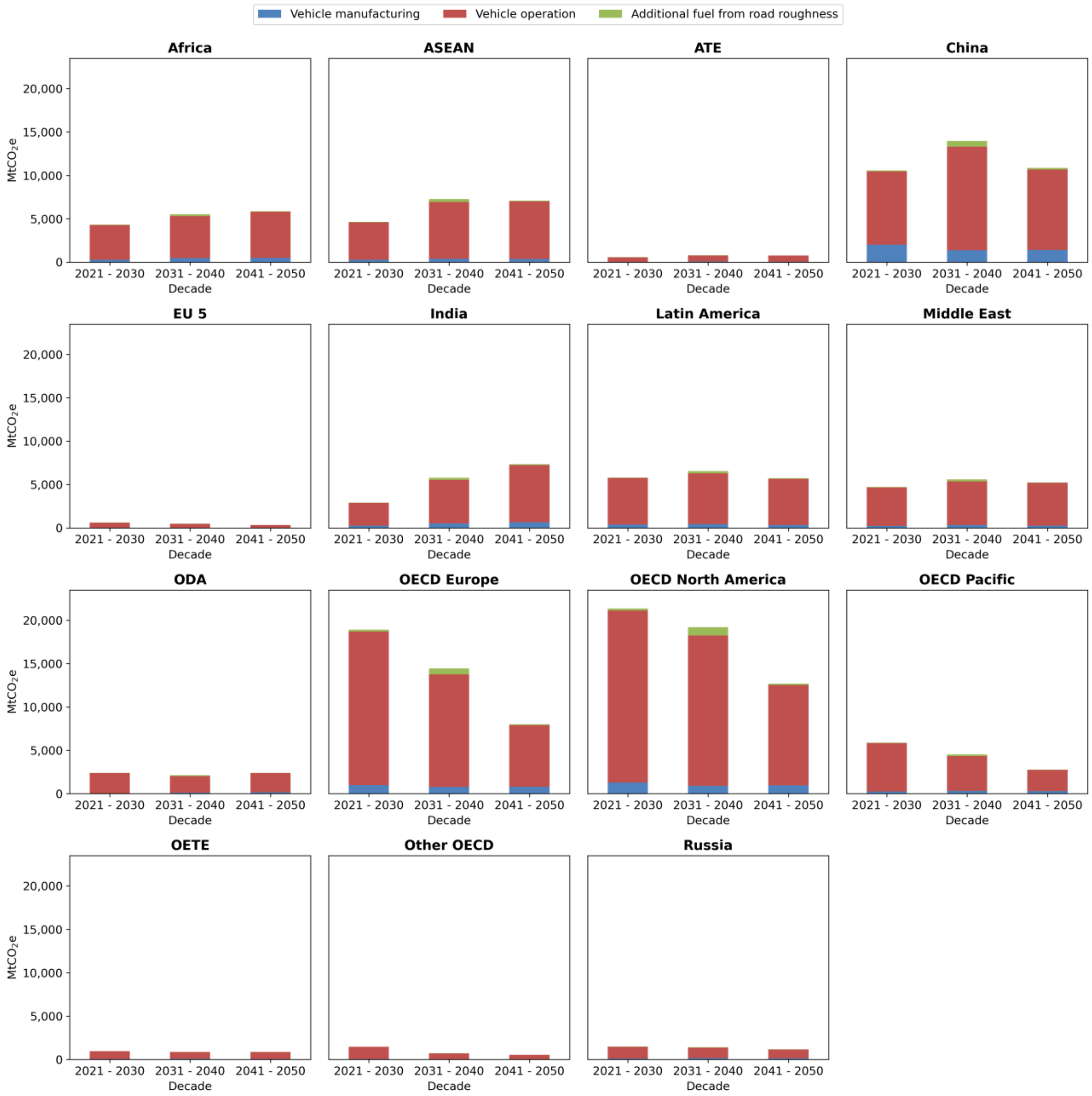

Figure 24. Regional GHG emissions of all vehicles by vehicle emission drivers

Sensitivity Analysis

Sensitivity analyses were completed to consider the following alternative scenarios:

- Change in cement technology: replacement of portland cement concrete in the base case with portland limestone cement (PLC)
- Differences in road roughness increase: comparison of increases of road roughness (in terms of IRI) from 1 to 6 m/km in 20 years (worst case), and 1 to 2 m/km in 20 years (best case), in comparison with the base case of an increase from 1 to 4 m/km in 20 years

- Maintenance scheduling: In the base case scenario, thin overlay (45 mm) and chip seal are applied to existing roads every 10 years and medium overlay (75 mm) every 20 years, whereas in the alternative scenario, thin overlay and chip seal are applied every 20 years and medium overlay every 40 years.

Partial portland cement replacement in pavements and bridges

In this case, portland limestone cement (PLC) replaces portland cement (PC) in the cement treated base layer. Fifteen percent of the portland cement is replaced with ground limestone in PLC. PLC has been used for many years in several countries and within the US but is not widely used across the world. Replacing PC with PLC is expected to result in decreased new road construction GHG emissions in regions using CTB. The GHG emissions from existing road M&R remain the same since only HMA layers undergo periodic maintenance (thin and medium asphalt overlay) and require no cement. Figure 25 shows the global new road construction GHG emissions for each decade using road lengths from Model 1, Model 2, and Model 3 with and without 15% PC replacement. Only a small decrease in the emissions is observed after replacement with PLC. This is not surprising since only 5 of 17 regions use CTB layers. Over the three decades in Model 1, a 2 – 3% reduction in emissions is observed following replacement with PLC. In Model 2, the GHG emissions reduction is 2 – 4%, while in Model 3, a 4 – 5% reduction in emissions is observed.

There are other potential cement types that replace 20 to 50% of the PC in cement with supplementary cementitious materials (SCM) or other materials, but they have not been as widely used as PLC. Their use can be part of future additional sensitivity analyses as more information becomes available.

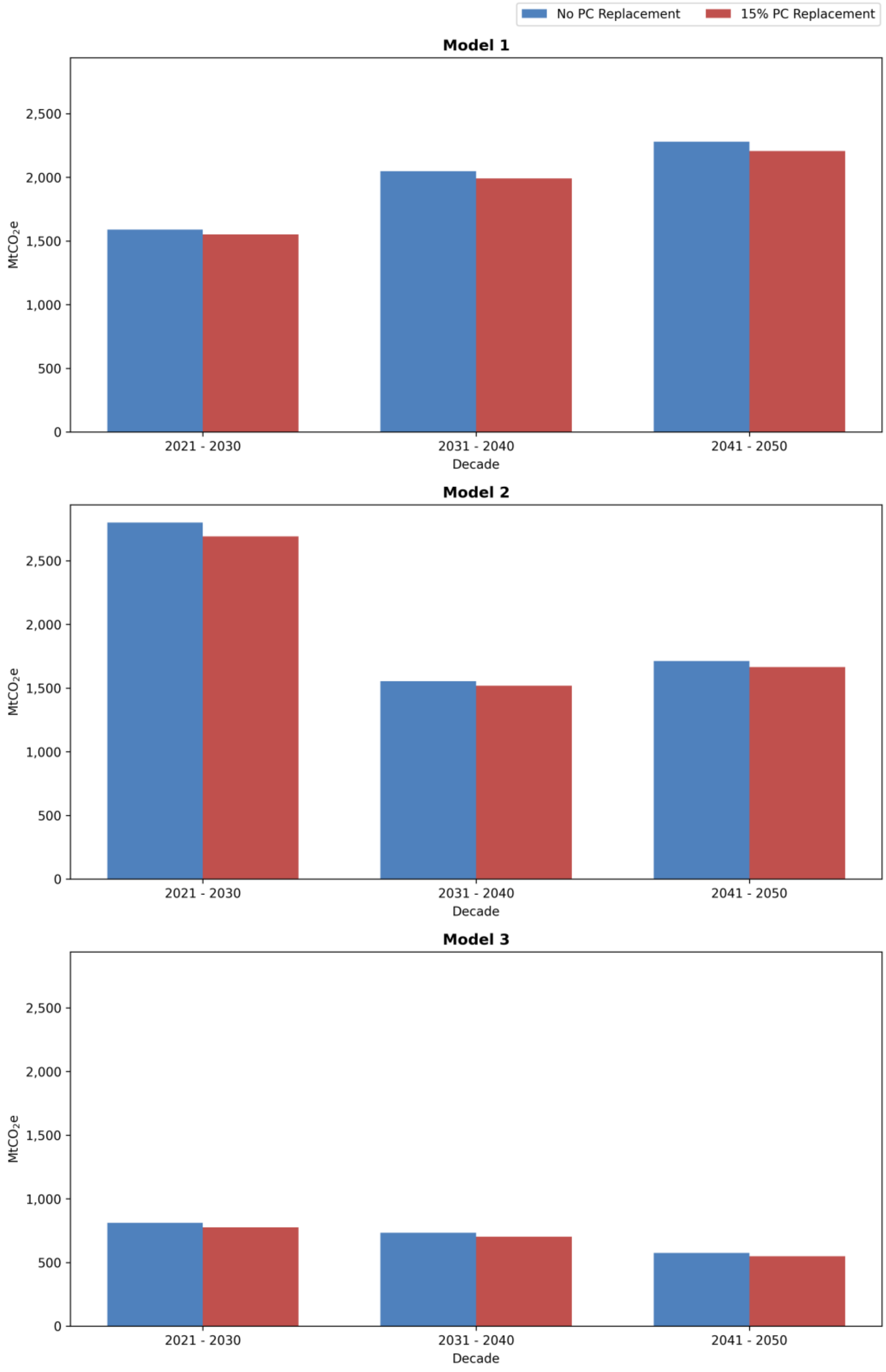

Figure 25. Global GHG emissions from new road construction by PC replacement in the cement treated base with PLC (15% replacement of PC with ground limestone)

Alternative scenarios for road roughness

Table 24 shows the two scenarios considered for road roughness sensitivity analysis: a worst-case scenario where road IRI increases from 1 m/km to 6 m/km over 20 years and a best-case scenario where IRI increases from 1 m/km to 2 m/km in the same period. The base-case scenario, for comparison, assumes an increase from 1 m/km to 4 m/km over 20 years. The modeling is intentionally simplified, assuming all roads have an initial low roughness of 1 m/km in 2020. Following maintenance, roads are restored to lower roughness levels, returning to the initial average IRI for the next decade. For instance, in the worst-case scenario, roads are restored to an average IRI of 1 – 3 m/km during 2041 – 2050 after the roads undergo M&R at the end of 2031 – 2040. Table 25 shows the fuel consumption for internal combustion engine (ICE) vehicles and electric vehicles derived from Table 19 and Table 20, respectively.

Table 24. Roughness scenarios by average IRI

	IRI (m/km)				
	Average IRI in 20 years	**2020**	**2021 – 2030**	**2031 – 2040**	**2041 – 2050**
Best	1 – 2	1	1 – 2	1 – 2	1 – 2
Base	1 – 4	1	1 – 2	3 – 4	1 – 2
Worse	1 – 6	1	1 – 3	4 – 6	1 – 3

Table 25. Fuel consumption for ICE and electric vehicles for the roughness scenarios

ICE vehicles									
Car	**L/km**				**Truck**	**L/km**			
	2020	2021 – 2030	2031 – 2040	2041 – 2050		2020	2021 – 2030	2031 – 2040	2041 – 2050
Best	0.0834	0.0846	0.0846	0.0846	Best	0.447	0.452	0.452	0.452
Base	0.0834	0.0846	0.0888	0.0846	Base	0.447	0.452	0.465	0.452
Worst	0.0834	0.0856	0.0920	0.0856	Worse	0.447	0.455	0.476	0.455
Electric vehicles									
Car	**MJ/km**				**Truck**	**MJ/km**			
	2020	2021 – 2030	2031 – 2040	2041 – 2050		2020	2021 – 2030	2031 – 2040	2041 – 2050
Best	2.665	2.705	2.705	2.705	Best	14.298	14.441	14.441	14.441
Base	2.665	2.705	2.838	2.705	Base	14.298	14.441	14.870	14.441
Worst	2.665	2.736	2.941	2.736	Worse	14.298	14.536	15.204	14.536

Figure 26 presents the GHG emissions from the additional fuel from roughness for all vehicles by the roughness scenarios. The results show that the GHG emissions obtained for the best-case and base scenarios are the same during 2021 – 2030 and 2041 – 2050, based on the roughness assumption presented in Table 25, where both scenarios have the same fuel consumption in these decades. In 2021 – 2030, the GHG emissions from the additional fuel from road roughness for the worst-case scenario is 72% higher than the base scenario, while the additional fuel from road roughness is the same for the base and best-case scenario cases, because of the simplified modeling. In 2031 – 2040, the additional GHG emission from road roughness for the worst-case scenario is approximately 59% higher than the base scenario, while the best-case scenario is 76% lower than the base case. In 2041 – 2050, the additional GHG emission from road roughness for the worst-case scenario is also 72% higher than the base scenario. The result suggests that road smoothness is critical in minimizing impact from roads. It should be noted that the global VKT for gasoline and diesel vehicles significantly reduce in 2041 – 2050.

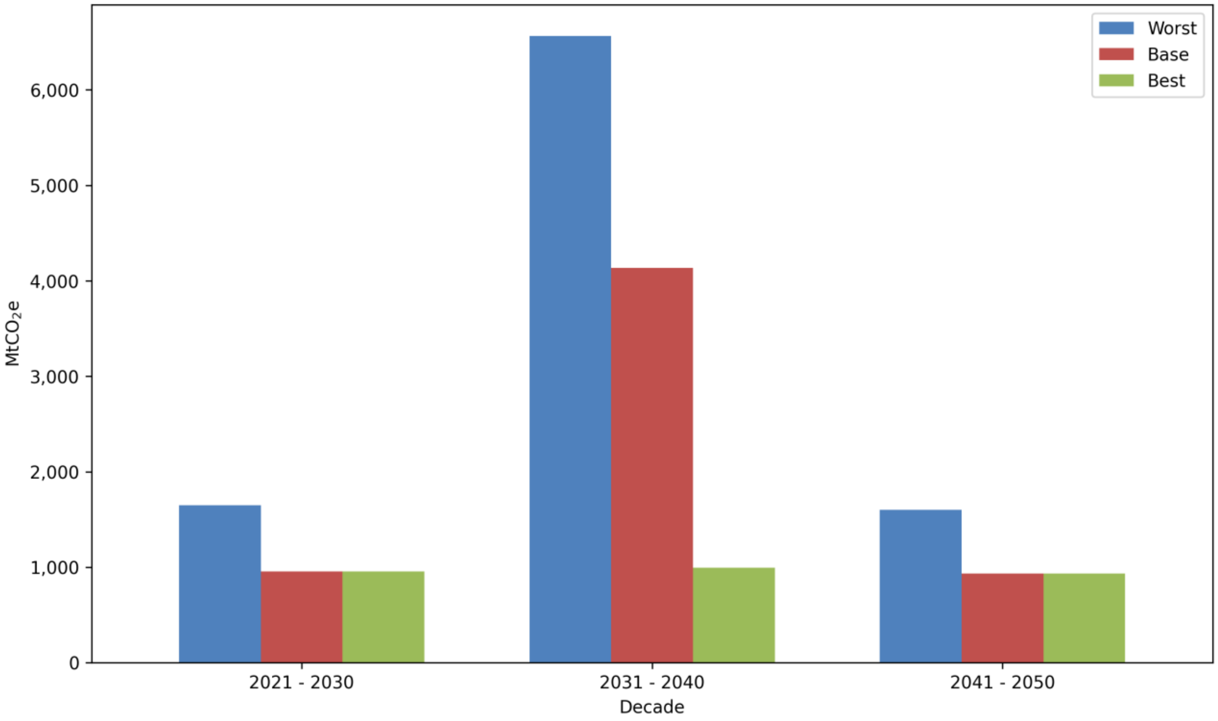

Figure 26. GHG emissions from additional fuel from road roughness for the roughness scenarios

Note: modeling of road roughness is greatly simplified for the entire world to obtain order of magnitude estimates

Alternative maintenance scheduling

Table 26 shows the maintenance schedule for the sensitivity analysis, where maintenance gets delayed due to limited financial resources. In this case, thin overlay and chip seal maintenance are deferred to the 20th year and medium overlay to the 40th year of a road's life. The analysis examines how much additional GHG emissions are generated when roads are maintained less frequently, resulting in increased fuel consumption due to higher road roughness but decreased emissions from the maintenance materials and construction. In other words, the alternative scenario illustrates the impact of delayed road maintenance on GHG emissions and the environmental trade-offs of reduced maintenance frequency.

Table 26. Maintenance scheduling for sensitivity analysis

Analysis year	New roads	Existing roads in 2021	Roads built after 2021
2020	2011 – 2020		
2030	2021 – 2030	half the roads get thin overlay + chip seal, half are getting medium overlay	
2040	2031 – 2040		built by 2030 (Thin overlay + Chip seal)
2050	2041 – 2050	half the roads get thin overlay + chip seal	built by 2040 (Thin overlay + Chip seal)

Figure 27 presents the GHG emissions from existing road M&R materials and construction for the base and alternative maintenance scenario. A similar trend is observed in each road length model where the alternative scenario has lower GHG emissions across the decades. Across the three road length models, GHG emissions in the alternative scenario are approximately 3 – 6% lower than the base scenario during 2021 – 2030, 94 – 96% lower in 2031 – 2040, and 79 – 85% lower in 2041 – 2050. This indicates that delayed maintenance in the alternative scenario reduces road project GHG emissions and can provide short-term financial savings, but it also results in roads with higher IRI. These rougher or poor-quality roads increase vehicle fuel consumption, resulting in higher operational emissions and burden shifting, where the environmental impact is transferred from road maintenance to vehicle operation.

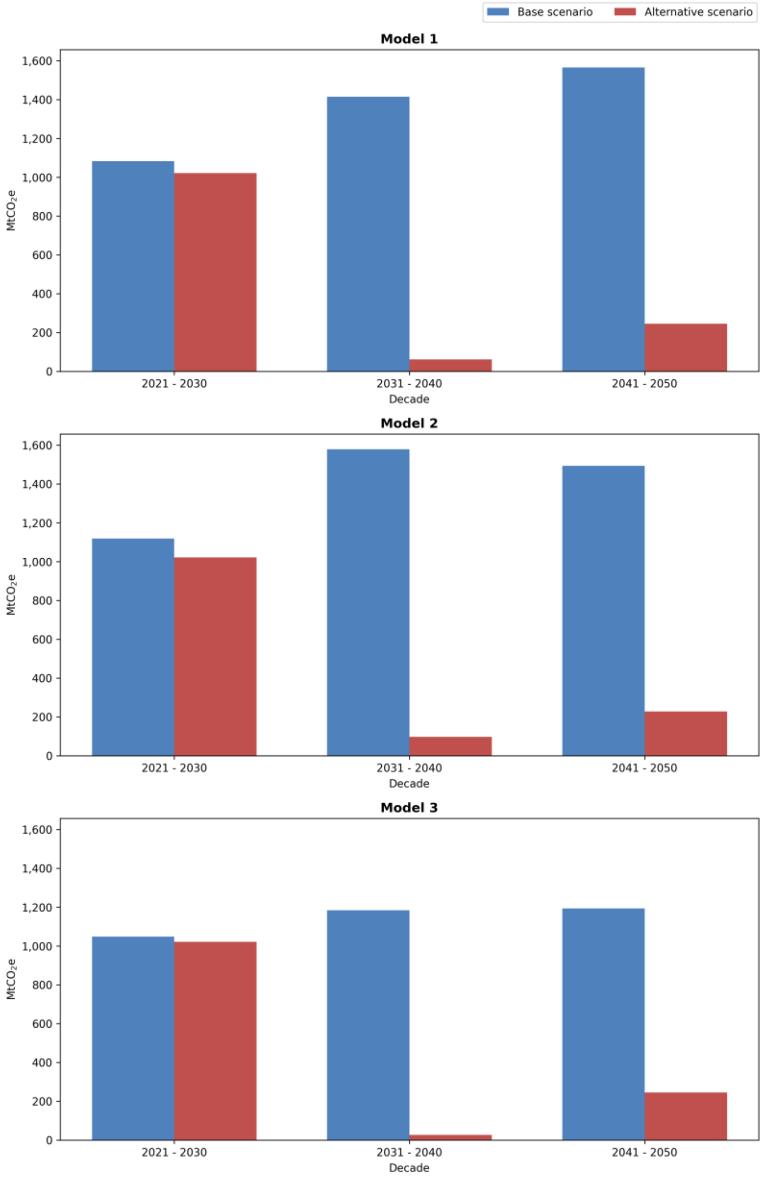

Figure 27. GHG emissions from maintenance materials and construction for different scenarios

Figure 28 shows the combined GHG emissions from M&R materials and construction and the additional fuel from rougher roads for the maintenance investment strategies for all the road length models. The high maintenance investment strategy represents the base maintenance and base roughness scenario, while the low maintenance investment represents the alternative maintenance and the worst-case roughness scenario. In the high maintenance investment strategy, GHG emissions from existing road M&R exceed the emissions from road roughness in all decades except 2031 – 2040. This is because more fuel is consumed in this decade as peak roughness is attained. In the low maintenance investment strategy, GHG emissions from road roughness are higher than emissions from road maintenance across all decades. Across the models, combined GHG emissions in the low maintenance investment case are 29 – 31% higher than in the high investment scenario during 2021–2030 and 17 – 24% higher in 2031 – 2040 due to increased roughness-related fuel consumption. However, by 2041 – 2050, emissions in the low maintenance scenario become 13 – 26% lower as the delayed maintenance is eventually completed and restores roads to a smoother condition, reducing roughness-related emissions and lowering overall impacts compared to the high maintenance investment scenario. This comparison highlights the trade-offs between frequent maintenance and delayed maintenance in terms of emissions and road conditions over time.

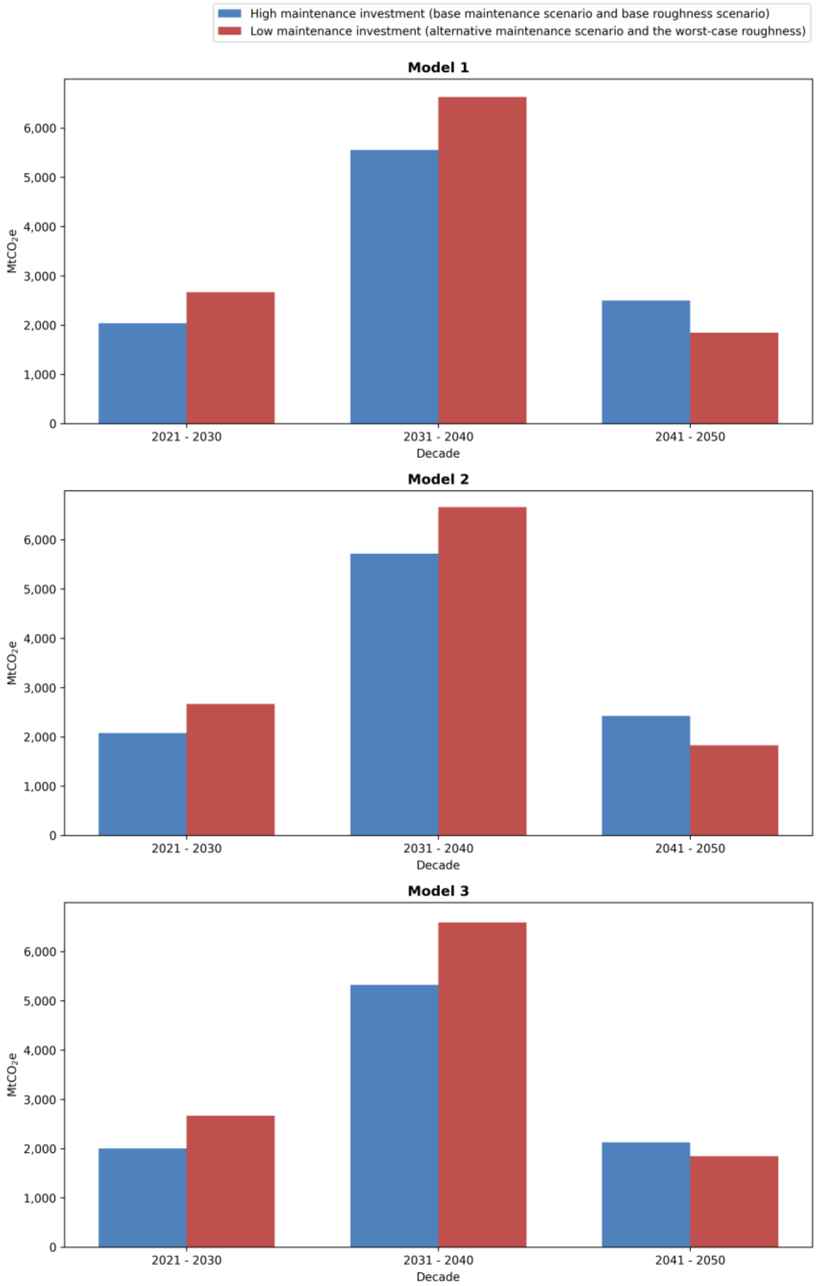

Figure 28. Combined GHG emissions from road roughness and maintenance

Road Transportation GHG emissions

Global and regional GHG emissions from road transportation

In this report, GHG emissions from road transportation include emissions from new road construction (A1 – A5 following ISO 21931 terminology), existing road M&R (stages B2 and B3, having their own A1 – A5), and vehicle-related emissions, which include vehicle manufacturing, vehicle operation (WTW), and additional fuel due to road roughness (a part of B1 in ISO 21931 terminology). Figure 29 shows the global GHG emissions from road transportation for all the decades using road project GHG emissions from Model 3. The trend in road transportation GHG emissions follows the pattern observed for global vehicle-related emissions, with the highest in 2031 – 2040 and the lowest in 2041 – 2050. The total GHG emissions in 2031 – 2040 increases by 3% compared to the previous decade, followed by a 19% decrease in 2041 – 2050. Across the decades, new road construction accounts for approximately 1% of the total GHG emissions, existing road M&R (1 – 2%), vehicle manufacturing (7 – 8%), vehicle operation (87 – 90%), and additional fuel from roughness (1 – 5%), with the peak occurring in 2031 – 2040.

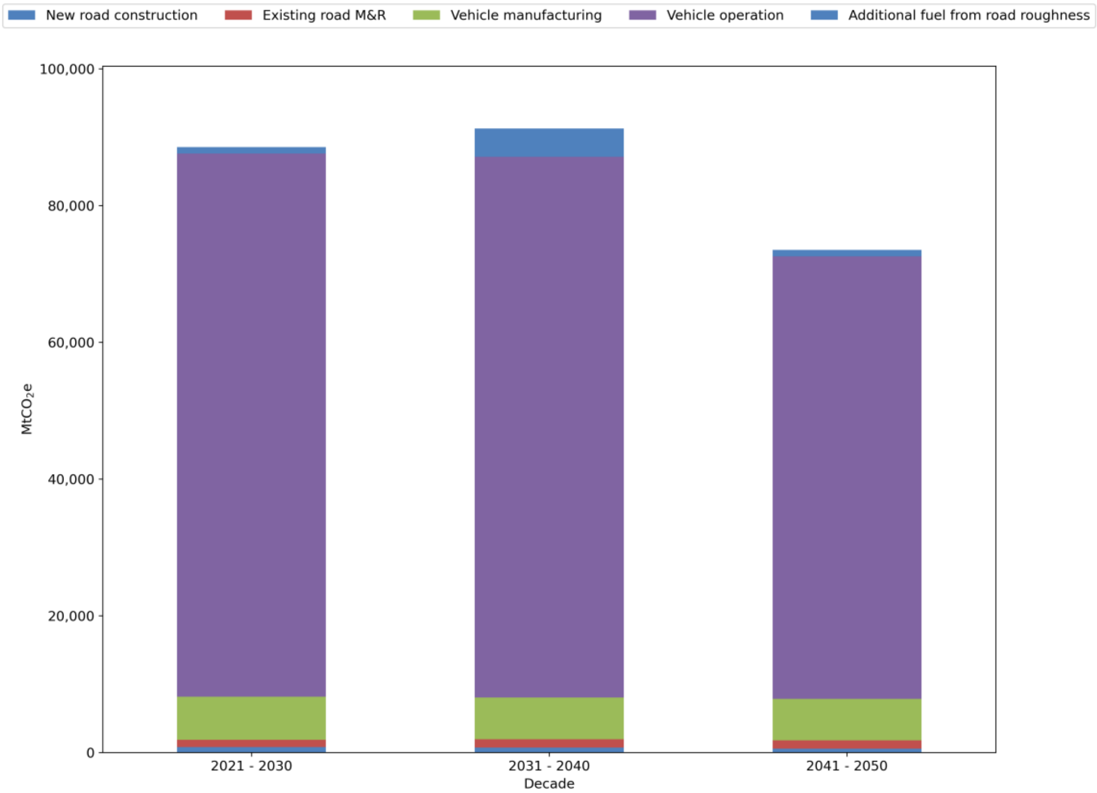

Figure 29. Global GHG emissions from road transportation for all decades

Figure 30 shows the regional contributions to GHG emissions from road transportation over the decades. OECD North America, OECD Europe, and China consistently are the largest contributors. OECD North America accounts for 24% of total emissions in 2021 – 2030, 21% in 2031 – 2040, and 18% in 2041 – 2050. OECD Europe contributes 22%, 16%, and 11% over the same periods, while China's share is 12%, 16%, and 15%, respectively. These three regions are responsible for 58%, 53%, and 43% of global GHG emissions from road transportation in 2021 – 2030, 2031 – 2040, and 2041 – 2050, respectively. ATE, EU5, OETE, Other OECD, and Others are the least contributors to global GHG emissions from road transportation.

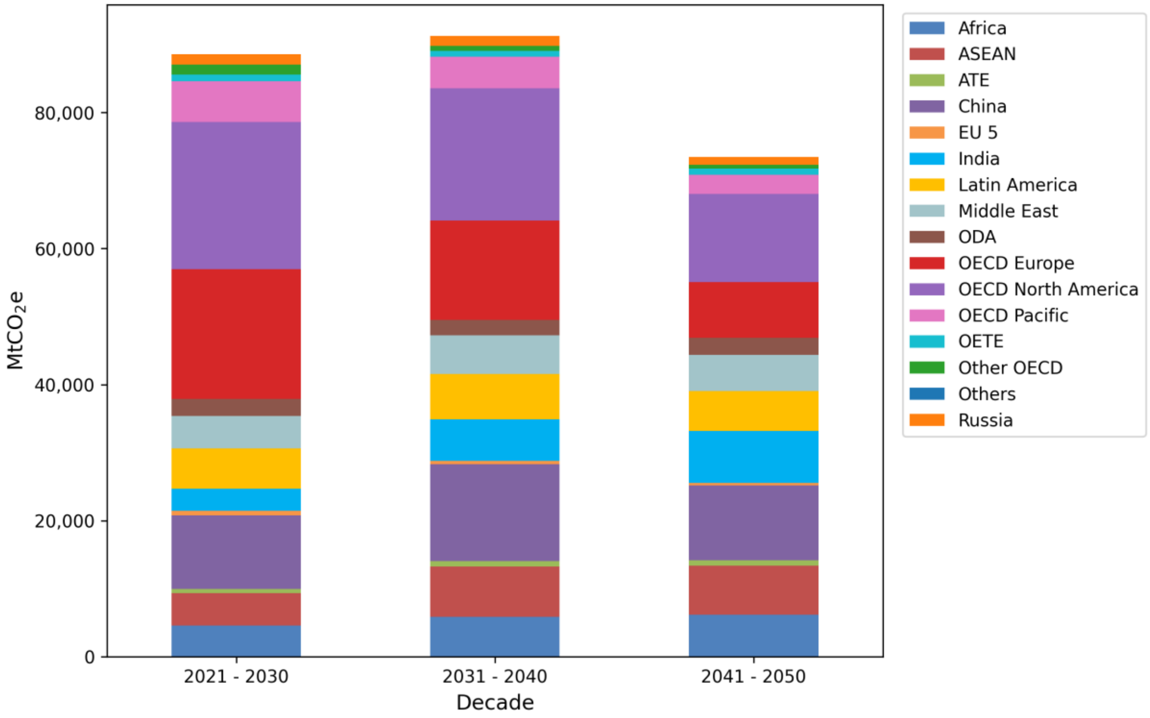

Figure 30. Total regional GHG emissions over the decades

Figure 31 presents the GHG emissions from road transportation for each region. The trend follows that observed for regional vehicle related GHG emissions, where OECD North America, OECD Europe, and China have the highest emissions, while EU5, ATE, OETE, and Other OECD have the lowest. The mean increase by decade in GHG emissions from road transportation is similar to the increase in vehicle related GHG emissions. Across all regions, new road construction contributes 0 – 5% of total road transportation GHG emissions, while existing road M&R accounts for 0.2 – 5%, except in the "Others" region, where it constitutes 100% of emissions across all decades. Vehicle manufacturing contributes roughly 3 – 18%, vehicle operation accounts for 78 – 96%, and additional fuel from road roughness contributes 1 – 5%. For instance, in Africa, new road construction contributes 3 – 4%, existing road M&R 2%, vehicle manufacturing 6 – 8%, and additional fuel from roughness 1 – 4%, with vehicle operation making up the difference. In OECD regions, new road construction contributes less than 1%, existing road M&R 1 – 2%, vehicle manufacturing 3 – 10%, vehicle operation 86 – 96%, and additional fuel from roughness 1 – 5% of total road transportation emissions across the decades.

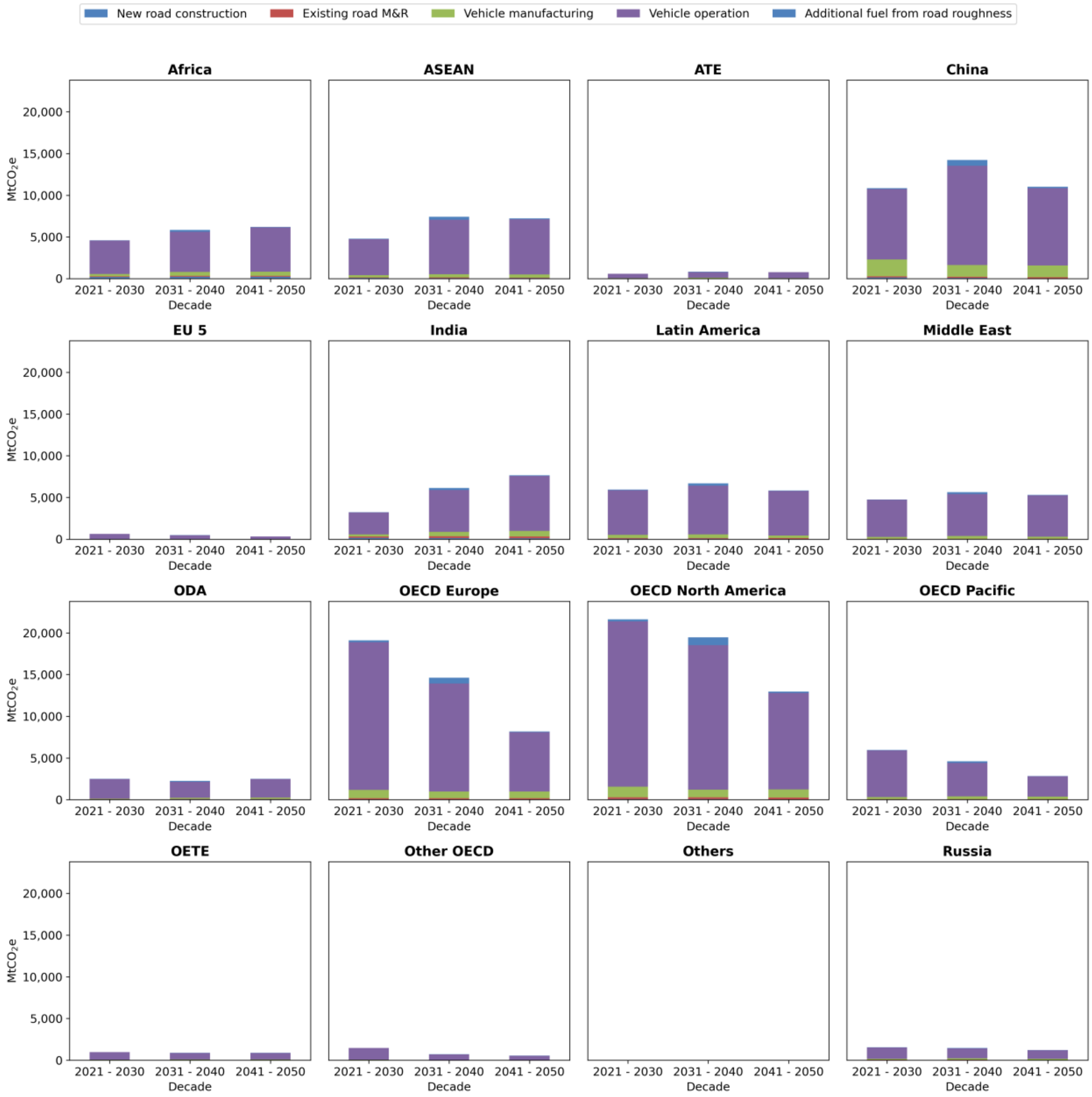

Figure 31. GHG emissions from road transportation for all regions

Cumulative GHG emissions from road transportation

This section presents the cumulative global and regional GHG emissions from road transportation from 2021 to 2050 (thirty years) based on the conservative (Model 3 and base case road roughness) scenario. Other scenarios are presented in the next section of this chapter. Cumulatively to 2050, approximately 88% of the total impact from global road transportation will be from vehicle operation, 7% from vehicle manufacturing, and 2.2% from road projects (new road construction and existing road M&R), as shown in Figure 32. Thus, vehicle-related emissions account for 97% of the total GHG emissions from road transportation. Figure 33 presents the cumulative GHG emissions from road transportation by 2050 across all regions. OECD North America, OECD Europe, and China collectively account for approximately 52% of the total cumulative emissions. By 2050, Africa, India, and Latin America will each contribute around 7% of global road transportation GHG emissions.

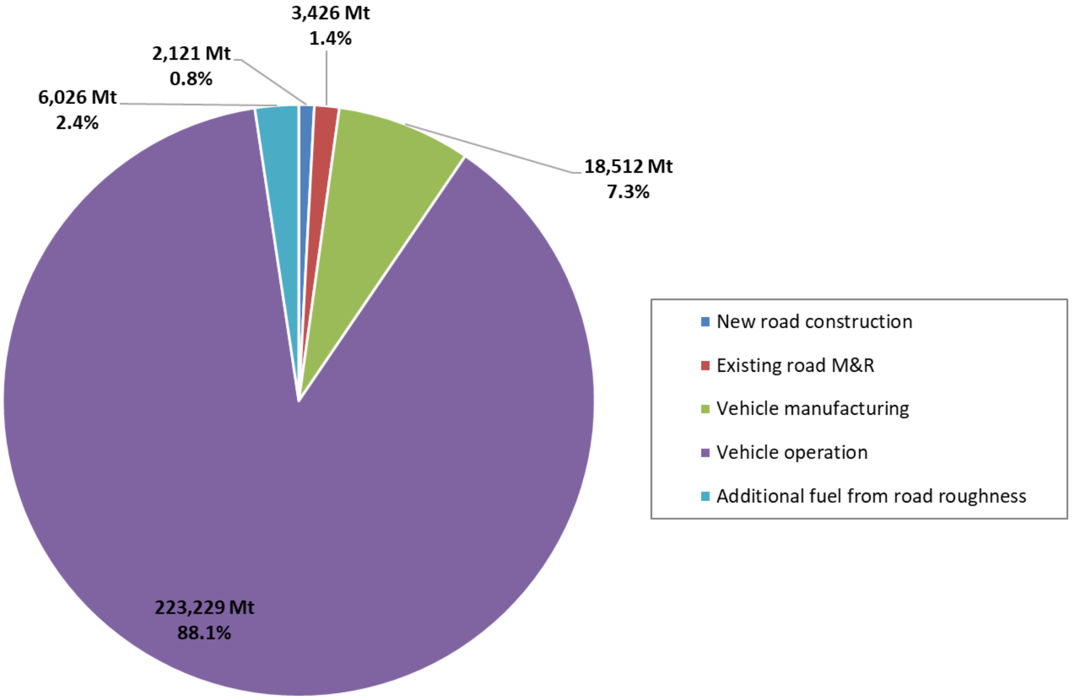

Figure 32. Cumulative GHG emissions from global road transportation by 2050

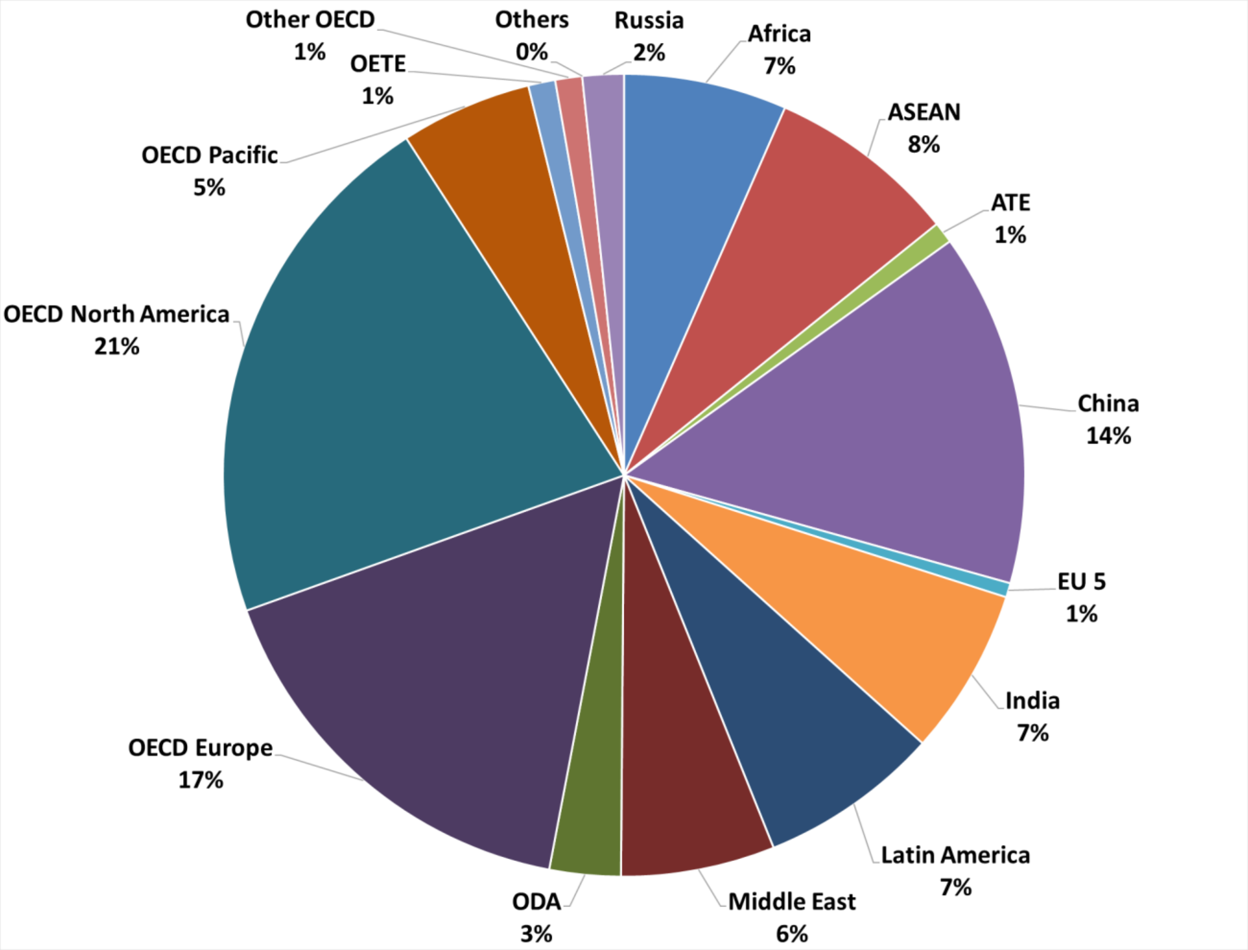

Figure 33. Regional contributions of cumulative GHG emissions by 2050

Figure 34 shows the cumulative GHG emissions to 2050 for each region by road transportation emission drivers. Across each region, new road construction accounts for 0.1 to 4% of the total GHG emissions from road transportation, existing road M&R (0.32 – 3%), vehicle manufacturing (1 – 3%), vehicle operation (82 – 93%), and additional fuel from road roughness (2 – 3%). While developed regions such as OECD Europe, EU 5, and Other OECD have the highest vehicle operation impacts, developing and emerging regions such as Africa, India, and ODA have the highest road project impacts.

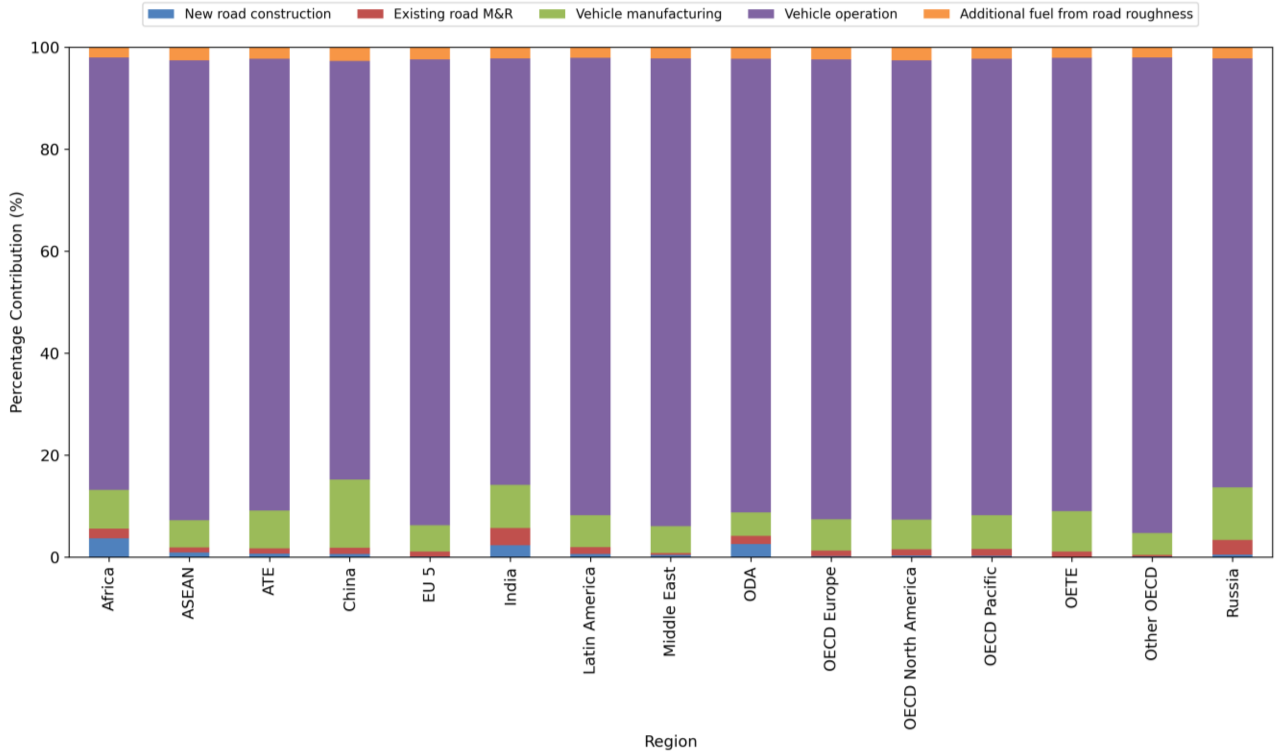

Figure 34. Cumulative GHG emissions for each region by road transportation emission drivers

Figure 35 shows the regional contributions of cumulative GHG emissions for all road transportation emission drivers. Africa has the highest GHG emissions from new road construction between 2021 and 2050, with 29% of the total new road construction GHG emissions. India and China account for 19% and 11% of the total, respectively. From the projection, OECD North America, India, and China have the highest GHG emissions from existing road M&R, representing 19%, 17%, and 13% of the total. Africa and Latin America account for 9% and 7% of the total. China, OECD North America, and OECED Europe are the most significant contributors to vehicle manufacturing impact, representing 26%, 17%, and 14%, respectively. OECD North America has the highest vehicle operation impact (22% of the total), followed by OECD Europe (17%) and China (13%). OECD North America, OECD Europe, and China also have the highest GHG emissions from road roughness. EU 5, OETE, and Other OECD countries contribute very low emissions to the total GHG emissions from each road transportation emission driver.

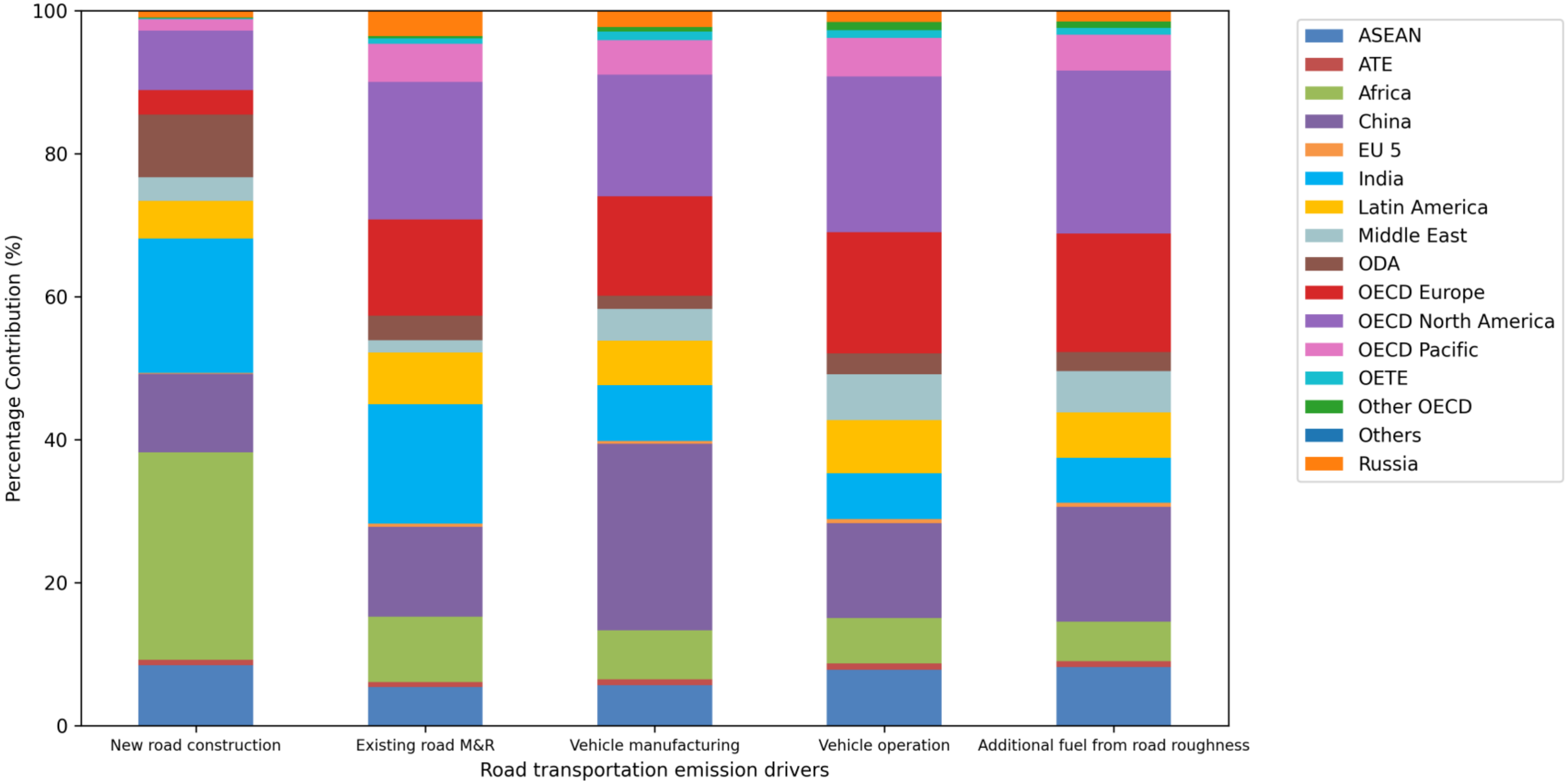

Figure 35. Regional contributions of cumulative GHG emissions for each road transportation emission driver by 2050

Emission rate by land area and road network length

Table 27 compares the emission levels from the road transportation sector across the global regions, focusing on total and per-unit emissions over 30 years (2021 to 2050) and annually. The emissions are normalized by each region's land area and road network length. Normalizing allows for better comparisons across regions of different sizes and levels of economic development. The annual rate is determined by dividing the total emissions by thirty years. A high emission rate per land area suggests intensive transportation activities or less efficient transportation systems within a confined geographical space. In contrast, a low rate indicates that the region emits relatively low levels of GHG over a region's land area.

In instances where total emissions and land area are both high, the emission rate might be relatively low. For instance, EU 5 and Other OECD regions exhibit this pattern, with relatively low total emissions from the road transportation sector but high annual emission rates. Among the regions, OECD Europe, India, and ASEAN have the highest annual emission rate by land area (10^3 km^2) with 0.27 Mt CO_2e, 0.19 Mt CO_2e, and 0.15 Mt CO_2e. On the other hand, Other OECD, the Middle East, and ASEAN have the highest rate by road length (10^3 km) with 0.86 Mt CO_2e, 0.79 Mt CO_2e, and 0.3 Mt CO_2e, respectively. It is important to note that the 'Others' region only includes the impact of road projects and not the impact of vehicle use.

The two right-most columns show the ratios of emission rates produced per area of land and kilometer of road, respectively, between OECD North America and other regions, using OECD North America as a benchmark for normalizing emissions for other regions. Apart from Others, Russia, ATE, and Africa have the lowest ratio per unit area of land, while Russia, India, and Africa have the lowest per km of road. A ratio per unit area of land of 0.21 in Africa suggests that emission level per land area in OECD North America is almost 5 times higher than that in Africa. A high benchmarked ratio, such as those of OECD Europe for land area and Other OECD and Middle East for road length, suggests that the region’s emission rate is relatively higher than that of OECD North America. A close to 1 emission benchmarked ratio suggests that the region’s emission rate is close or comparable to that of OECD North America.

Albuquerque et al. (Albuquerque et al., 2020) compared country-specific annual emission levels from the transportation sectors of seven countries: Abu Dhabi, Saudi Arabia, India, Russia, China, the United Kingdom, and the United States. Their results show that Gulf Cooperation Countries (GCC), including Abu Dhabi and Saudi Arabia, have the highest emission rates per kilometer of road, surpassing even traditionally large GHG producers such as China and the United States. In the study, the UK, US, and Abu Dhabi have the highest emission rate by land area, representing 0.489 Mt CO_2e, 0.179 Mt CO_2e, and 0.155 Mt CO_2e, respectively. In contrast, Abu Dhabi, Saudi Arabia, and the UK have the highest emission rates by road length representing 0.571 Mt CO_2e, 0.398 Mt CO_2e, and 0.302 Mt CO_2e, respectively. Despite low total emissions in GCC regions, shorter road lengths, high vehicle ownership, the prevalence of heavier vehicles, and usage per capita due to its higher income and cheaper fuel account for high emission rates. Albuquerque et al. (Albuquerque et al., 2020) only considered the center-line length of roads in the countries without accounting for the number of lanes on those roads, that is, the total lane length of roads. This is important because roads in different countries can vary significantly regarding the number of lanes they have. For instance, a one-kilometer stretch of a six-lane highway represents much more infrastructure and potential for vehicle traffic (and therefore emissions) than a one-kilometer stretch of a two-lane road. Therefore, comparing road lengths without considering the number of lanes might not accurately reflect the built road infrastructure's true extent or capacity for vehicle traffic and emissions.

Table 27. Estimated emission rates for total transportation sector by region

			Cumulative 30-year period emissions			Annual Emission Rate			Normalized by OECD North America as benchmark	
	Land area (10^3 km^2)	Road length (10^3 km)	Total (Mt CO_2e)	Mt CO_2e. / 10^3 km^2	Mt CO_2e / 10^3 km-road)	Total (Mt CO_2e)	Mt CO_2e. / 10^3 km^2	Mt CO_2e / 10^3 km-road)	Region/OECD North Am (CO_2e/Area)	Region/OECD North Am (CO_2e/km-road)
Africa	29,652	3,180	16,650	0.56	5.23	555	0.02	0.17	0.21	0.79
ASEAN	4,395	2,141	19,402	4.42	9.06	647	0.15	0.30	1.64	1.36
ATE	4,121	250	2,185	0.53	8.74	73	0.02	0.29	0.20	1.31
China	9,389	5,200	36,078	3.84	6.94	1,203	0.13	0.23	1.43	1.04
EU 5	404	181	1,460	3.61	8.05	49	0.12	0.27	1.34	1.21
India	2,973	6,372	17,036	5.73	2.67	568	0.19	0.09	2.13	0.40
Latin America	17,348	2,913	18,443	1.06	6.33	615	0.04	0.21	0.39	0.95
Middle East	5,428	661	15,714	2.90	23.77	524	0.10	0.79	1.07	3.57
ODA	4,090	1,250	7,267	1.78	5.81	242	0.06	0.19	0.66	0.87
OECD Europe	5,109	5,835	41,886	8.20	7.18	1,396	0.27	0.24	3.04	1.08
OECD North America	20,067	8,121	54,060	2.69	6.66	1,802	0.09	0.22	1.00	1.00
OECD Pacific	8,417	2,306	13,412	1.59	5.82	447	0.05	0.19	0.59	0.87
OETE	1,017	358	2,753	2.71	7.68	92	0.09	0.26	1.01	1.15
Other OECD	765	106	2,750	3.59	25.89	92	0.12	0.86	1.33	3.89
Others	4.24	7.035	1	0.13	0.08	0.0178	0.0042	0.0025	0.05	0.01
Russia	16,377	1,554	4,218	0.26	2.71	141	0.01	0.09	0.10	0.41

Scenario Analysis

Scenario analysis, accounting for different assumptions and predictions, is undertaken in this project to provide a comprehensive view of potential future outcomes. The analysis is needed to understand the range of possibilities for future GHG emissions from road transportation emission drivers and make informed decisions. Four distinct scenarios are developed: moderate, pessimistic, conservative, and optimistic, based on road network growth and roughness scenarios, as shown in Table 28.

Although Model 1 and Model 2 both suggest substantial growth in road length, Model 1 gives a lower mean increase in GHG emissions across the decades except for 2041 – 2050, where it predicts a higher length than Model 2. Model 3 predicts conservative road length growth. The moderate scenario combines GHG emissions from Model 1 with emissions from base-case road roughness. The pessimistic scenario uses GHG emissions from Model 2 combined with emissions from worst-case road roughness. The conservative scenario uses GHG emissions from Model 3 along with base-case road roughness, and the optimistic scenario combines emissions from Model 3 with best-case road roughness. All scenarios include vehicle-related emissions, which are the same across the scenarios, ensuring the analysis focuses on differences in maintenance and road roughness impacts.

Table 28. Scenario analysis for GHG emissions from global road transportation system

Scenario	Scenario definition
Moderate	Model 1 (new road construction + existing road M&R) + base-case roughness
Pessimistic	Model 2 (new road construction + existing road M&R) + worst-case roughness
Conservative	Model 3 (new road construction + existing road M&R) + base-case roughness
Optimistic	Model 3 (new road construction + existing road M&R) + best-case roughness

Note: All scenarios use base maintenance scheduling for existing road M&R and include vehicle-related GHG emissions

Figure 36 presents the trend for GHG emissions from road transportation across the decades. For all scenarios, 2031 – 2040 represents the decade with the highest GHG emissions, while 2041 – 2050 has the least emissions. GHG emissions from road transportation generally increase moderately between 2021 – 2030 and 2031 – 2040, with growth rates ranging from 3% to 4%, except for the Optimistic scenario, which shows a 1% decline. However, emissions significantly decline across all scenarios between 2031 – 2040 and 2041 – 2050, with reductions ranging from 16 to 20%, as smoother road conditions from maintenance reduce roughness-related fuel consumption. These trends highlight how emissions peak in 2031 – 2040 before declining sharply in the final decade due to maintenance and roughness mitigation effects.

Using the conservative scenario as a benchmark, GHG emissions in the moderate scenario are approximately 1% higher in 2021 – 2030, 2% higher in 2031 – 2040, and 3% higher in 2041 – 2050. The pessimistic scenario shows consistently higher emissions than the conservative scenario, at 3% higher across all decades. The optimistic scenario has emissions 3% lower than the conservative scenario in 2031 – 2040 but remains the same in the other decades. Figure 37 shows the trend of the cumulative GHG emissions. By 2050, the total cumulative GHG emissions from the pessimistic, moderate, conservative, and optimistic scenarios will be 261,812 $MtCO_2e$, 257,747 $MtCO_2e$, 253,314 $MtCO_2e$, and 250,171 $MtCO_2e$, respectively. This translates to an annual rate of 8,727 $MtCO_2e$, 8,592 $MtCO_2e$, 8,444 $MtCO_2e$, and 8,339 $MtCO_2e$. By 2050, the total GHG emissions from moderate and pessimistic scenarios will be 2% and 3% higher than the emissions from conservative scenario. The emissions from optimistic scenario will be 1% lower than those from conservative scenario. Overall, the differences between the scenarios are much smaller than the potential errors from the large assumptions that were made in this study.

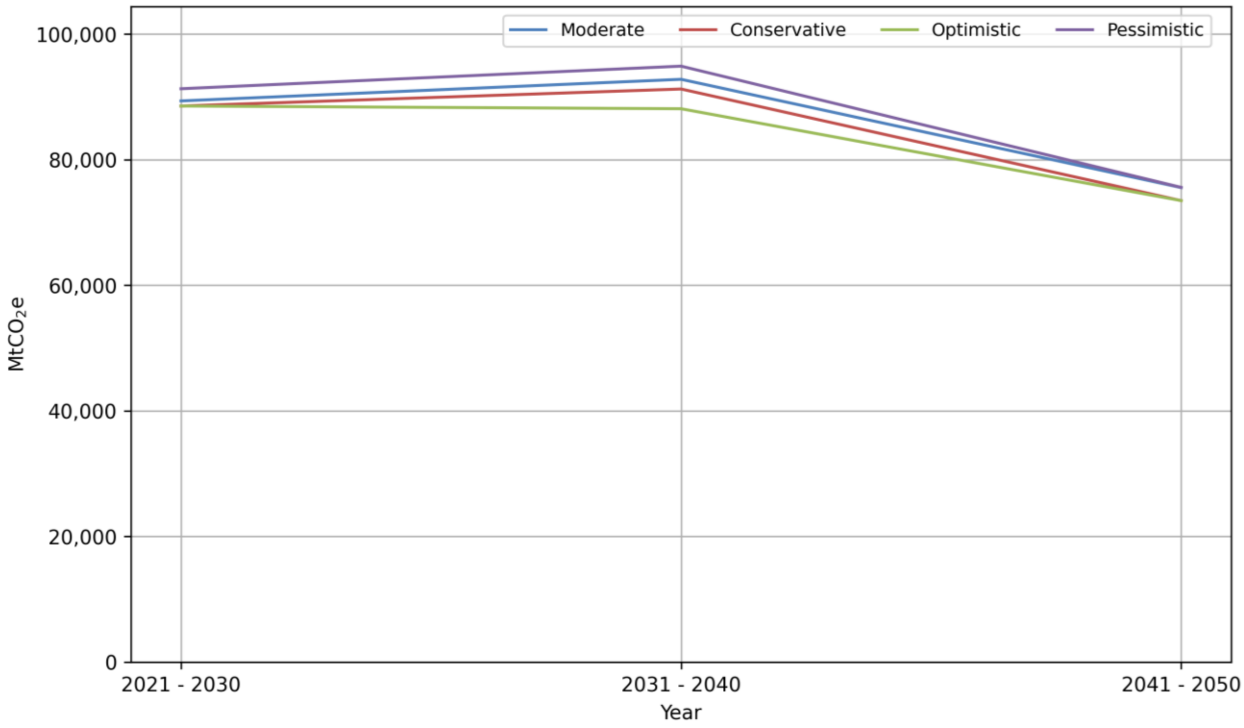

Figure 36. GHG emissions from global road transportation by scenarios

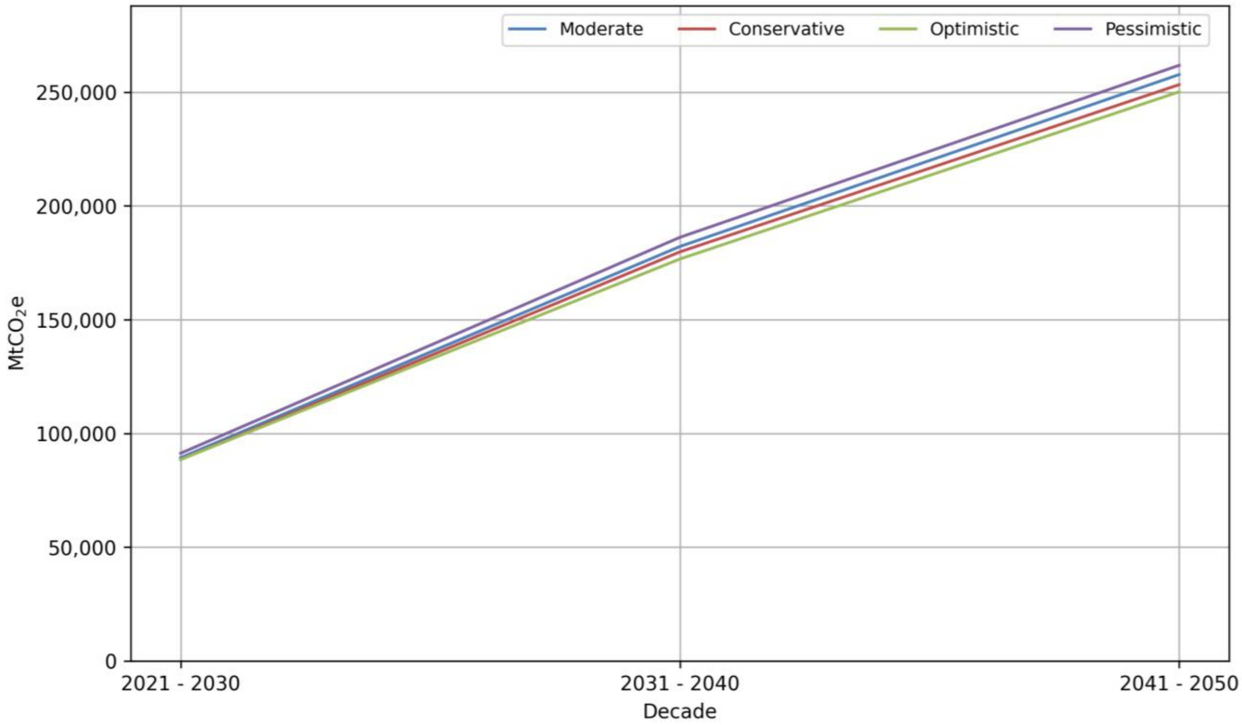

Figure 37. Cumulative GHG emissions from global road transportation by scenario

Summary, Conclusions, and Recommendations

Summary

The goal of this study was to develop a framework and first order estimation of GHG emissions from the built-out and maintenance and rehabilitation of the world's roadway infrastructure networks from 2020 to 2050. The current global road network size was estimated and its future build-out from 2021 to 2050 by decade was modelled using three approaches, and on a country-by-country basis. The types of pavement structures were estimated and greatly simplified based on available information for countries in different regions of the world. Maintenance and rehabilitation practices were also assumed. The same was done for simple reinforced concrete bridges and culverts.

The GHG emissions from road pavement, bridges, and maintenance and rehabilitation were calculated by decade based on the existing road networks and the modelling of their expansion. For comparison, the GHG emissions from vehicle manufacturing and operation were estimated using IEA Mobility Model (MoMo) data. Regional comparisons and sensitivity analyses were then performed. The report further presents the GHG emissions from road transportation, including the emissions from new road construction (A1 – A5 following ISO 21931 terminology), existing road M&R (stages B2 and B3, having their own A1 – A5), and vehicle-related emissions, which include vehicle manufacturing, vehicle operation (well to wheel, WTW), and additional fuel due to road roughness (a part of B1 in ISO 21931 terminology).

Conclusions

The following conclusions are based on the results of this study:

- The regression analysis shows varying projections of road length increases relative to the estimated 2020 global road network of 40.4 million lane-km. Model 1 predicts significant growth: 18.5% by 2030, 41.8% by 2040, and 67.0% by 2050, relative to 2020. Model 2 similarly forecasts increases of 29.1%, 47.3%, and 66.7%. In contrast, Model 3 projects more moderate growth: 8.1%, 15.5%, and 21.2%.
- Results from the road network growth models indicate that developing regions and emerging economies will prioritize constructing new roads over the next three decades more than developed regions.
- The OECD North America, India, China, Africa, and ASEAN regions have the highest road infrastructure (pavement, bridges, culverts, including pavement M&R) related GHG emissions in each decade. Developing regions, such as India and Africa, have relatively higher new road construction GHG emissions, and developed regions, such as OECD North America, have higher existing road M&R GHG emissions.
- Vehicle operation is the predominant contributor to vehicle related (operation, manufacture, additional operation emissions from road roughness) GHG emissions, contributing over 89% of the total emissions in each decade. Vehicle manufacturing contributes about 7 – 8% of total vehicle-related emissions across the decades. The

additional fuel consumption from road roughness accounts for 1 – 5% of the total vehicle-related emissions.

- Pavement roughness results in a small increase (1 – 6%) in gasoline and diesel vehicle GHG emissions due to higher fuel consumption during vehicle operation. For electric vehicles, pavement roughness causes a higher increase in GHG emissions (4 – 16%), with the extent of the increase determined by the composition of the electric grid mix.
- From the sensitivity analysis, across the three decades, emissions reductions from replacing conventional portland cement with portland limestone cement (PLC) in road bases range from 2 – 3% in Model 1, 2 – 4% in Model 2, and 4 – 5% in Model 3. This result highlights the limited impact of PLC replacement on overall road transportation GHG emissions for this one scenario analysis. Cement replacement in bridges and culverts was not considered. There are other cement technologies that can produce greater emissions reductions however they are not yet widely used.
- From the sensitivity analysis, delayed maintenance in the alternative scenario reduces road project GHG emissions but leads to roads with higher IRI. These rougher, lower-quality roads increase vehicle fuel consumption, resulting in higher vehicle-related emissions and burden shifting, where the environmental impact shifts from road maintenance to vehicle operation.
- The scenario analysis combines the effects from the three models of road network expansion and three sensitivity scenarios for road roughness development, along with fixed estimates of vehicle manufacturing and operation, to calculate the GHG emissions for the whole road transportation system. These scenarios are moderate (moderate road network expansion and base case roughness), pessimistic (most road network expansion and worst roughness development), conservative (least road expansion and base case roughness), and optimistic (least road expansion and best roughness development). The GHG emissions for the sensitivity analyses scenarios varied by 1 – 4%, depending on the scenario and the decade. The small differences are because of the overwhelming GHG emissions from vehicle operation and the large GHG emissions from vehicle manufacturing in each scenario, which were held fixed.
- By 2050, the total cumulative transportation (vehicles and roads) GHG emissions from the pessimistic, moderate, conservative, and optimistic scenarios will be 261,812 $MtCO_2e$, 257,747 $MtCO_2e$, 253,314 $MtCO_2e$, and 250,171 $MtCO_2e$, respectively. This translates to an annual rate of 8,727 $MtCO_2e$, 8,592 $MtCO_2e$, 8,444 $MtCO_2e$, and 8,339 $MtCO_2e$.
- Approximately 88% of the cumulative global GHG emissions from the conservative scenario will be from vehicle operation, 7% from manufacturing, and 2% from road projects (new road construction and existing road M&R).
- Based on the conservative scenario, across each region, new road construction accounts for 0.1 to 4% of the cumulative GHG emissions from road transportation, existing road M&R (0.32 – 3%), vehicle manufacturing (4 – 13%), vehicle operation (82 – 93%), and additional fuel from road roughness (2 – 3%). While developed regions such as OECD Europe, EU 5, and Other OECD have the highest vehicle operation impacts, developing

and emerging regions such as Africa, India, and ODA have the highest road project impacts. The maximum regional contribution of new road construction and existing road M&R to total system 30-year cumulative GHG emissions is 6%.

- In terms of the three greatest regional contributors to new road construction, Africa, India and China are estimated to account for 29, 19 and 11% of the GHG emissions from global new road construction, respectively, from 2021 to 2050. For existing road maintenance, the three greatest contributors are estimated to be OECD North America, India, and China representing 19%, 17%, and 13% of the total impact from global road maintenance to 2050.

Recommendations

Vehicle operation and manufacturing together have more than 40 times the global GHG emissions from road construction and maintenance. While road construction and maintenance have relatively low contributions to the global road life cycle GHG emissions, the percentages (1 to 6% of the global road transportation system values include vehicle manufacture and operation) are sufficiently large in terms of percentage and in terms of absolute values to warrant all possible efforts to reduce those contributions to net zero by 2050 or sooner. It is also clear that the primary focus needs to be on finding solutions in emerging economies, where the most growth in road networks will occur as standards of living increase and greater accessibility to locations that increase quality of life is possible.

The three limited scope sensitivity analyses indicate that even simple efforts to reduce materials embodied emissions and control road roughness can begin to provide reductions in GHG emissions. Increasing the durability of pavements will also help reduce GHG emissions by extending the time between maintenance and rehabilitation. Durability can be increased through better construction quality control, better materials, better pavement and drainage design, and use of low impact preservation treatments in a timely manner.

It is recommended that regionally appropriate pavement materials, construction, and asset management technologies be developed, communicated, and incentivized throughout the world to reduce the GHG emissions from road infrastructure.

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Data Summary

Products of Research

The appendices section provides detailed data collected and generated for this study, including road network data, socioeconomic data, vehicle fleet data, pavement, bridge, and culvert data, electricity and fuel mix data, emission factors, and GHG emissions data. Table 29 shows types of data collected and a brief description. References are provided for all externally sourced data. Emission factors and GHG emissions data were produced through life cycle analysis conducted as part of the project.

Table 29. Data type and description

Data Type	Description
Road network data	Current road length and road densities of world's countries
	Current and predicted road lengths using Model 1 for all regions
	Current and predicted road lengths using Model 2 for all regions
	Current and predicted road lengths using Model 3 for all regions
Socioeconomic data	Current population density, GDP / capita, land surface area for world's countries
	Projected population density, GDP / capita, land surface area for world's countries
Vehicle fleet data	Annual vehicle sales and VKTs for gasoline vehicles by region
	Annual vehicle sales and VKTs for diesel vehicles by region
	Annual vehicle sales and VKTs for electric vehicles by region
Pavement, bridge, and culvert data	Pavement design information (layer type and thickness) for representative countries
	Regional bridge densities for representative countries
Electricity mix data	Current electricity mixes for representative countries and regions
	Projected electricity mixes for representative countries and regions
Emission factors	Emission factors in $kgCO_2e$ for producing 1 kg of HMA at asphalt plants in different countries
	Emission factors in $kgCO_2e$/lane-km for pavement layers by region
	Emission factors in $kgCO_2e$ for 4-lane culvert by region
	Passenger car manufacturing and WTW emission factors by fuel and region
	Truck manufacturing and WTW emission factors by fuel and region
GHG emissions data	GHG emissions from road project using Model 1 road projection growth
	GHG emissions from road project using Model 2 road projection growth
	GHG emissions from road project using Model 3 road projection growth
	Vehicle-related GHG emissions for all vehicle fuel types
	Vehicle-related GHG emissions for gasoline vehicles
	Vehicle-related GHG emissions for diesel vehicles
	Vehicle-related GHG emissions for electric vehicles

Data Format and Content

The data sets are presented in the report appendices.

Data Access and Sharing

All the data can be accessed in the report.

Reuse and Redistribution

All the data can be accessed in the report.

Appendices

Appendix A: Road network data

Table 30. Road length and density of 223 countries

[Data sources:
CIA: (https://www.cia.gov/the-world-factbook/field/roadways/country-comparison/); IRF (https://datawarehouse.worldroadstatistics.org/);
Wikipedia (https://en.wikipedia.org/wiki/List_of_countries_by_road_network_size); Statista (https://www.statista.com/);
Knoema (https://knoema.com/); Encyclopedia of nations (https://www.nationsencyclopedia.com/); World Bank (https://openknowledge.worldbank.org/); Road density (http://en.worldstat.info/)]

Category	Short Code	Continent	OECD Membership	Total road length (km)	Year	Source	Road density	Year	Source
Afghanistan	AFG	Asia	Non-OECD	34,903	2017	CIA	0.05	2017	Wikipedia
Albania	ALB	Europe	Non-OECD	3,676	2020	IRF	0.13	2020	IRF
Algeria	DZA	Africa	Non-OECD	104,000	2015	CIA	0.05	2010	Knoema
American Samoa	ASM	Oceania	OECD	241	2016	CIA	1.21	2016	Wikipedia
Andorra	AND	Europe	Non-OECD	320	2019	CIA	0.68	2019	Wikipedia
Angola	AGO	Africa	Non-OECD	76,000	2019	IRF	0.06	2020	World Bank
Anguilla	AIA	Americas	Non-OECD	175	2004	CIA	1.92	2004	Wikipedia
Antigua and Barbuda	ATG	Americas	Non-OECD	1,170	2011	CIA	2.65	2011	Wikipedia
Argentina	ARG	Americas	Non-OECD	281,290	2019	IRF/CIA	0.1	2020	Wikipedia
Armenia	ARM	Asia	Non-OECD	7,514	2020	IRF	0.26	2020	IRF
Aruba	ABW	Americas	Non-OECD	1,000	2010	CIA	4.4		worldstat.info
Australia	AUS	Oceania	OECD	877,651	2018	IRF	0.11	2018	IRF
Austria	AUT	Europe	OECD	127,498	2020	IRF	1.55	2020	IRF
Azerbaijan	AZE	Asia	Non-OECD	19,228	2020	IRF	0.23	2020	IRF
Bahamas	BHS	Americas	Non-OECD	2,700	2011	CIA	0.19	2011	Wikipedia
Bahrain	BHR	Asia	Non-OECD	4,940	2020	IRF	6.33	2020	IRF
Bangladesh	BGD	Asia	Non-OECD	442,401	2020	IRF	3.4	2020	IRF
Barbados	BRB	Americas	Non-OECD	1,700	2015	CIA	3.95	2015	Wikipedia
Belarus	BLR	Europe	Non-OECD	102,961	2020	IRF	0.51	2020	IRF
Belgium	BEL	Europe	OECD	118,414	2015	CIA	5.05	2011	Knoema
Belize	BLZ	Americas	Non-OECD	3,281	2017	CIA	0.14	2017	CIA
Benin	BEN	Africa	Non-OECD	16,000	2006	CIA	0.14	2020	Wikipedia
Bermuda	BMU	Americas	Non-OECD	551	2020	IRF	10.2	2020	IRF
Bhutan	BTN	Asia	Non-OECD	18,265	2020	IRF	0.48	2020	IRF

Category	Short Code	Continent	OECD Membership	Total road length (km)	Year	Source	Road density	Year	Source
Bolivia	BOL	Americas	Non-OECD	194,949	2020	IRF	0.18	2020	IRF
Bosnia and Herzegovina	BIH	Europe	Non-OECD	9,110	2020	IRF	0.18	2020	IRF
Botswana	BWA	Africa	Non-OECD	32,563	2020	IRF	0.06	2020	IRF
Brazil	BRA	Americas	Non-OECD	1,577,888	2020	IRF	0.19	2020	IRF
British Virgin Islands	VGB	Americas	Non-OECD	200	2007	CIA	1.32	2007	Wikipedia
Brunei Darussalam	BRN	Asia	Non-OECD	3,772	2020	IRF	0.72	2020	IRF
Bulgaria	BGR	Europe	Non-OECD	19,917	2020	IRF	0.18	2020	IRF
Burkina Faso	BFA	Africa	Non-OECD	15,310	2018	IRF	0.06	2019	IRF
Burundi	BDI	Africa	Non-OECD	11,513	2020	IRF	0.45	2020	IRF
Cabo Verde	CPV	Africa	Non-OECD	2,256	2017	IRF	0.55	2020	IRF
Cambodia	KHM	Asia	Non-OECD	63,432	2019	IRF	0.37	2020	IRF
Cameroon	CMR	Africa	Non-OECD	123,101	2017	IRF	0.27	2018	IRF
Canada	CAN	Americas	OECD	1,042,718	2020	IRF	0.12	2020	IRF
Cayman Islands	CYM	Americas	Non-OECD	521	2020	IRF	2.17	2020	IRF
Central African Republic	CAF	Africa	Non-OECD	24,000	2018	CIA	0.04	2018	Wikipedia
Chad	TCD	Africa	Non-OECD	40,000	2018	IRF	0.03	2018	IRF
Chile	CHL	Americas	OECD	85,984	2020	IRF	0.12	2020	IRF
China	CHN	Asia	Non-OECD	5,198,120	2020	IRF	0.55	2020	IRF
China, Hong Kong	HKG	Asia	Non-OECD	2,150	2020	IRF	2.05	2020	IRF
China, Macao	MAC	Asia	Non-OECD	453	2020	IRF	13.78	2020	IRF
Christmas Island	CXR	Oceania	Non-OECD	142	2011	CIA			
Cocos (Keeling) Islands	CCK	Oceania	Non-OECD	22	2007	CIA	1.57	2007	Wikipedia
Colombia	COL	Americas	OECD	205,900	2020	IRF	0.19	2020	IRF
Comoros	COM	Africa	Non-OECD	880	2002	CIA	0.39	2002	Wikipedia
Congo	COG	Africa	Non-OECD	23,324	2017	Wikipedia	0.07	2017	Wikipedia
Congo, Dem. Rep.	COD	Africa	Non-OECD	152,373	2015	IRF/CIA	0.06	2020	IRF
Cook Islands	COK	Oceania	Non-OECD	295	2018	CIA	1.25	2018	Wikipedia
Costa Rica	CRI	Americas	Non-OECD	44,537	2020	IRF	0.87	2020	IRF
Cote d'Ivoire	CIV	Africa	Non-OECD	81,996	2007	CIA	0.25	2007	Knoema
Croatia	HRV	Europe	Non-OECD	26,749	2020	IRF	0.47	2020	IRF
Cuba	CUB	Americas	Non-OECD	60,000	2015	CIA	0.55	2000	Knoema
Curacao	CUW	Americas	OECD	550		CIA	1.24		Wikipedia
Cyprus	CYP	Asia	Non-OECD	13,139	2020	IRF	1.42	2020	IRF
Czech Republic	CZE	Europe	OECD	130,711	2020	IRF	1.69	2020	IRF

Category	Short Code	Continent	OECD Membership	Total road length (km)	Year	Source	Road density	Year	Source
Denmark	DNK	Europe	OECD	74,890	2020	IRF	1.87	2020	IRF
Djibouti	DJI	Africa	Non-OECD	2,893	2013	CIA	0.12	2013	Wikipedia
Dominica	DMA	Americas	Non-OECD	1,512	2018	CIA	2.01	2018	Wikipedia
Dominican Republic	DOM	Americas	Non-OECD	14,211	2017	IRF	2.02	2018	IRF
Ecuador	ECU	Americas	Non-OECD	43,979	2020	IRF	0.18	2020	IRF
Egypt, Arab Rep.	EGY	Africa	Non-OECD	65,050	2018	CIA	0.15	2020	IRF
El Salvador	SLV	Americas	Non-OECD	9,012	2017	CIA	0.43	2017	Wikipedia
Equatorial Guinea	GNQ	Africa	Non-OECD	2,880	2017	CIA	0.1	2017	Wikipedia
Eritrea	ERI	Africa	Non-OECD	16,000	2018	CIA	0.16	2018	IRF
Estonia	EST	Europe	OECD	58,986	2020	IRF	1.36	2020	IRF
Eswatini	SWZ	Africa	Non-OECD	3,769	2019	CIA	0.09	2019	IRF
Ethiopia	ETH	Africa	Non-OECD	144,028	2020	IRF	0.13	2020	IRF
Falkland Islands (Islas Malvinas)	FLK	Americas	Non-OECD	440	2008	CIA	0.04	2008	Wikipedia
Faroe Islands	FRO	Europe	Non-OECD	960	2017	CIA	0.69	2017	Wikipedia
Fiji	FJI	Oceania	Non-OECD	3,440	2011	CIA	0.19	2011	Wikipedia
Finland	FIN	Europe	OECD	77,908	2020	IRF	0.26	2020	IRF
France	FRA	Europe	OECD	1,103,800	2020	IRF	2.02	2020	IRF
French Polynesia	PYF	Oceania	Non-OECD	2,590	1999	CIA	0.65	1999	Wikipedia
Gabon	GAB	Africa	Non-OECD	14,300	2001	CIA	0.04	2017	IRF
Gambia, The	GMB	Africa	Non-OECD	3,944	2020	IRF	0.39	2020	IRF
Georgia	GEO	Asia	Non-OECD	21,109	2020	IRF	0.3	2020	IRF
Germany	DEU	Europe	OECD	642,721	2020	IRF	1.84	2020	IRF
Ghana	GHA	Africa	Non-OECD	65,725	2021	CIA	0.46	2009	Wikipedia
Gibraltar	GIB	Europe	Non-OECD	29	2007	CIA	4.83	2007	Wikipedia
Greece	GRC	Europe	OECD	117,884	2020	IRF	0.91	2020	IRF
Grenada	GRD	Americas	Non-OECD	1,127	2017	CIA	3.28	2017	Wikipedia
Guam	GUM	Oceania	OECD	1,045	2008	CIA	1.9	2008	Wikipedia
Guatemala	GTM	Americas	Non-OECD	17,876	2020	IRF	0.17	2020	IRF
Guernsey	GGY	Europe	Non-OECD	260	2017	CIA			
Guinea	GIN	Africa	Non-OECD	43,310	2020	IRF	0.18	2020	IRF
Guinea-Bissau	GNB	Africa	Non-OECD	4,400	2018	CIA	0.12	2018	Wikipedia
Guyana	GUY	Americas	Non-OECD	3,995	2008	CIA	0.02	2019	Wikipedia
Haiti	HTI	Americas	Non-OECD	4,102	2011	CIA	0.15	2009	Wikipedia
Honduras	HND	Americas	Non-OECD	16,893	2020	IRF	0.15	2020	IRF

Category	Short Code	Continent	OECD Membership	Total road length (km)	Year	Source	Road density	Year	Source
Hungary	HUN	Europe	OECD	215,551	2020	IRF	2.36	2020	IRF
Iceland	ISL	Europe	OECD	12,901	2020	IRF	0.13	2020	IRF
India	IND	Asia	Non-OECD	6,371,847	2019	IRF	2.14	2019	IRF
Indonesia	IDN	Asia	Non-OECD	543,450	2020	IRF	0.29	2020	IRF
Iran, Islamic Rep.	IRN	Asia	Non-OECD	220,346	2020	IRF	0.14	2020	IRF
Iraq	IRQ	Asia	Non-OECD	45,579	2020	IRF	0.1	2020	IRF
Ireland	IRL	Europe	OECD	98,902	2020	IRF	1.44	2020	IRF
Isle of Man	IMN	Europe	Non-OECD	1,107	2022	CIA	5.71	2008	Wikipedia
Israel	ISR	Asia	OECD	20,245	2020	IRF	0.94	2020	IRF
Italy	ITA	Europe	OECD	235,492	2020	IRF	0.79	2020	IRF
Jamaica	JAM	Americas	Non-OECD	22,198	2020	IRF	2.05	2020	IRF
Japan	JPN	Asia	OECD	1,226,800	2020	IRF	3.37	2020	IRF
Jersey	JEY	Europe	Non-OECD	576	2010	CIA	4.97	2010	Wikipedia
Jordan	JOR	Asia	Non-OECD	8,657	2020	IRF	0.1	2020	IRF
Kazakhstan	KAZ	Asia	Non-OECD	95,768	2020	IRF	0.04	2020	IRF
Kenya	KEN	Africa	Non-OECD	160,140	2020	IRF	0.28	2020	IRF
Kiribati	KIR	Oceania	Non-OECD	670	2017	CIA	0.92	2017	Wikipedia
Korea, Dem. People's Rep.	PRK	Asia	Non-OECD	25,554	2017	IRF/CIA	0.21	2006	Wikipedia
Korea, Rep.	KOR	Asia	OECD	104,828	2020	IRF	1.07	2020	IRF
Kuwait	KWT	Asia	Non-OECD	5,749	2018	CIA	0.47	2020	IRF
Kyrgyz Republic	KGZ	Asia	Non-OECD	34,000	2019	IRF	0.18	2019	IRF
Lao PDR	LAO	Asia	Non-OECD	58,287	2020	IRF	0.25	2020	IRF
Latvia	LVA	Europe	OECD	58,269	2020	IRF	0.94	2020	IRF
Lebanon	LBN	Asia	Non-OECD	6,686	2019	IRF	0.65	2019	IRF
Lesotho	LSO	Africa	Non-OECD	5,940	2011	CIA	0.2	2011	Wikipedia
Liberia	LBR	Africa	Non-OECD	10,600	2018	CIA	0.1	2018	Wikipedia
Libya	LBY	Africa	Non-OECD	37,000	2010	CIA	0.02	2010	Wikipedia
Liechtenstein	LIE	Europe	Non-OECD	845	2018	IRF	5.28	2020	IRF
Lithuania	LTU	Europe	OECD	85,573	2018	IRF	1.35	2020	IRF
Luxembourg	LUX	Europe	OECD	2,914	2018	IRF	1.2	2020	IRF
Madagascar	MDG	Africa	Non-OECD	31,640	2018	CIA	0.05	2018	Wikipedia
Malawi	MWI	Africa	Non-OECD	24,929	2016	IRF	0.26	2016	IRF
Malaysia	MYS	Asia	Non-OECD	291,947	2020	IRF	0.89	2020	IRF
Maldives	MDV	Asia	Non-OECD	93	2018	CIA	0.3	2018	IRF

Category	Short Code	Continent	OECD Membership	Total road length (km)	Year	Source	Road density	Year	Source
Mali	MLI	Africa	Non-OECD	89,024	2018	IRF	0.07	2018	IRF
Malta	MLT	Europe	Non-OECD	2,853	2020	IRF	8.92	2020	IRF
Marshall Islands	MHL	Oceania	Non-OECD	2,028	2007	CIA	11.2	2007	Wikipedia
Mauritania	MRT	Africa	Non-OECD	12,253	2018	CIA	0.01	2018	Wikipedia
Mauritius	MUS	Africa	Non-OECD	2,839	2020	IRF	1.4	2020	IRF
Mexico	MEX	Americas	OECD	397,938	2020	IRF	0.2	2020	IRF
Moldova	MDA	Europe	Non-OECD	13,411	2020	IRF	0.41	2020	IRF
Monaco	MCO	Europe	OECD	57	2020	IRF	28.12	2020	IRF
Mongolia	MNG	Asia	Non-OECD	111,917	2020	IRF	0.07	2020	IRF
Montenegro	MNE	Europe	Non-OECD	7,762	2010	CIA	0.72	2020	IRF
Morocco	MAR	Africa	Non-OECD	59,134	2020	IRF	0.13	2020	IRF
Mozambique	MOZ	Africa	Non-OECD	30,616	2020	IRF	0.04	2020	IRF
Myanmar	MMR	Asia	Non-OECD	157,000	2013	CIA	0.23	2013	Wikipedia
Namibia	NAM	Africa	Non-OECD	48,540	2020	IRF	0.06	2020	IRF
Nauru	NRU	Oceania	Non-OECD	30	2002	CIA	14.3	2002	Wikipedia
Nepal	NPL	Asia	Non-OECD	27,990	2020	IRF	0.23	2019	IRF
Netherlands	NLD	Europe	OECD	186,936	2020	IRF	5.55	2020	IRF
New Caledonia	NCL	Oceania	Non-OECD	5,622	2020	IRF	0.31	2020	IRF
New Zealand	NZL	Oceania	OECD	96,848	2020	IRF	0.37	2020	IRF
Nicaragua	NIC	Americas	Non-OECD	24,782	2020	IRF	0.21	2020	IRF
Niger	NER	Africa	Non-OECD	21,560	2020	IRF	0.02	2020	IRF
Nigeria	NGA	Africa	Non-OECD	195,000	2017	CIA	0.21	2017	Wikipedia
Niue	NIU	Oceania	Non-OECD	234	2017	CIA	0.9	2017	Wikipedia
Norfolk Island	NFK	Oceania	ODA	80	2008	CIA	2.22	2008	Wikipedia
North Macedonia	MKD	Europe	Non-OECD	14,477	2020	IRF	0.57	2020	IRF
Northern Mariana Islands	MNP	Oceania	OECD	536	2008	CIA	11.7	2008	Wikipedia
Norway	NOR	Europe	OECD	94,977	2020	IRF	0.26	2020	IRF
Oman	OMN	Asia	Non-OECD	79,796	2020	IRF	0.25	2020	IRF
Pakistan	PAK	Asia	Non-OECD	501,424	2020	IRF	0.65	2020	IRF
Palau	PLW	Oceania	Non-OECD	125	2018	CIA			
Panama	PAN	Americas	Non-OECD	17,419	2020	IRF	0.23	2020	IRF
Papua New Guinea	PNG	Oceania	Non-OECD	30,000	2017	IRF	0.07	2017	IRF
Paraguay	PRY	Americas	Non-OECD	78,621	2020	IRF	0.2	2020	IRF
Peru	PER	Americas	Non-OECD	168,878	2020	IRF	0.13	2020	IRF

Category	Short Code	Continent	OECD Membership	Total road length (km)	Year	Source	Road density	Year	Source
Philippines	PHL	Asia	Non-OECD	33,287	2020	IRF	0.11	2020	IRF
Poland	POL	Europe	OECD	430,267	2020	IRF	1.41	2020	IRF
Portugal	PRT	Europe	OECD	14,325	2020	IRF	0.16	2020	IRF
Puerto Rico	PRI	Americas	OECD	32,051	2020	IRF	3.61	2020	IRF
Qatar	QAT	Asia	Non-OECD	7,039	2016	IRF	1.28	2020	IRF
Romania	ROU	Europe	Non-OECD	118,684	2020	IRF	0.52	2020	IRF
Russian Federation	RUS	Europe	Non-OECD	1,553,664	2020	IRF	0.09	2020	IRF
Rwanda	RWA	Africa	Non-OECD	6,674	2020	IRF	0.27	2020	IRF
Saint Barthelemy	BLM	Americas	Non-OECD	40	2002	CIA			
Saint Helena	SHN	Africa	Excluded	198	2002	CIA	1.62	2002	Wikipedia
Saint Kitts and Nevis	KNA	Americas	Non-OECD	383	2002	CIA	1.47	2002	Wikipedia
Saint Lucia	LCA	Americas	Non-OECD	1,210	2011	CIA	2.24	2011	Wikipedia
Saint Pierre and Miquelon	SPM	Americas	Non-OECD	117	2009	CIA	0.48	2009	Wikipedia
Samoa	WSM	Oceania	Non-OECD	1,150	2018	CIA	0.4	2018	Wikipedia
San Marino	SMR	Europe	OECD	350	2020	IRF	5.84	2020	IRF
Sao Tome and Principe	STP	Africa	Non-OECD	1,300	2018	CIA	0.33	2001	Encyclopedia of nations
Saudi Arabia	SAU	Asia	Non-OECD	122,174	2019	IRF	0.06	2019	IRF
Senegal	SEN	Africa	Non-OECD	47,313	2020	IRF	0.25	2020	IRF
Serbia	SRB	Europe	Non-OECD	44,908	2020	IRF	0.51	2020	IRF
Seychelles	SYC	Africa	Non-OECD	542	2020	IRF	1.18	2020	IRF
Sierra Leone	SLE	Africa	Non-OECD	11,701	2015	CIA	0.16	2015	Wikipedia
Singapore	SGP	Asia	Non-OECD	9,530	2020	IRF	13.44	2020	IRF
Sint Maarten	SXM	Americas	Non-OECD	53		CIA	1.56		Wikipedia
Slovak Republic	SVK	Europe	OECD	57,801	2020	IRF	1.2	2020	IRF
Slovenia	SVN	Europe	OECD	38,652	2020	IRF	1.92	2020	IRF
Solomon Islands	SLB	Oceania	Non-OECD	1,390	2011	CIA	0.05		Wikipedia
Somalia	SOM	Africa	Non-OECD	15,000	2018	CIA	0.02	2016	Wikipedia
South Africa	ZAF	Africa	Non-OECD	750,000	2020	IRF	0.62	2020	IRF
South Sudan	SSD	Africa	Non-OECD	90,200	2019	CIA			
Spain	ESP	Europe	OECD	538,449	2020	IRF	1.08	2020	IRF
Sri Lanka	LKA	Asia	Non-OECD	31,300	2020	IRF	0.51	2020	IRF
Sudan	SDN	Africa	Non-OECD	31,000	2019	CIA	0.02	2019	Wikipedia
Suriname	SUR	Americas	Non-OECD	4,931	2020	IRF	0.03	2020	IRF

Category	**Short Code**	**Continent**	**OECD Membership**	**Total road length (km)**	**Year**	**Source**	**Road density**	**Year**	**Source**
Svalbard	SJM	Europe	Non-OECD	40	2020	CIA			
Sweden	SWE	Europe	OECD	573,134	2019	IRF/CIA	1.27	2018	Wikipedia
Switzerland	CHE	Europe	OECD	83,274	2020	IRF	2.11	2020	IRF
Syrian Arab Republic	SYR	Asia	Non-OECD	69,873	2010	CIA	0.32	2017	IRF
Tajikistan	TJK	Asia	Non-OECD	14,140	2018	IRF	0.1	2018	IRF
Tanzania	TZA	Africa	Non-OECD	87,581	2020	Wikipedia	0.09	2017	Wikipedia
Thailand	THA	Asia	Non-OECD	702,577	2020	IRF	1.38	2020	IRF
Timor-Leste	TLS	Asia	Non-OECD	8,811	2018	IRF	0.59	2018	IRF
Togo	TGO	Africa	Non-OECD	9,951	2018	CIA	0.02	2015	IRF
Tokelau	TKL	Oceania	Non-OECD	10	2019	CIA			
Tonga	TON	Oceania	Non-OECD	680	2011	CIA	0.91	2011	Wikipedia
Tunisia	TUN	Africa	Non-OECD	19,782	2020	IRF	0.13	2020	IRF
Turkey	TUR	Asia	OECD	256,328	2020	IRF	0.33	2020	IRF
Turkmenistan	TKM	Asia	Non-OECD	13,773	2020	IRF	0.03	2020	IRF
Turks and Caicos Islands	TCA	Americas	Non-OECD	121	2003	CIA	0.13	2003	Wikipedia
Tuvalu	TUV	Oceania	Non-OECD	8	2011	CIA	0.31	2011	Wikipedia
U.S. Virgin Islands	VIR	Americas	OECD	1,260	2008	CIA	3.63	2008	Wikipedia
Uganda	UGA	Africa	Non-OECD	146,000	2020	IRF	0.6	2019	Wikipedia
Ukraine	UKR	Europe	Non-OECD	162,152	2020	IRF	0.28	2020	IRF
United Arab Emirates	ARE	Asia	Non-OECD	19,000	2020	Statista	1.18	2020	IRF
United Kingdom	GBR	Europe	OECD	398,359	2020	IRF	1.65	2020	IRF
United States	USA	Americas	OECD	6,645,582	2020	IRF	0.73	2020	IRF
Uruguay	URY	Americas	Non-OECD	8,732	2020	IRF	0.05	2020	IRF
Uzbekistan	UZB	Asia	Non-OECD	44,515	2020	IRF	0.1	2020	IRF
Vanuatu	VUT	Oceania	Non-OECD	1,070	2000	IRF	0.09	2000	Wikipedia
Venezuela	VEN	Americas	Non-OECD	96,167	2014	CIA	0.11	2000	Knoema
Vietnam	VNM	Asia	Non-OECD	278,176	2019	IRF	1.25	2018	IRF
Yemen, Rep.	YEM	Asia	Non-OECD	71,300	2005	CIA	0.03	2017	IRF
Zambia	ZMB	Africa	Non-OECD	67,305	2020	IRF	0.09	2020	IRF
Zimbabwe	ZWE	Africa	Non-OECD	97,267	2019	CIA	0.25	2019	CIA

Table 31. Predicted road lengths using Model 1

	2020	2030	2040	2050
Africa	3,180,446	3,831,356	4,831,631	6,222,007
ASEAN	2,141,458	2,771,168	3,683,615	4,745,392
ATE	250,047	340,149	440,323	525,087
China	5,200,270	5,200,362	5,200,406	5,200,406
EU 5	181,342	224,311	279,222	333,340
India	6,371,847	8,155,056	10,728,105	13,795,882
Latin America	2,912,996	3,267,682	3,779,982	4,393,018
Middle East	661,139	800,425	980,165	1,160,622
ODA	1,250,183	1,488,681	1,821,120	2,213,912
OECD Europe	5,835,323	6,599,968	7,543,130	8,450,669
OECD North America	8,121,371	10,389,189	12,557,194	14,375,454
OECD Pacific	2,306,127	2,710,771	3,180,779	3,652,707
OETE	358,486	453,178	583,309	709,509
Other OECD	106,229	132,869	165,146	198,433
Others	7,035	7,035	7,035	7,035
Russia	1,553,664	1,553,664	1,553,664	1,553,664

Table 32. Predicted road lengths using Model 2

	2020	2030	2040	2050
Africa	3,180,446	3,497,934	3,897,364	4,393,171
ASEAN	2,141,458	3,285,651	4,012,309	4,640,248
ATE	250,047	270,619	298,336	321,647
China	5,200,270	8,181,081	8,406,326	9,043,101
EU 5	181,342	181,342	181,342	181,342
India	6,371,847	11,620,018	16,139,058	20,556,705
Latin America	2,912,996	3,260,876	3,486,025	3,724,006
Middle East	661,139	775,151	875,899	978,626
ODA	1,250,183	1,250,183	1,293,908	1,421,054
OECD Europe	5,835,323	6,239,490	6,423,557	6,637,155
OECD North America	8,121,371	9,147,225	10,025,940	10,916,995
OECD Pacific	2,306,127	2,447,460	2,456,874	2,464,228
OETE	358,486	358,486	358,486	405,030
Other OECD	106,229	115,150	118,396	123,921
Others	7,035	7,035	7,035	7,035
Russia	1,553,664	1,553,664	1,567,702	1,586,661

Table 33. Predicted road lengths using Model 3

	2020	2030	2040	2050
Africa	3,180,446	3,758,793	4,409,870	5,073,182
ASEAN	2,141,458	2,362,175	2,554,522	2,690,881
ATE	250,047	281,532	310,297	334,429
China	5,200,270	5,625,477	5,859,463	5,912,730
EU 5	181,342	187,111	191,037	192,878
India	6,371,847	7,172,132	7,942,033	8,549,501
Latin America	2,912,996	3,151,578	3,375,498	3,547,925
Middle East	661,139	740,028	813,857	876,540
ODA	1,250,183	1,437,424	1,635,187	1,818,055
OECD Europe	5,835,323	6,009,452	6,145,811	6,238,115
OECD North America	8,121,371	8,524,061	8,876,454	9,118,982
OECD Pacific	2,306,127	2,379,101	2,441,867	2,495,153
OETE	358,486	364,037	370,450	371,620
Other OECD	106,229	113,697	121,024	126,406
Others	7,035	7,035	7,035	7,035
Russia	1,553,664	1,611,170	1,652,366	1,663,951

Appendix B: Socio economic data

Table 34. Socio-economic data for predicting road length

(Population density: United Nations; GDP; in international PPP US$: Shared Socioeconomic Pathways Database; Country land area: World Bank)

Category	Short Code	Pop density (2000)	Pop density (2010)	Pop density (2020)	Pop density (2030)	Pop density (2040)	Pop density (2050)	GDP / capita, PPP (2000)	GDP / capita, PPP (2010)	GDP / capita, PPP (2020)	GDP / capita, PPP (2030)	GDP / capita, PPP (2040)	GDP / capita, PPP (2050)	Land surface area (km^2) (2000 – 2050)
Afghanistan	AFG	30	43	60	78	96	114	-	1,185	1,496	2,298	4,127	7,526	652,230
Albania	ALB	116	106	105	102	97	90	4,804	7,661	9,384	12,721	17,592	23,062	27,400
Algeria	DZA	13	15	18	21	23	25	6,081	7,564	9,417	13,037	16,932	22,094	2,381,741
American Samoa	ASM	291	274	231	206	184	168							200
Andorra	AND	141	152	165	173	175	171							470
Angola	AGO	13	19	27	36	47	58	2,634	5,172	6,996	7,783	8,813	12,158	1,246,700
Anguilla	AIA	126	150	177	182	180	174							468
Antigua and Barbuda	ATG	171	195	211	222	227	225	16,331						440
Argentina	ARG	13	15	16	17	18	18	10,282	14,363	20,012	27,683	37,243	46,757	2,736,690
Armenia	ARM	111	104	99	97	94	90	2,295	4,901	7,135	11,035	16,925	23,176	28,470
Aruba	ABW	495	557	592	583	560	523		1,411	2,145	3,644	6,476	10,926	180
Australia	AUS	2	3	3	4	4	4	29,746	35,728	42,774	50,160	58,600	66,798	7,692,020
Austria	AUT	97	101	108	110	110	108	31,803	35,365	41,592	47,586	54,891	62,058	82,520
Azerbaijan	AZE	99	112	124	130	133	131	2,471	8,783	10,491	12,430	14,554	17,689	82,646
Bahamas	BHS	61	70	76	80	83	84	26,057	28,125	32,282	37,717	44,341	51,029	10,010
Bahrain	BHR	909	1550	1,887	2,011	2,169	2,311	23,726	21,342	24,030	31,585	39,903	46,428	785
Bangladesh	BGD	992	1140	1,286	1,417	1,510	1,566	970	1,488	2,583	4,838	8,909	14,840	130,170
Barbados	BRB	615	639	653	658	648	623	18,176	17,597	20,245	24,761	31,107	38,385	430
Belarus	BLR	51	48	47	45	43	41	5,780	12,368	19,136	28,326	39,313	48,494	202,980
Belgium	BEL	339	359	382	392	398	399	30,624	33,389	37,104	42,910	50,588	57,800	30,280
Belize	BLZ	11	14	17	20	22	24	5,605	6,606	7,281	10,271	15,286	21,849	22,810
Benin	BEN	62	84	112	145	183	224	1,306	1,424	1,722	2,830	5,273	9,803	112,760
Bermuda	BMU	1137	1175	1,186	1,163	1,113	1,038							54
Bhutan	BTN	15	18	20	21	22	23	2,703	4,780	11,384	21,844	35,424	50,469	38,140
Bolivia	BOL	8	9	11	13	14	15	3,567	4,349	6,169	10,031	16,624	25,832	1,083,300

Category	Short Code	Pop density (2000)	Pop density (2010)	Pop density (2020)	Pop density (2030)	Pop density (2040)	Pop density (2050)	GDP / capita, PPP (2000)	GDP / capita, PPP (2010)	GDP / capita, PPP (2020)	GDP / capita, PPP (2030)	GDP / capita, PPP (2040)	GDP / capita, PPP (2050)	Land surface area (km^2) (2000 – 2050)
Bosnia and Herzegovina	BIH	82	74	65	61	57	53	5,015	7,464	10,177	16,003	23,256	29,751	51,200
Botswana	BWA	3	4	4	5	6	6	9,531	12,462	17,436	23,931	31,663	39,606	566,730
Brazil	BRA	21	23	26	27	28	28	7,909	10,093	13,429	18,514	25,526	33,571	8,358,140
British Virgin Islands	VGB	131	179	201	214	224	226							150
Brunei Darussalam	BRN	58	69	77	82	86	86	48,478	45,496	53,352	64,115	75,549	85,414	5,270
Bulgaria	BGR	75	70	64	58	53	48	7,270	11,574	16,892	26,656	37,833	47,128	108,560
Burkina Faso	BFA	43	59	79	101	124	148	866	1,136	1,637	2,858	5,329	9,620	273,600
Burundi	BDI	243	352	471	609	768	933	354	524	744	1,460	3,307	6,909	25,680
Cabo Verde	CPV	114	129	145	159	171	181	2,281	3,474	5,098	8,147	13,057	19,448	4,030
Cambodia	KHM	67	79	91	100	107	112	1,035	1,968	3,540	6,437	11,352	18,534	176,520
Cameroon	CMR	32	43	57	73	91	110	1,853	2,058	2,809	4,738	8,519	14,495	472,710
Canada	CAN	3	4	4	5	5	5	32,555	35,332	40,574	44,126	49,244	54,720	8,965,590
Cayman Islands	CYM	165	224	279	302	314	322							240
Central African Republic	CAF	6	7	9	11	15	19	766	708	970	1,699	3,418	6,754	622,980
Chad	TCD	7	9	13	18	23	29	750	1,337	1,557	2,597	4,989	9,318	1,259,200
Chile	CHL	20	23	26	26	27	27	10,469	13,614	19,880	27,636	37,085	46,894	743,532
China	CHN	132	140	148	147	143	137	2,654	6,800	14,986	28,166	42,978	55,893	9,388,210
China, Hong Kong	HKG	6125	6490	6,825	6,812	6,650	6,347	29,266	41,802	55,189	66,032	75,363	81,805	1,050
China, Macao	MAC	13497	17416	21,134	23,855	25,896	27,552	23,791	57,590	65,466	70,233	74,198	76,643	33
Christmas Island	CXR													135
Cocos (Keeling) Islands	CCK													14
Colombia	COL	35	40	45	48	50	51	6,619	8,479	11,644	15,806	22,735	31,224	1,109,500
Comoros	COM	288	353	433	516	595	670	1,050	984	1,177	2,209	4,523	8,667	1,861

Category	Short Code	Pop density (2000)	Pop density (2010)	Pop density (2020)	Pop density (2030)	Pop density (2040)	Pop density (2050)	GDP / capita, PPP (2000)	GDP / capita, PPP (2010)	GDP / capita, PPP (2020)	GDP / capita, PPP (2030)	GDP / capita, PPP (2040)	GDP / capita, PPP (2050)	Land surface area (km^2) (2000 – 2050)
Congo	COG	9	13	17	21	26	30	3,120	3,808	6,061	9,886	15,914	24,080	341,500
Congo, Dem. Rep.	COD	21	29	41	56	75	96		316	526	1,338	3,391	7,429	2,267,050
Cook Islands	COK	66	72	71	72	73	74							236
Costa Rica	CRI	78	91	100	106	111	112	8,137	10,452	14,222	19,713	26,975	34,665	51,060
Cote d'Ivoire	CIV	53	66	84	108	134	162	1,811	1,694	2,632	6,072	12,708	22,446	318,000
Croatia	HRV	81	78	73	69	64	60	12,164	16,183	18,886	23,547	29,405	34,613	55,960
Cuba	CUB	104	106	106	103	99	94		5,747	7,929	11,086	15,968	22,468	103,800
Curacao	CUW	331	376	412	427	425								444
Cyprus	CYP	103	122	134	142	147	151	16,741	18,901	18,434	21,218	25,937	30,869	9,240
Czech Republic	CZE	133	136	136	136	136	137	16,936	23,696	30,779	41,385	53,425	63,039	77,199
Denmark	DNK	126	131	137	144	149	152	31,653	32,463	36,460	40,722	46,377	53,233	40,000
Djibouti	DJI	32	40	47	54	60	65	1,756	2,119	3,063	5,364	9,465	15,197	23,180
Dominica	DMA	91	92	96	100	101	99	8,444						750
Dominican Republic	DOM	177	202	228	248	263	273	5,785	8,387	11,678	16,227	22,475	29,576	47,531
Ecuador	ECU	51	60	71	78	85	90	5,381	7,201	9,269	12,957	19,039	27,129	248,360
Egypt, Arab Rep.	EGY	72	88	108	126	144	161	4,141	5,544	7,587	12,488	20,269	29,449	995,450
El Salvador	SLV	288	295	304	316	323	320	5,171	5,978	7,217	10,106	15,032	21,681	20,720
Equatorial Guinea	GNQ	24	39	57	71	86	99	8,682	30,769	31,542	38,771	47,660	57,770	28,050
Eritrea	ERI	20	26	29	35	42	49	642	490	532	801	1,516	3,049	121,041
Estonia	EST	32	31	31	30	28	27	10,992	16,594	24,709	33,512	43,180	51,310	42,750
Eswatini	SWZ	59	63	68	75	86	95	4,226	4,754	4,507	6,424	10,385	16,477	17,200
Ethiopia	ETH	67	89	117	149	182	215	527	932	1,469	2,619	5,234	10,085	1,128,571
Falkland Islands (Islas Malvinas)	FLK	0	0	0	0	0	0							12,173
Faroe Islands	FRO	33	35	38	39	41	43							1,366
Fiji	FJI	46	50	50	54	57	60	3,886	4,152	4,834	6,930	11,022	17,133	18,270
Finland	FIN	17	18	18	18	18	18	27,348	31,700	37,150	42,661	49,888	56,597	303,940

Category	Short Code	Pop density (2000)	Pop density (2010)	Pop density (2020)	Pop density (2030)	Pop density (2040)	Pop density (2050)	GDP / capita, PPP (2000)	GDP / capita, PPP (2010)	GDP / capita, PPP (2020)	GDP / capita, PPP (2030)	GDP / capita, PPP (2040)	GDP / capita, PPP (2050)	Land surface area (km^2) (2000 – 2050)
France	FRA	106	113	117	119	120	119	29,100	29,596	32,396	37,404	44,447	51,807	547,557
French Polynesia	PYF	68	77	82	88	93	94		16,579	18,148	20,408	24,748	30,216	3,471
Gabon	GAB	5	7	9	11	13	15	13,251	13,615	16,010	21,229	28,924	38,363	257,670
Gambia, The	GMB	142	191	254	322	394	462	1,157	1,834	2,483	4,160	7,479	12,847	10,120
Georgia	GEO	61	55	54	53	51	49	2,330	4,651	8,462	14,362	22,996	32,617	69,490
Germany	DEU	234	233	239	237	233	226	30,247	33,138	38,793	43,694	50,685	58,061	349,390
Ghana	GHA	86	112	141	170	200	230	1,067	1,478	2,646	4,730	8,634	14,513	227,533
Gibraltar	GIB	2774	3126	3,271	3,277	3,233	3,136							10
Greece	GRC	84	84	80	77	74	70	20,188	24,113	25,334	32,193	40,734	48,843	128,900
Grenada	GRD	316	335	364	383	395	401	9,102						340
Guam	GUM	296	305	313	334	351	362							540
Guatemala	GTM	110	136	162	187	210	230	3,960	4,297	4,990	7,794	12,902	20,427	107,160
Guernsey	GGY	924	950	981	1,018	1,040	1,039							78
Guinea	GIN	34	42	54	68	82	96	887	978	2,269	6,318	14,002	25,204	245,720
Guinea-Bissau	GNB	44	56	72	88	106	123	1,146	1,064	1,406	2,589	5,546	11,098	28,120
Guyana	GUY	4	4	4	4	4	4	2,492	3,106	4,836	7,547	11,907	18,539	196,850
Haiti	HTI	303	357	410	461	507	547	1,137	992	1,548	3,003	6,257	11,810	27,560
Honduras	HND	61	77	93	107	120	131	2,888	3,518	4,299	6,649	11,237	18,227	111,890
Hungary	HUN	113	110	108	107	102	97	13,674	16,982	19,826	25,464	32,341	39,094	91,260
Iceland	ISL	3	3	4	4	4	4	29,867	32,575	38,030	46,096	55,477	64,155	100,830
India	IND	356	417	470	510	542	562	1,705	2,983	5,079	9,108	15,581	23,798	2,973,190
Indonesia	IDN	112	128	142	153	161	166	2,623	3,877	6,759	12,636	22,045	33,521	1,877,519
Iran, Islamic Rep.	IRN	40	46	54	57	59	61	7,503	10,954	11,974	15,737	21,229	26,864	1,622,500
Iraq	IRQ	57	72	98	122	147	172	4,703	3,231	6,369	8,587	11,425	14,696	434,128
Ireland	IRL	55	66	72	77	81	84	32,393	36,014	40,016	45,547	51,228	55,889	68,890
Isle of Man	IMN	132	147	147	150	152	152							570
Israel	ISR	283	339	405	468	533	600	24,228	26,711	32,774	40,220	49,174	58,061	21,640
Italy	ITA	192	202	201	194	187	177	27,695	27,105	29,043	33,399	39,326	46,053	295,717
Jamaica	JAM	241	252	260	259	249	230	6,553	6,902	7,684	9,911	13,949	19,765	10,830
Japan	JPN	337	340	332	315	295	275	28,874	30,816	34,682	41,046	48,642	56,607	364,500

Category	Short Code	Pop density (2000)	Pop density (2010)	Pop density (2020)	Pop density (2030)	Pop density (2040)	Pop density (2050)	GDP / capita, PPP (2000)	GDP / capita, PPP (2010)	GDP / capita, PPP (2020)	GDP / capita, PPP (2030)	GDP / capita, PPP (2040)	GDP / capita, PPP (2050)	Land surface area (km^2) (2000 – 2050)
Jersey	JEY	743	829	934	1,026	1,105	1,168							116
Jordan	JOR	57	78	123	134	152	169	3,569	5,131	6,507	10,544	17,308	25,775	88,794
Kazakhstan	KAZ	6	6	7	8	9	9	5,379	11,118	18,230	29,697	39,910	45,578	2,699,700
Kenya	KEN	53	71	90	109	129	147	1,283	1,481	2,052	3,438	6,188	10,736	569,140
Kiribati	KIR	122	149	174	205	232	260	2,355						810
Korea, Dem. People's Rep.	PRK	194	205	215	221	220	214							120,410
Korea, Rep.	KOR	473	493	524	518	498	463	19,146	27,413	38,961	52,529	65,215	76,440	97,600
Kuwait	KWT	109	165	245	256	277	289	38,359	45,618	55,237	68,303	83,550	93,877	17,820
Kyrgyz Republic	KGZ	26	29	33	39	44	49	1,489	2,051	3,088	5,340	9,385	14,657	191,800
Lao PDR	LAO	24	27	32	36	40	42	1,346	2,313	4,353	7,959	13,860	21,815	230,800
Latvia	LVA	38	34	30	27	25	23	8,494	12,873	19,630	28,015	37,554	45,830	62,230
Lebanon	LBN	422	488	554	461	464	483	8,628	12,618	16,751	23,761	32,769	41,912	10,230
Lesotho	LSO	66	67	74	82	90	95	550	1,437	2,086	3,542	6,777	12,594	30,360
Liberia	LBR	30	42	53	65	79	92	477	482	833	1,883	4,216	8,571	96,320
Libya	LBY	3	4	4	4	5	5	12,623	15,699	21,644	29,410	37,834	44,585	1,759,540
Liechtenstein	LIE	206	225	242	256	263	264							160
Lithuania	LTU	57	50	45	41	38	35	9,526	15,361	22,600	29,520	37,611	44,030	62,620
Luxembourg	LUX	168	196	243	269	288	302	61,175	68,734	74,291	80,581	84,974	88,075	2,574
Madagascar	MDG	28	37	49	61	75	89	904	869	984	1,742	3,571	7,090	581,800
Malawi	MWI	119	156	205	264	328	393	667	796	1,070	1,934	3,901	7,688	94,280
Malaysia	MYS	70	87	101	112	120	125	10,209	13,214	18,292	26,218	36,413	46,549	328,550
Maldives	MDV	942	1205	1,715	1,709	1,806	1,900	4,323	7,383	9,352	13,098	19,293	26,576	300
Mali	MLI	9	13	17	24	31	39	759	967	1,136	2,067	4,109	7,839	1,220,190
Malta	MLT	1267	1329	1,636	1,725	1,707	1,659	20,166	22,643	27,188	34,923	44,870	53,329	320
Marshall Islands	MHL	301	297	241	249	269	285							180
Mauritania	MRT	3	3	4	6	7	9	1,550	2,203	3,129	4,838	7,822	12,349	1,030,700
Mauritius	MUS	599	632	639	643	633	604	9,084	12,112	17,475	25,935	36,422	47,837	1,997
Mexico	MEX	50	57	64	69	72	73	11,853	12,429	15,668	20,776	28,281	37,399	1,943,950
Moldova	MDA	129	112	94	97	94	91	1,469	2,785	4,940	9,602	17,365	26,017	32,885
Monaco	MCO	21789	22267	24,780	24,068	24,458	25,278							2

Category	Short Code	Pop density (2000)	Pop density (2010)	Pop density (2020)	Pop density (2030)	Pop density (2040)	Pop density (2050)	GDP / capita, PPP (2000)	GDP / capita, PPP (2010)	GDP / capita, PPP (2020)	GDP / capita, PPP (2030)	GDP / capita, PPP (2040)	GDP / capita, PPP (2050)	Land surface area (km²) (2000 – 2050)
Mongolia	MNG	2	2	2	2	3	3	2,208	3,620	9,126	18,351	31,140	43,182	1,557,507
Montenegro	MNE	46	46	46	45	44	42	7,112	10,165	12,261	16,226	21,352	26,154	13,450
Morocco	MAR	64	73	82	90	96	101	2,947	4,297	6,583	11,550	19,688	29,770	446,300
Mozambique	MOZ	23	29	40	52	66	80	506	823	1,411	2,682	5,418	10,663	786,380
Myanmar	MMR	70	76	82	87	91	92	598	1,442	2,484	4,351	7,308	11,216	652,670
Namibia	NAM	2	3	3	4	4	5	4,489	5,871	7,659	11,366	16,694	23,028	823,290
Nauru	NRU	519	512	616	668	705	735							20
Nepal	NPL	167	185	199	225	242	254	903	1,079	1,426	2,451	4,687	8,630	143,350
Netherlands	NLD	472	494	518	533	537	532	33,824	37,008	41,684	47,387	54,425	62,272	33,670
New Caledonia	NCL	12	14	16	17	18	19		16,932	22,434	29,541	37,956	45,897	18,280
New Zealand	NZL	15	16	19	21	22	22	22,308	25,386	28,995	33,329	40,323	49,040	263,310
Nicaragua	NIC	43	49	56	64	70	76	2,138	2,499	3,332	5,742	10,562	17,820	120,340
Niger	NER	9	13	19	28	39	53	597	650	906	1,536	3,016	5,976	1,266,700
Nigeria	NGA	135	177	229	288	352	414	1,469	2,135	3,215	5,359	9,212	15,338	910,770
Niue	NIU	8	7	7	7	8	8							260
Norfolk Island	NFK													36
North Macedonia	MKD	82	84	85	83	81	77	7,395	9,185	12,640	18,874	26,811	33,981	25,220
Northern Mariana Islands	MNP	176	118	109	112	113	110							460
Norway	NOR	15	16	18	19	20	21	43,643	46,745	53,421	58,260	63,791	68,645	364,285
Oman	OMN	8	9	15	16	18	20	18,995	24,563	30,757	41,702	55,209	64,382	309,500
Pakistan	PAK	200	252	295	355	418	477	1,845	2,411	2,934	4,517	7,650	12,427	770,880
Palau	PLW	43	40	39	39	38	36	12,554						460
Panama	PAN	40	49	58	66	72	77	8,132	12,638	21,453	31,716	43,423	55,463	74,180
Papua New Guinea	PNG	12	17	22	26	30	33	1,951	2,217	3,653	5,853	10,269	17,363	452,860
Paraguay	PRY	13	14	16	18	20	21	3,794	4,648	6,281	10,270	17,194	26,465	397,300
Peru	PER	21	23	26	29	31	33	5,543	8,558	13,837	21,803	32,370	44,229	1,280,000
Philippines	PHL	260	315	374	432	483	526	2,697	3,560	4,847	7,298	11,547	17,631	298,170

Category	Short Code	Pop density (2000)	Pop density (2010)	Pop density (2020)	Pop density (2030)	Pop density (2040)	Pop density (2050)	GDP / capita, PPP (2000)	GDP / capita, PPP (2010)	GDP / capita, PPP (2020)	GDP / capita, PPP (2030)	GDP / capita, PPP (2040)	GDP / capita, PPP (2050)	Land surface area (km^2) (2000 – 2050)
Poland	POL	126	126	126	126	121	114	11,800	17,255	23,458	30,880	38,772	44,578	306,130
Portugal	PRT	112	115	112	109	106	101	20,877	21,600	23,182	28,075	33,818	39,651	91,606
Puerto Rico	PRI	440	428	376	375	346	314		17,272	21,988	28,076	35,119	41,774	8,870
Qatar	QAT	56	148	238	246	267	290	64,829	69,790	101,201	110,736	114,634	115,901	11,490
Romania	ROU	95	88	85	83	80	76	6,922	10,897	14,517	21,530	30,649	40,022	230,080
Russian Federation	RUS	9	9	9	9	8	8	8,586	14,096	20,831	30,950	42,554	50,517	16,376,870
Rwanda	RWA	335	426	543	676	815	951	661	1,041	1,624	2,964	5,554	9,684	24,670
Saint Barthelemy	BLM	322	409	485	505	493	464							21
Saint Helena	SHN	15	14	14	13	11	10							308
Saint Kitts and Nevis	KNA	175	182	183	186	185	180	13,560						260
Saint Lucia	LCA	259	277	291	298	297	289	8,501	8,270	9,144	12,554	18,535	26,447	610
Saint Pierre and Miquelon	SPM	27	26	26	25	24	22							242
Samoa	WSM	65	69	76	88	100	113	3,059	3,945	4,770	6,972	10,604	16,074	2,780
San Marino	SMR	440	518	557	548	543	525							60
Sao Tome and Principe	STP	150	190	228	276	330	382	-	1,758	5,448	11,644	21,282	33,116	960
Saudi Arabia	SAU	10	14	17	19	21	23	20,321	20,535	26,028	32,879	39,321	44,828	2,149,690
Senegal	SEN	50	65	85	110	138	169	1,525	1,738	2,255	3,843	7,016	12,404	192,530
Serbia	SRB	103	100	96	89	82	75	4,827	7,100	8,792	11,959	15,904	19,973	84,090
Seychelles	SYC	175	202	231	244	251	255	18,810						460
Sierra Leone	SLE	64	90	115	141	166	190	424	742	1,286	2,259	4,456	8,386	72,180
Singapore	SGP	5935	7560	8,653	9,154	9,382	9,279	39,091	52,075	67,148	80,147	87,124	90,486	718
Sint Maarten	SXM	897	972	1,283	1,322	1,293	1,146							34
Slovak Republic	SVK	110	110	111	113	110	106	12,688	20,043	26,864	34,850	43,683	50,895	48,080
Slovenia	SVN	99	102	105	105	103	99	19,801	25,281	29,398	35,508	42,444	48,517	20,136
Solomon Islands	SLB	15	19	24	30	36	43	2,262	2,431	3,323	5,569	9,577	15,576	27,990

Category	Short Code	Pop density (2000)	Pop density (2010)	Pop density (2020)	Pop density (2030)	Pop density (2040)	Pop density (2050)	GDP / capita, PPP (2000)	GDP / capita, PPP (2010)	GDP / capita, PPP (2020)	GDP / capita, PPP (2030)	GDP / capita, PPP (2040)	GDP / capita, PPP (2050)	Land surface area (km^2) (2000 – 2050)
Somalia	SOM	14	19	26	36	46	58		34	50	120	337	872	627,340
South Africa	ZAF	38	42	48	53	57	60	7,511	9,470	12,992	18,589	25,763	33,277	1,213,090
South Sudan	SSD	11	17	19	22	27	31							631,930
Spain	ESP	81	93	94	94	92	88	25,113	26,961	28,543	31,818	36,479	41,199	499,557
Sri Lanka	LKA	299	330	346	354	355	348	3,063	4,555	8,144	13,837	22,028	31,626	61,860
Sudan	SDN	15	19	25	32	40	48	1,397	2,023	2,641	4,385	7,769	13,196	1,868,000
Suriname	SUR	3	4	4	4	4	5	4,964	7,105	10,409	16,344	24,605	34,091	156,000
Svalbard	SJM													62,045
Sweden	SWE	22	23	25	27	28	29	29,185	33,762	40,443	46,803	54,125	61,016	407,284
Switzerland	CHE	180	196	216	229	237	244	34,792	38,376	44,069	50,652	58,588	67,288	39,510
Syrian Arab Republic	SYR	89	122	113	162	191	209	3,756	4,749	6,820	11,276	18,446	27,961	183,630
Tajikistan	TJK	44	53	67	80	93	106	969	1,938	3,084	5,970	11,517	19,001	138,790
Tanzania	TZA	39	51	70	92	118	147	843	1,255	1,847	3,377	6,423	11,475	885,800
Thailand	THA	123	134	140	141	139	133	5,497	7,673	11,543	19,018	29,500	41,294	510,890
Timor-Leste	TLS	59	73	87	101	112	122		1,318	2,507	4,923	10,029	19,018	14,870
Togo	TGO	92	121	155	194	238	285	870	898	1,264	2,201	4,299	8,343	54,390
Tokelau	TKL	139	114	152	170	188	202							12
Tonga	TON	158	165	162	176	190	202	3,866	4,067	4,698	6,876	10,800	16,527	720
Tunisia	TUN	64	70	78	84	89	92	6,146	8,564	11,831	19,519	29,713	39,316	155,360
Turkey	TUR	83	95	109	115	121	125	9,828	12,542	17,543	24,134	32,237	40,735	769,630
Turkmenistan	TKM	10	11	13	15	16	18	2,322	7,422	15,099	25,912	37,563	45,656	469,930
Turks and Caicos Islands	TCA	20	31	47	51	54	56							950
Tuvalu	TUV	321	352	369	397	418	440							30
U.S. Virgin Islands	VIR	309	303	287	267	244	221							350
Uganda	UGA	120	162	222	292	365	439	774	1,149	1,626	2,911	5,538	10,162	200,520
Ukraine	UKR	84	79	76	66	62	57	3,718	6,079	9,270	15,277	24,046	33,075	579,400
United Arab Emirates	ARE	46	119	131	141	150	161	69,078	42,351	48,987	60,324	71,718	79,490	71,020
United Kingdom	GBR	242	259	276	285	291	295	29,597	32,470	37,398	44,143	51,976	59,770	241,930

Category	Short Code	Pop density (2000)	Pop density (2010)	Pop density (2020)	Pop density (2030)	Pop density (2040)	Pop density (2050)	GDP / capita, PPP (2000)	GDP / capita, PPP (2010)	GDP / capita, PPP (2020)	GDP / capita, PPP (2030)	GDP / capita, PPP (2040)	GDP / capita, PPP (2050)	Land surface area (km^2) (2000 – 2050)
United States	USA	31	34	37	38	40	41	39,532	42,164	50,950	60,437	68,873	75,434	9,147,420
Uruguay	URY	19	19	20	20	20	19	9,556	12,595	18,187	26,267	36,576	47,287	175,020
Uzbekistan	UZB	59	67	79	90	99	107	1,624	2,866	4,936	8,734	14,469	20,839	440,650
Vanuatu	VUT	16	20	26	32	40	47	3,794	3,988	4,792	7,495	12,875	21,497	12,190
Venezuela	VEN	27	31	31	35	38	39	9,550	10,918	13,383	17,351	22,189	28,137	882,050
Vietnam	VNM	252	279	308	328	338	341	1,574	2,845	4,925	8,677	14,298	21,293	313,429
Yemen, Rep.	YEM	35	47	61	76	91	105	2,116	2,373	2,267	3,413	5,600	8,585	527,970
Zambia	ZMB	13	19	25	33	42	50	1,029	1,384	2,112	3,862	7,362	13,153	743,390
Zimbabwe	ZWE	31	33	41	50	59	68		415	565	1,038	2,352	5,071	386,850

Appendix C: Vehicle fleet data

Table 35. PLDV and Truck VKT data collected from IEA MoMo

	PLDV (2000)	PLDV (2010)	PLDV (2020)	PLDV (2030)	PLDV (2040)	PLDV (2050)	Truck (2000)	Truck (2010)	Truck (2020)	Truck (2030)	Truck (2040)	Truck (2050)
Colombia	50.6	35.7	46.7	62.1	73.6	89.6	6.37	7.70	23.01	28.47	33.21	36.11
Canada	198.1	254.6	287.0	288.7	247.6	200.7	103.03	128.14	164.81	167.22	183.39	193.11
Mexico	259.6	385.8	331.2	368.1	422.7	455.7	50.64	83.66	95.02	109.29	125.98	139.94
USA	3232.0	3706.2	4361.5	4334.1	3677.0	2990.6	580.40	532.25	476.45	561.19	627.65	698.20
Chile	22.1	26.0	60.9	69.1	78.0	84.5	11.91	18.44	74.18	29.08	39.93	44.17
France	0.0	402.2	452.6	426.4	353.2	289.3	105.67	122.88	116.37	130.55	93.54	89.53
Germany	504.0	472.7	672.1	636.1	516.2	405.5	69.78	66.08	58.29	73.22	75.04	79.58
Italy	355.1	345.0	309.9	272.4	221.9	171.6	80.36	108.93	127.24	85.60	88.64	87.05
UK	387.4	391.8	397.5	403.7	329.8	276.8	55.56	60.03	67.37	66.77	72.87	77.25
EU20-EUG4	731.8	676.3	934.7	958.0	788.6	596.8	190.63	225.26	209.66	222.97	225.06	234.38
EU Nordic	115.6	124.5	131.7	144.0	138.6	123.0	31.57	31.67	23.62	23.32	27.02	28.51
Non-EU Nordic	30.5	33.7	39.7	49.4	48.6	43.3	4.26	8.96	11.56	10.46	11.44	11.67
Non-EU OE2	87.2	99.3	150.8	168.9	157.6	142.8	13.29	48.99	113.34	107.34	128.63	137.22
OECD Pacific	646.9	825.0	1209.6	1117.6	902.1	797.1	404.80	300.66	267.49	285.52	278.93	279.58
Australia and NZ	104.2	165.2	247.0	261.3	235.2	208.2	52.87	71.49	70.59	86.39	83.72	86.63
Japan	404.2	520.4	702.3	609.1	459.9	413.0	331.19	194.81	125.89	130.62	117.70	111.39
Korea	138.4	139.3	260.4	247.1	207.0	175.9	20.74	34.36	71.01	68.50	77.51	81.56
Israel	26.7	33.6	60.0	63.2	63.6	66.1	12.34	12.65	8.29	12.43	13.93	16.50
EU 5	44.4	75.1	75.0	83.3	65.4	51.2	4.48	13.35	30.90	24.66	28.36	27.87
OETE	97.6	145.8	109.1	153.7	158.5	157.2	14.72	22.07	45.39	32.58	44.44	53.60
Russia	234.0	294.7	286.4	283.7	278.1	284.4	34.39	40.32	51.90	45.48	54.07	57.00
ATE	47.2	95.0	125.3	184.9	216.4	289.1	12.95	17.56	24.77	30.82	38.97	45.83
China	80.6	511.8	1484.5	2674.4	3084.0	3054.0	87.20	313.20	361.31	631.34	651.75	709.43
ODA	98.0	121.7	259.1	503.1	838.1	1255.9	55.29	67.89	132.10	94.49	138.64	157.64
ASEAN9	353.7	433.4	663.4	1343.3	1684.4	1753.0	54.66	68.70	67.95	130.43	164.41	195.38
India	48.3	114.2	384.2	1123.7	2059.7	2843.1	54.26	95.49	122.23	251.19	362.24	470.80
Middle East	362.8	657.1	766.2	771.0	937.6	1103.6	109.56	177.80	223.80	280.39	330.39	381.38
Indonesia	59.8	108.5	99.8	206.9	353.8	471.6	54.47	59.57	120.50	166.97	219.58	258.49
Brazil	175.6	229.7	331.4	367.2	399.6	466.5	71.84	115.80	136.60	146.58	169.08	186.29

	PLDV (2000)	PLDV (2010)	PLDV (2020)	PLDV (2030)	PLDV (2040)	PLDV (2050)	Truck (2000)	Truck (2010)	Truck (2020)	Truck (2030)	Truck (2040)	Truck (2050)
Other Latin America	303.9	210.1	318.8	249.3	324.5	460.3	73.96	112.49	124.84	181.04	191.35	214.97
North Africa	90.0	156.3	244.6	369.5	456.8	571.1	37.50	66.24	76.05	117.31	114.02	137.60
South Africa	32.9	52.5	58.6	64.9	89.5	134.4	46.29	61.60	62.48	86.98	86.13	96.49
Other Africa	2.2	62.5	164.5	250.3	539.5	1155.7	14.09	21.55	73.93	61.50	128.19	177.71

Table 36. PLDV and Truck VKT by country upon allocating VKT data from IEA MoMo by the 2020 GDP, PPP (current international $) (World Bank)

		PLDV (2000)	PLDV (2010)	PLDV (2020)	PLDV (2030)	PLDV (2040)	PLDV (2050)	Truck (2000)	Truck (2010)	Truck (2020)	Truck (2030)	Truck (2040)	Truck (2050)
Afghanistan	AFG	1.26	1.56	3.33	6.47	10.78	16.15	0.71	0.87	1.70	1.22	1.78	2.03
Albania	ALB	4.67	6.99	5.23	7.36	7.60	7.53	0.71	1.06	2.18	1.56	2.13	2.57
Algeria	DZA	18.14	31.50	49.28	74.46	92.04	115.07	7.56	13.35	15.32	23.64	22.97	27.73
Angola	AGO	0.13	3.57	9.39	14.28	30.79	65.96	0.80	1.23	4.22	3.51	7.32	10.14
Argentina	ARG	77.20	53.37	80.97	63.34	82.42	116.91	18.79	28.57	31.71	45.99	48.60	54.61
Armenia	ARM	1.72	3.45	4.56	6.72	7.87	10.51	0.47	0.64	0.90	1.12	1.42	1.67
Aruba	ABW	0.31	0.21	0.32	0.25	0.33	0.47	0.07	0.11	0.13	0.18	0.19	0.22
Australia	AUS	88.79	140.80	210.47	222.68	200.43	177.41	45.05	60.92	60.15	73.61	71.34	73.82
Austria	AUT	14.50	13.40	18.53	18.99	15.63	11.83	3.78	4.46	4.16	4.42	4.46	4.65
Azerbaijan	AZE	5.89	11.86	15.64	23.07	27.01	36.08	1.62	2.19	3.09	3.85	4.86	5.72
Bahamas	BHS	1.04	0.72	1.09	0.86	1.11	1.58	0.25	0.39	0.43	0.62	0.66	0.74
Bahrain	BHR	5.16	9.34	10.89	10.96	13.32	15.68	1.56	2.53	3.18	3.98	4.69	5.42
Bangladesh	BGD	22.22	27.58	58.73	114.03	189.98	284.67	12.53	15.39	29.94	21.42	31.43	35.73
Barbados	BRB	0.32	0.22	0.33	0.26	0.34	0.48	0.08	0.12	0.13	0.19	0.20	0.22
Belarus	BLR	19.14	28.61	21.40	30.15	31.11	30.84	2.89	4.33	8.91	6.39	8.72	10.52
Belgium	BEL	58.77	54.32	75.07	76.94	63.33	47.93	15.31	18.09	16.84	17.91	18.07	18.82
Belize	BLZ	0.29	0.20	0.31	0.24	0.31	0.44	0.07	0.11	0.12	0.17	0.18	0.21
Benin	BEN	0.03	0.78	2.05	3.12	6.72	14.40	0.18	0.27	0.92	0.77	1.60	2.21
Bhutan	BTN	0.18	0.22	0.46	0.90	1.50	2.25	0.10	0.12	0.24	0.17	0.25	0.28
Bolivia	BOL	7.46	5.16	7.82	6.12	7.96	11.29	1.81	2.76	3.06	4.44	4.70	5.27
Bosnia and Herzegovina	BIH	5.87	8.77	6.56	9.24	9.54	9.45	0.89	1.33	2.73	1.96	2.67	3.22
Botswana	BWA	0.02	0.69	1.82	2.77	5.98	12.81	0.16	0.24	0.82	0.68	1.42	1.97

		PLDV (2000)	PLDV (2010)	PLDV (2020)	PLDV (2030)	PLDV (2040)	PLDV (2050)	Truck (2000)	Truck (2010)	Truck (2020)	Truck (2030)	Truck (2040)	Truck (2050)
Brazil	BRA	175.64	229.73	331.44	367.18	399.59	466.48	71.84	115.80	136.60	146.58	169.08	186.29
Brunei Darussalam	BRN	1.07	1.31	2.00	4.05	5.08	5.28	0.16	0.21	0.20	0.39	0.50	0.59
Bulgaria	BGR	7.78	13.16	13.15	14.59	11.45	8.97	0.78	2.34	5.41	4.32	4.97	4.88
Burkina Faso	BFA	0.03	0.83	2.18	3.32	7.16	15.34	0.19	0.29	0.98	0.82	1.70	2.36
Burundi	BDI	0.01	0.16	0.41	0.62	1.34	2.86	0.03	0.05	0.18	0.15	0.32	0.44
Cabo Verde	CPV	0.00	0.08	0.20	0.31	0.67	1.43	0.02	0.03	0.09	0.08	0.16	0.22
Cambodia	KHM	3.07	3.77	5.77	11.68	14.64	15.24	0.48	0.60	0.59	1.13	1.43	1.70
Cameroon	CMR	0.06	1.77	4.65	7.08	15.27	32.70	0.40	0.61	2.09	1.74	3.63	5.03
Canada	CAN	198.14	254.64	286.96	288.66	247.61	200.73	103.03	128.14	164.81	167.22	183.39	193.11
Central African Republic	CAF	0.00	0.08	0.20	0.31	0.67	1.43	0.02	0.03	0.09	0.08	0.16	0.22
Chad	TCD	0.02	0.43	1.12	1.70	3.67	7.86	0.10	0.15	0.50	0.42	0.87	1.21
Chile	CHL	22.14	26.01	60.94	69.05	77.97	84.53	11.91	18.44	74.18	29.08	39.93	44.17
China	CHN	79.28	503.35	1,460.11	2,630.42	3,033.25	3,003.76	85.76	308.04	355.37	620.96	641.03	697.76
China, Hong Kong	HKG	1.33	8.42	24.42	44.00	50.73	50.24	1.43	5.15	5.94	10.39	10.72	11.67
China, Macao	MAC	0.68	0.84	1.79	3.47	5.77	8.65	0.38	0.47	0.91	0.65	0.96	1.09
Colombia	COL	50.61	35.74	46.67	62.13	73.58	89.58	6.37	7.70	23.01	28.47	33.21	36.11
Comoros	COM	0.00	0.05	0.12	0.18	0.40	0.85	0.01	0.02	0.05	0.05	0.09	0.13
Congo	COG	0.01	0.33	0.86	1.30	2.81	6.02	0.07	0.11	0.38	0.32	0.67	0.92
Congo, Dem. Rep.	COD	0.07	1.90	5.01	7.62	16.43	35.19	0.43	0.66	2.25	1.87	3.90	5.41
Costa Rica	CRI	8.47	5.86	8.89	6.95	9.05	12.83	2.06	3.14	3.48	5.05	5.33	5.99
Cote d'Ivoire	CIV	0.07	1.93	5.09	7.74	16.69	35.75	0.44	0.67	2.29	1.90	3.97	5.50
Croatia	HRV	5.88	9.95	9.94	11.04	8.66	6.78	0.59	1.77	4.09	3.27	3.76	3.69
Cuba	CUB	10.19	7.04	10.69	8.36	10.88	15.43	2.48	3.77	4.19	6.07	6.42	7.21
Cyprus	CYP	1.78	3.01	3.01	3.34	2.62	2.05	0.18	0.53	1.24	0.99	1.14	1.12
Czech Republic	CZE	41.55	38.40	53.08	54.40	44.78	33.89	10.82	12.79	11.91	12.66	12.78	13.31
Denmark	DNK	33.87	36.48	38.58	42.18	40.61	36.05	9.25	9.28	6.92	6.83	7.92	8.35
Djibouti	DJI	0.00	0.10	0.25	0.38	0.82	1.76	0.02	0.03	0.11	0.09	0.19	0.27
Dominican Republic	DOM	16.15	11.17	16.94	13.25	17.25	24.46	3.93	5.98	6.63	9.62	10.17	11.43
Ecuador	ECU	14.54	10.05	15.25	11.93	15.52	22.02	3.54	5.38	5.97	8.66	9.15	10.29

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Egypt, Arab Rep.	EGY	51.22	88.95	139.17	210.27	259.91	324.93	21.34	37.69	43.27	66.75	64.87	78.29
El Salvador	SLV	4.43	3.06	4.65	3.63	4.73	6.71	1.08	1.64	1.82	2.64	2.79	3.13
Equatorial Guinea	GNQ	0.01	0.42	1.10	1.68	3.61	7.74	0.09	0.14	0.50	0.41	0.86	1.19
Eritrea	ERI	0.01	0.16	0.43	0.66	1.42	3.04	0.04	0.06	0.19	0.16	0.34	0.47
Estonia	EST	4.82	4.45	6.16	6.31	5.19	3.93	1.26	1.48	1.38	1.47	1.48	1.54
Eswatini	SWZ	0.01	0.19	0.49	0.75	1.61	3.44	0.04	0.06	0.22	0.18	0.38	0.53
Ethiopia	ETH	0.18	4.99	13.12	19.96	43.04	92.20	1.12	1.72	5.90	4.91	10.23	14.18
Fiji	FJI	0.23	0.29	0.61	1.18	1.97	2.95	0.13	0.16	0.31	0.22	0.33	0.37
Finland	FIN	26.48	28.52	30.16	32.98	31.75	28.18	7.23	7.25	5.41	5.34	6.19	6.53
France	FRA	-	402.24	452.62	426.36	353.18	289.32	105.67	122.88	116.37	130.55	93.54	89.53
French Polynesia	PYF	0.11	0.14	0.30	0.59	0.98	1.47	0.06	0.08	0.15	0.11	0.16	0.18
Gabon	GAB	0.02	0.57	1.49	2.26	4.88	10.46	0.13	0.20	0.67	0.56	1.16	1.61
Gambia, The	GMB	0.00	0.10	0.26	0.39	0.84	1.81	0.02	0.03	0.12	0.10	0.20	0.28
Georgia	GEO	2.44	4.90	6.46	9.53	11.16	14.91	0.67	0.91	1.28	1.59	2.01	2.36
Germany	DEU	504.04	472.70	672.15	636.08	516.19	405.51	69.78	66.08	58.29	73.22	75.04	79.58
Ghana	GHA	0.11	3.13	8.23	12.52	26.99	57.82	0.70	1.08	3.70	3.08	6.41	8.89
Greece	GRC	31.55	29.16	40.30	41.31	34.00	25.73	8.22	9.71	9.04	9.61	9.70	10.11
Guatemala	GTM	11.83	8.18	12.41	9.71	12.63	17.91	2.88	4.38	4.86	7.05	7.45	8.37
Guinea	GIN	0.02	0.64	1.67	2.54	5.48	11.74	0.14	0.22	0.75	0.62	1.30	1.81
Guinea-Bissau	GNB	0.00	0.07	0.17	0.27	0.57	1.23	0.01	0.02	0.08	0.07	0.14	0.19
Guyana	GUY	2.07	1.43	2.17	1.70	2.21	3.14	0.50	0.77	0.85	1.23	1.30	1.46
Haiti	HTI	2.41	1.67	2.53	1.98	2.58	3.65	0.59	0.89	0.99	1.44	1.52	1.71
Honduras	HND	4.43	3.06	4.65	3.63	4.73	6.71	1.08	1.64	1.82	2.64	2.79	3.13
Hungary	HUN	32.34	29.89	41.31	42.34	34.85	26.38	8.43	9.96	9.27	9.86	9.95	10.36
Iceland	ISL	1.65	1.82	2.14	2.67	2.62	2.34	0.23	0.48	0.62	0.56	0.62	0.63
India	IND	48.31	114.21	384.25	1,123.67	2,059.67	2,843.07	54.26	95.49	122.23	251.19	362.24	470.80
Indonesia	IDN	138.35	169.54	259.49	525.46	658.88	685.72	21.38	26.87	26.58	51.02	64.31	76.43
Iran, Islamic Rep.	IRN	91.54	165.78	193.32	194.53	236.57	278.45	27.64	44.86	56.47	70.74	83.36	96.22
Iraq	IRQ	27.64	50.06	58.37	58.74	71.44	84.08	8.35	13.55	17.05	21.36	25.17	29.06
Ireland	IRL	54.88	50.72	70.10	71.85	59.14	44.76	14.30	16.89	15.72	16.72	16.88	17.58

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Israel	ISR	26.65	33.65	59.96	63.24	63.56	66.12	12.34	12.65	8.29	12.43	13.93	16.50
Italy	ITA	355.08	345.01	309.94	272.43	221.95	171.57	80.36	108.93	127.24	85.60	88.64	87.05
Jamaica	JAM	2.11	1.46	2.21	1.73	2.25	3.19	0.51	0.78	0.86	1.25	1.33	1.49
Japan	JPN	404.22	520.43	702.26	609.14	459.93	412.97	331.19	194.81	125.89	130.62	117.70	111.39
Jordan	JOR	7.10	12.86	15.00	15.09	18.35	21.60	2.14	3.48	4.38	5.49	6.47	7.47
Kazakhstan	KAZ	19.72	39.66	52.31	77.17	90.33	120.68	5.41	7.33	10.34	12.87	16.27	19.13
Kenya	KEN	0.16	4.48	11.78	17.92	38.64	82.77	1.01	1.54	5.29	4.40	9.18	12.73
Korea, Rep.	KOR	138.43	139.32	260.36	247.08	206.98	175.92	20.74	34.36	71.01	68.50	77.51	81.56
Kuwait	KWT	14.17	25.67	29.93	30.12	36.63	43.12	4.28	6.95	8.74	10.95	12.91	14.90
Kyrgyz Republic	KGZ	1.36	2.74	3.61	5.33	6.23	8.33	0.37	0.51	0.71	0.89	1.12	1.32
Lao PDR	LAO	2.42	2.97	4.54	9.20	11.53	12.00	0.37	0.47	0.47	0.89	1.13	1.34
Latvia	LVA	5.84	5.40	7.46	7.65	6.29	4.76	1.52	1.80	1.67	1.78	1.80	1.87
Lebanon	LBN	4.90	8.88	10.36	10.42	12.68	14.92	1.48	2.40	3.03	3.79	4.47	5.16
Lesotho	LSO	0.00	0.09	0.24	0.36	0.77	1.65	0.02	0.03	0.11	0.09	0.18	0.25
Liberia	LBR	0.00	0.13	0.35	0.53	1.13	2.43	0.03	0.05	0.16	0.13	0.27	0.37
Libya	LBY	4.87	8.46	13.23	19.99	24.71	30.89	2.03	3.58	4.11	6.35	6.17	7.44
Lithuania	LTU	10.63	9.82	13.57	13.91	11.45	8.67	2.77	3.27	3.04	3.24	3.27	3.40
Luxembourg	LUX	7.12	6.58	9.10	9.33	7.68	5.81	1.86	2.19	2.04	2.17	2.19	2.28
Madagascar	MDG	0.03	0.76	1.99	3.02	6.52	13.96	0.17	0.26	0.89	0.74	1.55	2.15
Malawi	MWI	0.02	0.51	1.34	2.03	4.38	9.39	0.11	0.18	0.60	0.50	1.04	1.44
Malaysia	MYS	38.89	47.65	72.94	147.69	185.20	192.74	6.01	7.55	7.47	14.34	18.08	21.48
Maldives	MDV	0.23	0.28	0.60	1.17	1.95	2.92	0.13	0.16	0.31	0.22	0.32	0.37
Mali	MLI	0.03	0.82	2.15	3.27	7.06	15.12	0.18	0.28	0.97	0.80	1.68	2.32
Malta	MLT	1.13	1.92	1.91	2.12	1.67	1.31	0.11	0.34	0.79	0.63	0.72	0.71
Mauritania	MRT	0.02	0.44	1.15	1.75	3.77	8.09	0.10	0.15	0.52	0.43	0.90	1.24
Mauritius	MUS	0.02	0.49	1.28	1.96	4.21	9.03	0.11	0.17	0.58	0.48	1.00	1.39
Mexico	MEX	259.59	385.82	331.21	368.10	422.71	455.71	50.64	83.66	95.02	109.29	125.98	139.94
Moldova	MDA	3.63	5.43	4.06	5.72	5.91	5.86	0.55	0.82	1.69	1.21	1.66	2.00
Mongolia	MNG	0.85	1.05	2.24	4.36	7.26	10.87	0.48	0.59	1.14	0.82	1.20	1.37
Montenegro	MNE	1.48	2.21	1.65	2.33	2.40	2.38	0.22	0.33	0.69	0.49	0.67	0.81
Morocco	MAR	11.07	19.23	30.08	45.45	56.18	70.23	4.61	8.15	9.35	14.43	14.02	16.92
Mozambique	MOZ	0.02	0.70	1.83	2.79	6.00	12.86	0.16	0.24	0.82	0.68	1.43	1.98
Myanmar	MMR	9.04	11.08	16.96	34.34	43.06	44.82	1.40	1.76	1.74	3.33	4.20	5.00

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Namibia	NAM	0.01	0.41	1.09	1.66	3.57	7.65	0.09	0.14	0.49	0.41	0.85	1.18
Nepal	NPL	2.53	3.14	6.70	13.00	21.66	32.46	1.43	1.75	3.41	2.44	3.58	4.07
Netherlands	NLD	98.26	90.82	125.51	128.64	105.89	80.14	25.60	30.25	28.15	29.94	30.22	31.47
New Caledonia	NCL	0.21	0.26	0.56	1.09	1.82	2.73	0.12	0.15	0.29	0.21	0.30	0.34
New Zealand	NZL	15.41	24.44	36.53	38.65	34.79	30.79	7.82	10.57	10.44	12.78	12.38	12.81
Nicaragua	NIC	3.01	2.08	3.16	2.47	3.21	4.56	0.73	1.11	1.24	1.79	1.89	2.13
Niger	NER	0.02	0.57	1.49	2.27	4.89	10.48	0.13	0.20	0.67	0.56	1.16	1.61
Nigeria	NGA	0.66	18.42	48.44	73.71	158.90	340.39	4.15	6.35	21.78	18.11	37.76	52.34
North Macedonia	MKD	3.83	5.72	4.28	6.03	6.22	6.17	0.58	0.87	1.78	1.28	1.74	2.10
Norway	NOR	28.85	31.85	37.52	46.76	45.94	40.99	4.03	8.48	10.94	9.89	10.82	11.04
Oman	OMN	10.92	19.78	23.06	23.21	28.22	33.22	3.30	5.35	6.74	8.44	9.94	11.48
Pakistan	PAK	26.64	33.07	70.43	136.74	227.81	341.36	15.03	18.45	35.91	25.68	37.68	42.85
Panama	PAN	10.91	7.54	11.44	8.95	11.65	16.52	2.65	4.04	4.48	6.50	6.87	7.72
Papua New Guinea	PNG	0.79	0.98	2.09	4.06	6.77	10.14	0.45	0.55	1.07	0.76	1.12	1.27
Paraguay	PRY	6.82	4.72	7.16	5.60	7.29	10.34	1.66	2.53	2.80	4.07	4.30	4.83
Peru	PER	32.28	22.31	33.85	26.48	34.46	48.88	7.85	11.95	13.26	19.23	20.32	22.83
Philippines	PHL	40.13	49.18	75.27	152.42	191.12	198.91	6.20	7.80	7.71	14.80	18.65	22.17
Poland	POL	130.96	121.03	167.27	171.44	141.12	106.80	34.11	40.31	37.52	39.90	40.28	41.94
Portugal	PRT	35.15	32.49	44.90	46.02	37.88	28.67	9.16	10.82	10.07	10.71	10.81	11.26
Qatar	QAT	17.67	32.00	37.32	37.56	45.67	53.76	5.34	8.66	10.90	13.66	16.09	18.58
Romania	ROU	27.84	47.09	47.04	52.23	40.99	32.09	2.81	8.37	19.37	15.46	17.78	17.47
Russian Federation	RUS	233.97	294.74	286.40	283.67	278.09	284.36	34.39	40.32	51.90	45.48	54.07	57.00
Rwanda	RWA	0.02	0.55	1.46	2.21	4.77	10.22	0.12	0.19	0.65	0.54	1.13	1.57
Saint Lucia	LCA	0.20	0.14	0.21	0.17	0.21	0.30	0.05	0.07	0.08	0.12	0.13	0.14
Samoa	WSM	0.02	0.03	0.06	0.12	0.20	0.30	0.01	0.02	0.03	0.02	0.03	0.04
Sao Tome and Principe	STP	0.00	0.02	0.04	0.06	0.13	0.29	0.00	0.01	0.02	0.02	0.03	0.04
Saudi Arabia	SAU	122.99	222.74	259.74	261.37	317.85	374.13	37.14	60.27	75.87	95.05	112.00	129.28
Senegal	SEN	0.04	1.05	2.76	4.19	9.04	19.37	0.24	0.36	1.24	1.03	2.15	2.98
Serbia	SRB	15.05	22.50	16.83	23.71	24.46	24.25	2.27	3.41	7.00	5.03	6.86	8.27
Sierra Leone	SLE	0.01	0.24	0.63	0.96	2.06	4.42	0.05	0.08	0.28	0.24	0.49	0.68

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Singapore	SGP	24.64	30.20	46.22	93.60	117.36	122.15	3.81	4.79	4.73	9.09	11.46	13.61
Slovak Republic	SVK	17.07	15.78	21.81	22.35	18.40	13.92	4.45	5.26	4.89	5.20	5.25	5.47
Slovenia	SVN	8.43	7.79	10.76	11.03	9.08	6.87	2.19	2.59	2.41	2.57	2.59	2.70
Solomon Islands	SLB	0.03	0.04	0.09	0.17	0.29	0.43	0.02	0.02	0.05	0.03	0.05	0.05
Somalia	SOM	0.01	0.35	0.91	1.38	2.98	6.38	0.08	0.12	0.41	0.34	0.71	0.98
South Africa	ZAF	32.91	52.53	58.64	64.94	89.46	134.37	46.29	61.60	62.48	86.98	86.13	96.49
Spain	ESP	179.70	166.09	229.53	235.25	193.64	146.55	46.81	55.32	51.49	54.75	55.27	57.55
Sri Lanka	LKA	5.61	6.96	14.82	28.78	47.95	71.85	3.16	3.88	7.56	5.41	7.93	9.02
Sudan	SDN	0.10	2.84	7.48	11.37	24.52	52.52	0.64	0.98	3.36	2.79	5.83	8.08
Suriname	SUR	0.69	0.47	0.72	0.56	0.73	1.04	0.17	0.25	0.28	0.41	0.43	0.49
Sweden	SWE	55.25	59.51	62.93	68.80	66.24	58.80	15.09	15.13	11.29	11.15	12.91	13.62
Switzerland	CHE	15.79	17.97	27.30	30.58	28.54	25.86	2.41	8.87	20.52	19.44	23.29	24.85
Syrian Arab Republic	SYR	9.18	16.63	19.40	19.52	23.74	27.94	2.77	4.50	5.67	7.10	8.36	9.65
Tajikistan	TJK	1.59	3.19	4.21	6.21	7.26	9.71	0.43	0.59	0.83	1.03	1.31	1.54
Tanzania	TZA	0.10	2.83	7.44	11.32	24.40	52.26	0.64	0.97	3.34	2.78	5.80	8.04
Thailand	THA	50.79	62.24	95.27	192.92	241.90	251.75	7.85	9.87	9.76	18.73	23.61	28.06
Togo	TGO	0.01	0.33	0.87	1.33	2.86	6.13	0.07	0.11	0.39	0.33	0.68	0.94
Tonga	TON	0.01	0.02	0.04	0.07	0.12	0.17	0.01	0.01	0.02	0.01	0.02	0.02
Tunisia	TUN	4.72	8.20	12.82	19.37	23.95	29.94	1.97	3.47	3.99	6.15	5.98	7.21
Turkey	TUR	71.39	81.29	123.49	138.31	129.07	116.95	10.88	40.12	92.82	87.91	105.34	112.38
Turkmenistan	TKM	3.43	6.91	9.11	13.44	15.74	21.02	0.94	1.28	1.80	2.24	2.83	3.33
Uganda	UGA	0.07	1.83	4.81	7.33	15.79	33.83	0.41	0.63	2.16	1.80	3.75	5.20
Ukraine	UKR	41.27	61.70	46.14	65.00	67.07	66.49	6.23	9.34	19.20	13.78	18.80	22.67
United Arab Emirates	ARE	47.37	85.79	100.04	100.67	122.42	144.10	14.30	23.21	29.22	36.61	43.14	49.79
United Kingdom	GBR	387.36	391.75	397.47	403.65	329.84	276.77	55.56	60.03	67.37	66.77	72.87	77.25
United States	USA	3,231.98	3,706.19	4,361.47	4,334.06	3,677.01	2,990.62	580.40	532.25	476.45	561.19	627.65	698.20
Uruguay	URY	6.22	4.30	6.52	5.10	6.64	9.42	1.51	2.30	2.55	3.70	3.92	4.40
Uzbekistan	UZB	11.08	22.29	29.41	43.38	50.78	67.84	3.04	4.12	5.81	7.23	9.15	10.75
Vanuatu	VUT	0.02	0.02	0.05	0.10	0.16	0.24	0.01	0.01	0.03	0.02	0.03	0.03
Venezuela	VEN	14.53	10.05	15.24	11.92	15.52	22.01	3.54	5.38	5.97	8.66	9.15	10.28

		PLDV (2000)	**PLDV (2010)**	**PLDV (2020)**	**PLDV (2030)**	**PLDV (2040)**	**PLDV (2050)**	**Truck (2000)**	**Truck (2010)**	**Truck (2020)**	**Truck (2030)**	**Truck (2040)**	**Truck (2050)**
Vietnam	VNM	45.28	55.49	84.93	171.98	215.65	224.43	7.00	8.80	8.70	16.70	21.05	25.01
Yemen, Rep.	YEM	4.16	7.53	8.78	8.84	10.75	12.65	1.26	2.04	2.57	3.21	3.79	4.37
Zambia	ZMB	0.04	1.12	2.95	4.49	9.67	20.72	0.25	0.39	1.33	1.10	2.30	3.19
Zimbabwe	ZWE	0.02	0.59	1.56	2.38	5.12	10.98	0.13	0.20	0.70	0.58	1.22	1.69

Table 37. Vehicle fleet information for gasoline vehicles

PLDV Vehicle travel (bil km / yr)						
	2000	**2010**	**2020**	**2030**	**2040**	**2050**
Africa	98.8	199.3	347.3	462.1	522.1	446.9
ASEAN	244.5	347.6	428.8	808.3	736.7	401.6
ATE	45.8	88.9	85.0	117.5	87.5	56.1
China	67.7	374.0	1,496.3	1,715.9	719.1	131.2
EU 5	36.8	42.1	18.3	27.8	13.0	2.3
India	36.1	70.0	182.7	385.5	536.2	407.1
Latin America	427.2	381.7	576.4	496.6	348.9	205.1
Middle East	362.8	623.4	683.4	626.8	431.4	226.7
ODA	62.9	48.5	142.9	258.7	284.8	214.2
OECD Europe	1,592.5	1,160.0	1,031.0	872.4	350.8	71.9
OECD North America	3,557.5	4,089.3	4,091.5	3,298.6	1,256.6	300.1
OECD Pacific	533.6	697.3	682.4	323.1	110.3	23.1
OETE	81.0	116.8	73.9	96.7	74.5	38.6
Other OECD	45.4	51.5	91.3	71.0	31.2	12.4
Russia	220.9	278.7	264.3	230.0	135.1	48.1
PLDV – Gasoline ICE sales, millions per year						
	2000	**2010**	**2020**	**2030**	**2040**	**2050**
Africa	0.85	1.48	1.63	3.08	2.69	1.34
ASEAN	0.76	1.57	1.82	3.53	0.94	0.32
ATE	0.18	0.85	0.27	0.89	0.30	0.12
China	1.12	12.58	20.08	5.15	0.00	0.00
EU 5	0.37	0.39	0.18	0.14	0.00	0.00
India	0.49	1.28	1.30	4.64	1.28	0.65
Latin America	2.17	4.63	3.23	4.49	1.72	0.49
Middle East	0.99	2.69	1.94	2.78	1.10	0.31
ODA	0.38	0.51	0.34	1.41	0.52	0.25
OECD Europe	11.80	7.26	7.94	2.17	0.11	0.03
OECD North America	15.99	15.66	17.02	6.03	0.90	0.11
OECD Pacific	6.07	5.49	1.68	0.81	0.04	0.00
OETE	0.34	0.56	0.54	0.72	0.27	0.05
Other OECD	0.19	0.37	0.46	0.14	0.03	0.00
Russia	1.17	2.21	1.47	1.76	0.28	0.05

Truck Vehicle travel (bil km / yr)						
	2000	**2010**	**2020**	**2030**	**2040**	**2050**
Africa	35.26	40.05	41.67	28.99	25.46	21.44
ASEAN	23.82	33.98	62.47	51.80	29.31	15.13
ATE	7.44	9.41	11.20	11.75	13.43	12.82
China	26.02	36.91	66.07	192.23	162.55	136.70
EU 5	0.32	0.35	1.09	0.42	0.14	0.02
India	1.25	2.18	3.90	2.21	1.71	0.97
Latin America	36.36	58.41	65.32	62.79	43.85	25.21
Middle East	17.58	47.87	100.50	86.73	78.59	49.10
ODA	10.42	13.03	26.46	14.72	15.59	11.87
OECD Europe	61.39	27.33	16.74	9.12	4.61	2.03
OECD North America	441.36	394.34	383.45	248.31	126.14	79.80
OECD Pacific	186.37	121.91	55.92	13.02	2.23	0.30
OETE	2.27	1.59	7.56	0.86	1.67	1.25
Other OECD	9.47	7.26	20.61	1.37	0.97	0.79
Russia	11.91	15.54	21.59	15.72	19.00	15.79
Truck Vehicle – Gasoline ICE sales, millions per year						
	2000	**2010**	**2020**	**2030**	**2040**	**2050**
Africa	0.22	0.27	0.24	0.36	0.21	0.24
ASEAN	0.13	0.26	0.34	0.23	0.10	0.06
ATE	0.07	0.10	0.11	0.19	0.08	0.10
China	0.33	0.66	3.02	1.87	1.38	1.03
EU 5	0.00	0.00	0.00	0.00	0.00	0.00
India	0.03	0.10	0.13	0.10	0.07	0.03
Latin America	0.27	0.49	0.56	0.44	0.26	0.11
Middle East	0.21	0.55	0.62	0.75	0.64	0.31
ODA	0.07	0.05	0.04	0.08	0.05	0.04
OECD Europe	0.19	0.09	0.06	0.03	0.01	0.00
OECD North America	2.13	1.83	2.09	1.16	0.48	0.28
OECD Pacific	1.28	0.56	0.19	0.05	0.00	0.00
OETE	0.02	0.03	0.03	0.06	0.05	0.03
Other OECD	0.02	0.02	0.01	0.01	0.00	0.00
Russia	0.22	0.18	0.20	0.39	0.36	0.20

Table 38. Vehicle fleet information for diesel vehicles

PLDV Vehicle travel (bil km / yr)							**Truck Vehicle travel (bil km / yr)**						
	2000	**2010**	**2020**	**2030**	**2040**	**2050**		**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
Africa	23.87	66.35	99.13	75.87	21.80	4.09	Africa	62.63	109.34	170.77	222.94	258.38	289.87
ASEAN	167.70	174.52	302.10	362.04	164.74	38.59	ASEAN	84.03	92.78	124.68	210.18	250.48	283.89
ATE	1.17	2.78	2.29	2.54	0.86	0.21	ATE	5.52	8.16	13.56	18.71	24.10	29.02
China	8.90	31.29	45.78	37.09	8.99	1.03	China	61.18	276.05	282.74	319.38	212.52	190.64
EU 5	7.62	29.24	42.13	35.09	9.98	1.12	EU 5	4.16	13.01	29.80	18.34	13.04	9.89
India	12.16	44.18	189.86	265.19	172.24	57.94	India	53.01	92.38	117.34	234.33	315.03	365.92
Latin America	69.63	30.69	43.89	19.20	5.06	0.93	Latin America	115.81	177.59	219.13	272.92	276.77	273.49
Middle East	0.00	0.00	0.00	1.01	0.55	0.13	Middle East	91.62	125.85	113.72	177.33	208.58	242.93
ODA	24.49	35.03	71.08	75.24	33.18	9.86	ODA	44.86	54.86	105.64	64.86	73.08	62.96
OECD Europe	584.62	1,325.57	1,917.34	1,050.75	251.96	32.21	OECD Europe	489.68	645.19	708.38	539.47	330.80	243.30
OECD North America	115.50	164.97	252.79	127.10	26.22	2.42	OECD North America	292.26	348.56	350.09	416.82	409.48	425.43
OECD Pacific	78.80	73.05	162.73	137.79	28.14	2.28	OECD Pacific	217.54	175.43	202.44	181.88	125.49	106.69
OETE	15.64	27.68	34.20	34.78	14.60	3.15	OETE	12.45	20.48	37.84	30.95	39.29	43.63
Other OECD	3.37	7.89	25.28	13.08	3.68	0.59	Other OECD	14.78	23.83	61.83	29.68	24.74	21.04
Russia	12.63	15.65	21.07	17.10	5.86	0.88	Russia	22.40	24.36	29.77	28.40	30.22	31.19
PLDV – Diesel ICE sales, millions per year							**Truck Vehicle – Diesel ICE sales, millions per year**						
	2000	**2010**	**2020**	**2030**	**2040**	**2050**		**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
Africa	0.11	0.31	0.28	0.03	0.00	0.00	Africa	0.42	0.74	0.96	1.67	1.66	1.75
ASEAN	0.17	0.42	0.69	0.07	0.00	0.00	ASEAN	0.30	0.47	0.67	0.81	0.80	0.61
ATE	0.01	0.01	0.00	0.00	0.00	0.00	ATE	0.02	0.03	0.03	0.08	0.06	0.09
China	0.07	0.27	0.09	0.01	0.00	0.00	China	0.83	2.52	3.47	1.66	1.29	1.03
EU 5	0.11	0.35	0.22	0.00	0.00	0.00	EU 5	0.05	0.05	0.03	0.03	0.01	0.01
India	0.10	0.66	1.24	0.17	0.01	0.00	India	0.15	0.54	0.75	0.80	0.90	0.58
Latin America	0.16	0.13	0.12	0.01	0.00	0.00	Latin America	0.39	0.69	0.91	0.91	0.71	0.61
Middle East	0.00	0.00	0.00	0.00	0.00	0.00	Middle East	0.17	0.33	0.29	0.50	0.51	0.54
ODA	0.11	0.15	0.10	0.02	0.00	0.00	ODA	0.19	0.14	0.12	0.24	0.16	0.12
OECD Europe	5.18	7.73	4.73	0.06	0.00	0.00	OECD Europe	2.19	2.15	2.14	1.18	0.52	0.37
OECD North America	0.32	0.37	0.43	0.01	0.00	0.00	OECD North America	0.54	0.47	0.79	0.77	0.75	0.67
OECD Pacific	0.28	0.42	0.80	0.02	0.00	0.00	OECD Pacific	0.77	0.53	0.63	0.50	0.26	0.22
OETE	0.04	0.12	0.19	0.01	0.00	0.00	OETE	0.08	0.15	0.16	0.27	0.24	0.21
Other OECD	0.01	0.03	0.04	0.00	0.00	0.00	Other OECD	0.05	0.08	0.14	0.09	0.04	0.04
Russia	0.05	0.06	0.13	0.01	0.00	0.00	Russia	0.08	0.11	0.09	0.14	0.12	0.12

Table 39. Vehicle fleet information for electric vehicles

PLDV Vehicle travel (bil km / yr)							**Truck Vehicle travel (bil km / yr)**						
	2000	**2010**	**2020**	**2030**	**2040**	**2050**		**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
Africa	0.00	0.00	0.01	9.33	74.64	488.00	Africa	0.00	0.00	0.01	4.88	13.33	22.48
ASEAN	0.00	0.00	0.08	35.37	328.28	1018.95	ASEAN	0.00	0.00	0.00	7.05	21.71	32.27
ATE	0.00	0.00	0.00	0.34	4.39	66.61	ATE	0.00	0.00	0.00	0.00	0.02	0.16
China	0.00	0.03	25.86	467.45	1603.35	3569.76	China	0.00	0.00	2.51	70.69	195.46	286.49
EU 5	0.00	0.00	0.03	6.55	23.30	36.95	EU 5	0.00	0.00	0.00	2.62	6.90	7.36
India	0.00	0.01	0.12	66.77	631.99	1782.92	India	0.00	0.00	0.00	4.08	11.15	20.61
Latin America	0.00	0.00	0.03	6.00	52.33	342.85	Latin America	0.00	0.00	0.00	1.41	9.37	24.87
Middle East	0.00	0.00	0.00	1.31	27.13	251.19	Middle East	0.00	0.00	0.00	0.02	0.41	4.29
ODA	0.00	0.00	0.03	10.85	195.34	771.57	ODA	0.00	0.00	0.00	0.73	3.40	9.44
OECD Europe	0.01	0.12	17.91	374.96	1,092.28	1,501.15	OECD Europe	0.00	0.07	2.18	80.42	170.56	202.46
OECD North America	0.00	0.12	20.98	418.50	1,581.86	2,406.52	OECD North America	0.00	0.00	0.09	29.32	110.17	173.90
OECD Pacific	0.00	0.06	4.35	106.29	330.67	534.80	OECD Pacific	0.00	0.00	0.55	30.36	63.63	66.76
OETE	0.00	0.00	0.00	0.29	4.75	35.18	OETE	0.00	0.00	0.00	0.02	0.11	0.54
Other OECD	0.00	0.00	0.01	8.68	41.33	93.43	Other OECD	0.00	0.00	0.02	2.18	8.34	14.41
Russia	0.00	0.00	0.01	6.62	39.28	133.37	Russia	0.00	0.00	0.00	0.01	0.08	0.46
PLDV – Electric sales, millions per year							**Truck Vehicle – Electric sales, millions per year**						
	2000	**2010**	**2020**	**2030**	**2040**	**2050**		**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
Africa	0.00	0.00	0.00	0.33	1.30	7.91	Africa	0.00	0.00	0.00	0.04	0.08	0.11
ASEAN	0.00	0.00	0.00	0.51	3.56	6.70	ASEAN	0.00	0.00	0.00	0.18	0.18	0.25
ATE	0.00	0.00	0.00	0.01	0.13	1.30	ATE	0.00	0.00	0.00	0.00	0.00	0.00
China	0.00	0.00	0.93	8.01	15.05	21.19	China	0.00	0.00	0.05	1.38	1.86	2.17
EU 5	0.00	0.00	0.00	0.24	0.43	0.27	EU 5	0.00	0.00	0.00	0.02	0.02	0.02
India	0.00	0.00	0.00	2.49	8.16	13.27	India	0.00	0.00	0.00	0.27	0.45	0.48
Latin America	0.00	0.00	0.00	0.19	1.64	6.23	Latin America	0.00	0.00	0.00	0.03	0.12	0.24
Middle East	0.00	0.00	0.00	0.03	0.54	4.05	Middle East	0.00	0.00	0.00	0.00	0.01	0.08
ODA	0.00	0.00	0.00	0.22	2.25	5.06	ODA	0.00	0.00	0.00	0.01	0.02	0.04
OECD Europe	0.00	0.00	0.94	7.33	11.58	10.26	OECD Europe	0.00	0.00	0.03	0.99	1.10	1.04
OECD North America	0.00	0.01	0.27	5.68	13.10	15.26	OECD North America	0.00	0.00	0.00	0.35	0.83	1.06
OECD Pacific	0.00	0.01	0.08	2.55	3.61	3.32	OECD Pacific	0.00	0.00	0.05	0.60	0.52	0.44
OETE	0.00	0.00	0.00	0.01	0.16	0.61	OETE	0.00	0.00	0.00	0.00	0.00	0.02
Other OECD	0.00	0.00	0.00	0.17	0.37	0.57	Other OECD	0.00	0.00	0.00	0.03	0.06	0.09
Russia	0.00	0.00	0.00	0.23	0.97	1.62	Russia	0.00	0.00	0.00	0.00	0.00	0.03

Appendix D: Pavement, bridge, and culvert data

Table 40. Pavement design information

		Course thickness (mm)					
Country	**Road type**	**Surface**	**Binder**	**Base 1**	**Base 2**	**Subbase**	**References**
Australia	Motorways or Highways						
Australia	Main or National Road	40[1]	40[2]	150[3]	150[4]	150[5]	*(69)*
Australia	Secondary or Regional Road						
Australia	Other Road (Urban and Rural)						
Austria	Motorways or Highways	40[1]	120[2]	130[3]	200[4]	300[5]	*(32)*
Austria	Main or National Road	40[1]		120[3]	200[4]	300[5]	*(32)*
Austria	Secondary or Regional Road						
Austria	Other Road (Urban and Rural)						
Brazil	Motorways or Highways						
Brazil	Main or National Road	50[1]	140[2]	190[4]		210[6]	*(70)*
Brazil	Secondary or Regional Road	40[1]	35[2]	150[4]		300[5]	*(71)*
Brazil	Other Road (Urban and Rural)						
Canada	Motorways or Highways	40[1]	140[2]	150[4]		600[5]	*(72)*
Canada	Main or National Road	40[1]	110[2]	150[4]		450[5]	*(72)*
Canada	Secondary or Regional Road	40[1]	90[2]	150[4]		450[5]	*(72)*
Canada	Other Road (Urban and Rural)	40[1]	80[2]	150[4]		350[5]	*(72)*
Chile	Motorways or Highways						
Chile	Main or National Road	50[1]	60[2]	70[3]	120[4]	120[5]	*(46)*
Chile	Secondary or Regional Road	50[1]	50[2]	70[3]	120[4]	120[5]	*(46)*
Chile	Other Road (Urban and Rural)	60[1]	80[2]		120[4]	120[5]	*(46)*
China	Motorways or Highways	180[1]		400[7]		200[8]	*(20)*

		Course thickness (mm)					
Country	**Road type**	**Surface**	**Binder**	**Base 1**	**Base 2**	**Subbase**	**References**
China	Main or National Road	150[1]		400[7]		200[8]	*(20)*
China	Secondary or Regional Road	90[1]		200[7]		200[8]	*(20)*
China	Other Road (Urban and Rural)	60[1]		200[7]		200[5]	*(20)*
Colombia	Motorways or Highways	40[1]	60[2]	150[4]		220[8]	*(44)*
Colombia	Main or National Road	240[1]		150[4]		150[5]	*(73)*
Colombia	Secondary or Regional Road	190[1]		150[4]		150[5]	*(73)*
Colombia	Other Road (Urban and Rural)	170[1]		100[4]		150[5]	*(73)*
Germany	Motorways or Highways						
Germany	Main or National Road	40[1]	80[2]	220[3]		510[9]	*(33)*
Germany	Secondary or Regional Road						
Germany	Other Road (Urban and Rural)						
India	Motorways or Highways	50[1]	200[10]	150[11]		300[5]	*(74)*
India	Main or National Road	40[1]	60[10]	250[11]		200[5]	*(74)*
India	Secondary or Regional Road	30[1]	90[10]	250[11]		200[5]	*(74)*
India	Other Road (Urban and Rural)	40[1]	90[10]	250[11]		330[5]	*(74)*
Iran	Motorways or Highways	60[1]	180[2]	200[4]		300[5]	*(75)*
Iran	Main or National Road	140[1]		200[4]		250[5]	*(76)*
Iran	Secondary or Regional Road						
Iran	Other Road (Urban and Rural)						
Israel	Motorways or Highways						
Israel	Main or National Road	150[1]		200[4]	150[4]	280[5]	*(77)*
Israel	Secondary or Regional Road	80[1]		120[4]	120[4]	240[5]	*(77)*
Israel	Other Road (Urban and Rural)	40[1]		120[4]	200[4]		*(77)*

		Course thickness (mm)					
Country	**Road type**	**Surface**	**Binder**	**Base 1**	**Base 2**	**Subbase**	**References**
Italy	Motorways or Highways	50[1]	70[2]	150[3]	200[3]	200[5]	(*78*)
Italy	Main or National Road	50[1]	35[2]	105[3]		300[12]	(*79*)
Italy	Secondary or Regional Road	40[1]	60[2]	100[3]		350[12]	(*80*)
Italy	Other Road (Urban and Rural)						
Japan	Motorways or Highways						
Japan	Main or National Road	60[1]		160[4]		300[5]	(*81*)
Japan	Secondary or Regional Road						
Japan	Other Road (Urban and Rural)						
Kenya	Motorways or Highways	100[1]		150[7]		200[8]	(*82*)
Kenya	Main or National Road	50[1]		150[7]		175[8]	(*82*)
Kenya	Secondary or Regional Road	SD[13]		150[4]		125[5]	(*83*)
Kenya	Other Road (Urban and Rural)	SD[13]				175[9]	(*83*)
Mexico	Motorways or Highways	270[1]		200[4]		200[5]	(*84*)
Mexico	Main or National Road	220[1]		200[4]		200[5]	(*84*)
Mexico	Secondary or Regional Road	160[1]		200[4]		200[5]	(*84*)
Mexico	Other Road (Urban and Rural)	50[1]		200[4]			(*84*)
Mongolia	Motorways or Highways	50[1]		200[4]		300[5]	(*85*)
Mongolia	Main or National Road						
Mongolia	Secondary or Regional Road	50[1]		100[4]		220[5]	(*86*)
Mongolia	Other Road (Urban and Rural)	30[1]		40[3]		200[5]	(*87*)
Netherlands	Motorways or Highways						
Netherlands	Main or National Road	50[1]	250[2]	500[4]		300[5]	(*88*)
Netherlands	Secondary or Regional Road	200[1]		300[4]		200[5]	(*88*)

		Course thickness (mm)					
Country	**Road type**	**Surface**	**Binder**	**Base 1**	**Base 2**	**Subbase**	**References**
Netherlands	Other Road (Urban and Rural)						
Nigeria	Motorways or Highways	150[1]		250[4]		175[8]	*(89)*
Nigeria	Main or National Road	100[1]		200[4]		175[8]	*(89)*
Nigeria	Secondary or Regional Road	SD[13]		200[4]		150[5]	*(89)*
Nigeria	Other Road (Urban and Rural)	SD[13]		150[4]		100[5]	*(89)*
Pakistan	Motorways or Highways	50[1]		160[3]	250[4]	250[5]	*(90)*
Pakistan	Main or National Road	50[1]		160[3]	200[4]	200[5]	*(91)*
Pakistan	Secondary or Regional Road						
Pakistan	Other Road (Urban and Rural)						
Qatar	Motorways or Highways	70[1]	70[2]	70[3]	200[4]	150[5]	*(92)*
Qatar	Main or National Road	50[1]		250[3]		200[5]	*(92)*
Qatar	Secondary or Regional Road	50[1]	80[2]	100[3]		250[5]	*(92)*
Qatar	Other Road (Urban and Rural)						
Russia	Motorways or Highways	50[1]	210[2]	210[7]	150[4]	600[5]	*(93)*
Russia	Main or National Road	50[1]	70[2]	150[4]	300[7]	600[5]	*(94)*
Russia	Secondary or Regional Road						
Russia	Other Road (Urban and Rural)						
Singapore	Motorways or Highways	70[1]		120[3]	250[4]	300[5]	*(95)*
Singapore	Main or National Road	50[1]		120[3]	250[4]	300[5]	
Singapore	Secondary or Regional Road	40[1]		90[3]	200[4]	300[5]	
Singapore	Other Road (Urban and Rural)	25[1]		75[3]	200[4]	200[5]	
South Africa	Motorways or Highways	50[1]		150[4]		200[8]	*(96)*
South Africa	Main or National Road	40[1]		150[4]		200[8]	*(96) (96)*

		Course thickness (mm)					
Country	**Road type**	**Surface**	**Binder**	**Base 1**	**Base 2**	**Subbase**	**References**
South Africa	Secondary or Regional Road	SD[13]		150[4]		150[8]	(*96*)
South Africa	Other Road (Urban and Rural)	SD[13]		125[4]		150[5]	
Spain	Motorways or Highways	200[1]		220[7]		250[8]	(*97*)
Spain	Main or National Road	180[1]		220[7]		200[8]	(*97*)
Spain	Secondary or Regional Road	150[1]		220[7]		220[8]	(*97*)
Spain	Other Road (Urban and Rural)	150[1]		200[7]		200[8]	(*97*)
Sweden	Motorways or Highways	35[1]	60[2]	125[3]	80[4]	420[5]	(*98*)
Sweden	Main or National Road						
Sweden	Secondary or Regional Road	45[1]			80[4]	420[5]	(*98*)
Sweden	Other Road (Urban and Rural)						
Turkey	Motorways or Highways	50[1]	100[2]	120[3]	200[4]	200[5]	(*99*)
Turkey	Main or National Road	50[1]	80[2]	110[3]	200[4]	200[5]	(*99*)
Turkey	Secondary or Regional Road	50[1]	60[2]	80[3]	200[4]	200[5]	(*99*)
Turkey	Other Road (Urban and Rural)						
United Arab Emirates	Motorways or Highways	100[1]	150[2]	280[3]	100[4]	150[5]	(*48*)
United Arab Emirates	Main or National Road	150[1]	280[2]	500[3]		430[5]	(*100*)
United Arab Emirates	Secondary or Regional Road	50[1]	60[2]	200[3]		300[5]	
United Arab Emirates	Other Road (Urban and Rural)						
United Kingdom	Motorways or Highways	40[1]	60[2]	100[4]		225[5]	(*101*)
United Kingdom	Main or National Road	45[1]	55[2]	230[4]		190[5]	(*102*)

		Course thickness (mm)					
Country	**Road type**	**Surface**	**Binder**	**Base 1**	**Base 2**	**Subbase**	**References**
United Kingdom	Secondary or Regional Road						
United Kingdom	Other Road (Urban and Rural)						
United States	Motorways or Highways	150[1]		460[4]			(*17*)
United States	Main or National Road	90[1]		150[4]		340[5]	(*103*)
United States	Secondary or Regional Road	250[1]		150[4]		190[5]	(*103*)
United States	Other Road (Urban and Rural)						
Vietnam	Motorways or Highways	50[1]	70[2]	150[4]		300[5]	(*104*)
Vietnam	Main or National Road	130[1]		250[4]		300[5]	(*105*)
Vietnam	Secondary or Regional Road	100[1]		250[4]		300[5]	(*105*)
Vietnam	Other Road (Urban and Rural)	80[1]		250[4]		300[5]	(*105*)

[1] Asphalt concrete (wearing course)
[2] Asphalt concrete (binder course)
[3] Asphalt treated base
[4] Granular base
[5] Granular subbase
[6] Dense Macadam
[7] Cement treated base
[8] Cement treated subbase
[9] Frost blanket
[10] Dense bituminous macadam
[11] Wet mix macadam
[12] Asphalt treated subbase
[13] Surface dressing

Table 41. Representative countries for estimating regional bridge densities

Region	Representative countries for bridge	Number of bridges	Area of land (Km^2)	Bridge density	References (number of bridges)
Africa	South Africa	9,500	1,213,090	0.008	(*106*)
ASEAN	Vietnam	4,300	313,429	0.014	(*107*)
ATE	Turkey	8,676	769,630	0.011	(*108*)
China	China	961,100	9,388,210	0.102	(*109*)
EU 5	Ukraine	28,000	579,400	0.048	(*110*)
India	India	32,218	2,973,190	0.013	(*111*)
Latin America	Brazil	120,000	8,358,140	0.014	(*112*)
Middle East	Saudi Arabia	6,000	2,149,690	0.003	(*113*)
ODA	Mongolia	433	1,557,507	0.0003	(*114*)
OECD Europe	UK	73,208	241,930	0.303	(*115*)
OECD North America	USA	620,669	9,147,420	0.068	(*116*)
OECD Pacific	Australia	53,000	7,692,020	0.007	(*117*)
OETE	Ukraine	28,000	603,628	0.046	(*110*)
Other OECD	Australia	53,000	7,692,020	0.007	(*117*)
Others	Fiji	1,200	18,270	0.066	(*118*)
Russia	Russia	42,000	16,376,870	0.003	(*119*)

Appendix E: Electricity and mixing fuel data

Table 42. Projected Electricity Mix for representative countries and regions (US Energy Information Administration)

	2030 Electricity Grid Mix									
Country	**Coal (%)**	**Gas (%)**	**Hydro (%)**	**Solar (%)**	**Wind (%)**	**Oil (%)**	**Nuclear (%)**	**Other (%)**	**Bioenergy (%)**	**Geothermal (%)**
China	42.08	8.20	15.79	15.44	11.84	0.02	6.37	0.25	0.00	0.01
India	34.93	2.86	11.26	30.27	14.79	0.10	2.73	3.06	0.00	0.00
Russia	13.72	48.75	16.88	0.61	0.51	0.03	19.40	0.05	0.00	0.05
Canada	1.27	12.43	61.24	0.61	12.70	0.09	11.00	0.66	0.00	0.00
US	15.54	34.91	6.60	11.10	15.04	0.20	14.08	1.96	0.00	0.57
Brazil	0.69	8.76	59.33	1.20	17.65	0.46	3.35	8.56	0.00	0.00
Australia	19.25	15.92	11.13	22.59	28.24	0.03	0.00	0.88	0.00	1.96
Mexico & Other OECD Americas	4.80	50.08	25.59	3.51	6.00	3.24	3.53	1.87	0.00	1.38
OECD Europe	5.41	20.14	17.39	14.22	22.13	0.69	17.40	1.69	0.00	0.93
Other Non-OECD Europe & Eurasia	21.05	30.83	17.61	5.67	4.68	0.85	19.19	0.05	0.00	0.07
Other Non-OECD Asia	35.86	30.84	16.72	4.59	3.70	2.17	1.66	1.49	0.00	2.97
Other Non-OECD Americas	2.06	24.98	60.07	1.33	4.11	0.92	3.26	2.16	0.00	1.11
Total OECD	12.15	28.78	14.38	10.87	15.57	0.70	15.21	1.66	0.00	0.68
Total Non-OECD	30.87	20.29	17.40	12.81	9.49	1.31	6.14	1.11	0.00	0.58
	2040 Electricity Grid Mix									
Country	**Coal (%)**	**Gas (%)**	**Hydro (%)**	**Solar (%)**	**Wind (%)**	**Oil (%)**	**Nuclear (%)**	**Other (%)**	**Bioenergy (%)**	**Geothermal (%)**
China	35.75	7.47	14.55	23.8	10.06	0.01	7.99	0.36	0	0.01
India	30.76	1.3	7.63	31.13	23.35	0.01	2.71	3.11	0	0
Russia	15.86	44.54	16.18	1.03	3.76	0.01	18.33	0.24	0	0.05
Canada	0	17.82	54.34	0.54	19.15	0	6.45	1.7	0	0
US	12.73	35.03	6.04	15.64	15.35	0.16	12.21	2.03	0	0.81
Brazil	0	4.59	52.83	1.25	29.62	0.01	2.93	8.77	0	0
Australia	14.76	9.77	11.04	26.24	35.56	0.02	0	0.93	0	1.68
Mexico & Other OECD Americas	4.05	47.12	22.27	8.51	10.72	0.74	3.54	1.87	0	1.18
OECD Europe	5.21	15.63	15.92	14.06	31.95	0.16	13.71	2.46	0	0.9
Other Non-OECD Europe & Eurasia	20.11	25.08	15.4	11.68	9.23	0.67	17.43	0.32	0	0.08
Other Non-OECD Asia	37.66	19.2	14.96	12.07	10.45	0.41	1.31	1.58	0	2.36
Other Non-OECD Americas	4.62	22.59	57.58	4.77	4.32	0.03	2.51	2.14	0	1.44
Total OECD	10.78	26.02	13.32	12.98	21.5	0.23	12.39	2.02	0	0.76
Total Non-OECD	27.9	15.75	15.21	20.54	12	0.22	6.48	1.29	0	0.61

	2050 Electricity Grid Mix									
Country	**Coal (%)**	**Gas (%)**	**Hydro (%)**	**Solar (%)**	**Wind (%)**	**Oil (%)**	**Nuclear (%)**	**Other (%)**	**Bioenergy (%)**	**Geothermal (%)**
China	31.66	7.15	12.89	30.09	8.91	0.01	8.92	0.36	0	0.01
India	21.22	0.75	5.41	46.64	20	0.01	2.62	3.35	0	0
Russia	15.63	43.92	16.21	1.66	4.7	0.01	17.58	0.24	0	0.05
Canada	0	20.91	48.94	0.49	24.48	0	3.18	2	0	0
US	10.87	35.79	5.38	19.62	14.47	0.11	10.88	1.97	0	0.91
Brazil	0.43	3.28	52.45	1.34	31.58	0.01	2.12	8.79	0	0
Australia	11.7	6.92	10.95	33.26	34.7	0.04	0	0.96	0	1.47
Mexico & Other OECD Americas	3.91	34.23	19.29	23.17	14.14	0.17	2.2	1.87	0	1.02
OECD Europe	4.33	14	14.82	16.67	39.39	0.13	7.25	2.61	0	0.8
Other Non-OECD Europe & Eurasia	19.37	22.37	13.52	15.36	12.01	0.65	16.32	0.33	0	0.07
Other Non-OECD Asia	45.03	13.59	13.86	13.86	9.05	0.01	1.06	1.59	0	1.95
Other Non-OECD Americas	1.77	17.85	58.22	12.89	3.73	0.01	2.15	2.15	0	1.23
Total OECD	8.82	24.57	12.27	16.48	25.9	0.13	8.99	2.09	0	0.75
Total Non-OECD	24.79	13.71	13.72	28.2	11.31	0.04	6.29	1.41	0	0.53

Appendix F: Emission factors

Table 43. Emissions factors in kgCO$_2$e for producing 1 kg of HMA at asphalt plants in different countries

Region	Representative country/region	2021 Electricity + Fuel	2030 Electricity + Fuel	2040 Electricity + Fuel	2050 Electricity + Fuel
Africa	South Africa	3.64E-02	3.52E-02	3.46E-02	3.45E-02
ASEAN	Other Non-OECD Asia	3.58E-02	3.59E-02	3.58E-02	3.59E-02
ATE	Other Non-OECD Europe & Eurasia	3.54E-02	3.52E-02	3.51E-02	3.50E-02
China	China	3.58E-02	3.56E-02	3.54E-02	3.52E-02
EU 5	Other Non-OECD Europe & Eurasia	3.54E-02	3.52E-02	3.51E-02	3.50E-02
India	India	3.61E-02	3.55E-02	3.53E-02	3.49E-02
Latin America	Brazil	3.06E-02	3.08E-02	3.07E-02	3.07E-02
Middle East	Total Non-OECD	3.27E-02	3.18E-02	3.15E-02	3.14E-02
ODA	Other Non-OECD Asia	3.58E-02	3.59E-02	3.58E-02	3.59E-02
OECD Europe	OECD Europe	3.51E-02	3.45E-02	3.45E-02	3.44E-02
OECD North America	Mexico & Other OECD Americas	3.15E-02	3.13E-02	3.12E-02	3.10E-02
OECD Pacific	Australia	3.20E-02	3.08E-02	3.07E-02	3.07E-02
OETE	Other Non-OECD Europe & Eurasia	3.54E-02	3.52E-02	3.51E-02	3.50E-02
Other OECD	Total OECD	3.52E-02	3.49E-02	3.48E-02	3.47E-02
Others	Total Non-OECD	3.27E-02	3.18E-02	3.15E-02	3.14E-02
Russia	Russia	3.51E-02	3.52E-02	3.52E-02	3.52E-02

Table 44. Emission factors in $kgCO_2e$/lane-km for pavement layers by region

	178 mm thick lane-km section (HMA=2.4e6kg)				**400 mm (1.3ft) thick lane-km section (5% cement)**			**(450mm) 1.5ft thick lane-km section**		
Region	**Asphalt binder**	**Crushed Aggregate**	**HMA transport (cradle-site)**	**Construction**	**CTB (cradle-to-gate)**	**Transport (Gate-site)**	**Construction**	**AB (cradle-to-gate)**	**Transport (Gate-site)**	**Construction**
Africa	4.08E+04	4.01E+03	4.13E+04	1.48E+03	1.58E+05	2.58E+04	4.56E+02	1.14E+04	2.97E+04	5.27E+02
ASEAN	4.08E+04	4.01E+03	4.13E+04	1.48E+03	1.58E+05	2.58E+04	4.56E+02	1.14E+04	2.97E+04	5.27E+02
ATE	4.08E+04	4.01E+03	4.13E+04	1.48E+03	1.58E+05	2.58E+04	4.56E+02	1.14E+04	2.97E+04	5.27E+02
China	4.08E+04	4.01E+03	4.13E+04	1.48E+03	1.58E+05	2.58E+04	4.56E+02	1.14E+04	2.97E+04	5.27E+02
Colombia	4.08E+04	4.01E+03	4.13E+04	1.48E+03	1.58E+05	2.58E+04	4.56E+02	1.14E+04	2.97E+04	5.27E+02
EU 5	4.08E+04	4.01E+03	4.13E+04	1.48E+03	1.58E+05	2.58E+04	4.56E+02	1.14E+04	2.97E+04	5.27E+02
India	4.08E+04	4.01E+03	4.13E+04	1.48E+03	1.58E+05	2.58E+04	4.56E+02	1.14E+04	2.97E+04	5.27E+02
Latin America	4.08E+04	4.01E+03	4.13E+04	1.48E+03	1.58E+05	2.58E+04	4.56E+02	1.14E+04	2.97E+04	5.27E+02
Middle East	4.08E+04	4.01E+03	4.13E+04	1.48E+03	1.58E+05	2.58E+04	4.56E+02	1.14E+04	2.97E+04	5.27E+02
ODA	4.08E+04	4.01E+03	4.13E+04	1.48E+03	1.58E+05	2.58E+04	4.56E+02	1.14E+04	2.97E+04	5.27E+02
OECD Europe	4.08E+04	4.01E+03	4.13E+04	1.48E+03	1.58E+05	2.58E+04	4.56E+02	1.14E+04	2.97E+04	5.27E+02
OECD North America	4.08E+04	4.01E+03	4.13E+04	1.48E+03	1.58E+05	2.58E+04	4.56E+02	1.14E+04	2.97E+04	5.27E+02
OECD Pacific	4.08E+04	4.01E+03	4.13E+04	1.48E+03	1.58E+05	2.58E+04	4.56E+02	1.14E+04	2.97E+04	5.27E+02
OETE	4.08E+04	4.01E+03	4.13E+04	1.48E+03	1.58E+05	2.58E+04	4.56E+02	1.14E+04	2.97E+04	5.27E+02
Other OECD	4.08E+04	4.01E+03	4.13E+04	1.48E+03	1.58E+05	2.58E+04	4.56E+02	1.14E+04	2.97E+04	5.27E+02
Others	4.08E+04	4.01E+03	4.13E+04	1.48E+03	1.58E+05	2.58E+04	4.56E+02	1.14E+04	2.97E+04	5.27E+02
Russia	6.56E+04	6.46E+03	6.64E+04	2.39E+03	2.55E+05	4.15E+04	7.35E+02	1.83E+04	4.79E+04	8.48E+02

Table 45. Emission factors in kgCO$_2$e for 4-lane culvert by region

	4- lane Culvert (12 x 12 x 0.5) ft^3				
Region	**PCC production**	**Reinforcement**	**Concrete to site Transport (Gate-Site)**	**Reinforcement to Site Transport (Gate-Site)**	**Construction culvert**
Africa	2.20E+04	9.40E+03	1.39E+03	3.46E+01	6.42E+02
ASEAN	2.20E+04	9.40E+03	1.39E+03	3.46E+01	6.42E+02
ATE	2.20E+04	9.40E+03	1.39E+03	3.46E+01	6.42E+02
China	2.20E+04	9.40E+03	1.39E+03	3.46E+01	6.42E+02
Colombia	2.20E+04	9.40E+03	1.39E+03	3.46E+01	6.42E+02
EU 5	2.20E+04	9.40E+03	1.39E+03	3.46E+01	6.42E+02
India	2.20E+04	9.40E+03	1.39E+03	3.46E+01	6.42E+02
Latin America	2.20E+04	9.40E+03	1.39E+03	3.46E+01	6.42E+02
Middle East	2.20E+04	9.40E+03	1.39E+03	3.46E+01	6.42E+02
ODA	2.20E+04	9.40E+03	1.39E+03	3.46E+01	6.42E+02
OECD Europe	2.20E+04	9.40E+03	1.39E+03	3.46E+01	6.42E+02
OECD North America	2.20E+04	9.40E+03	1.39E+03	3.46E+01	6.42E+02
OECD Pacific	2.20E+04	9.40E+03	1.39E+03	3.46E+01	6.42E+02
OETE	2.20E+04	9.40E+03	1.39E+03	3.46E+01	6.42E+02
Other OECD	2.20E+04	9.40E+03	1.39E+03	3.46E+01	6.42E+02
Others	2.20E+04	9.40E+03	1.39E+03	3.46E+01	6.42E+02
Russia	2.20E+04	9.40E+03	1.39E+03	3.46E+01	6.42E+02

Table 46. Passenger car manufacturing and WTW emission factors by fuel and region

	Gasoline		**Diesel**		**Electric**						
	Single car manufacturing (kgCO$_2$e)	WTW emission factor (kgCO$_2$e/km)	Single car manufacturing (kgCO$_2$e)	WTW emission factor for diesel (kgCO$_2$e/km)	Single car manufacturing (kgCO$_2$e)	WTW emission factor for electricity (Wh / km)	WTW emission factor for electricity (MJ/km)	2020 WTW emission factor for electricity (kgCO$_2$/km)	2030 WTW emission factor for electricity (kgCO$_2$/km)	2040 WTW emission factor for electricity (kgCO$_2$/km)	2050 WTW emission factor for electricity (kgCO$_2$/km)
Africa	4.60E+03	0.184	4.60E+03	0.941	4.60E+03	1.72E+02	0.6192	0.123	0.069	0.039	0.032
ASEAN	4.60E+03	0.184	4.60E+03	0.941	4.60E+03	1.72E+02	0.6192	0.094	0.101	0.093	0.101
ATE	4.60E+03	0.184	4.60E+03	0.941	4.60E+03	1.72E+02	0.6192	0.074	0.066	0.061	0.058
China	4.60E+03	0.184	4.60E+03	0.941	4.60E+03	1.72E+02	0.6192	0.094	0.087	0.076	0.068
EU 5	4.60E+03	0.184	4.60E+03	0.941	4.60E+03	1.72E+02	0.6192	0.074	0.066	0.061	0.058
India	4.60E+03	0.184	4.60E+03	0.941	4.60E+03	1.72E+02	0.6192	0.110	0.079	0.071	0.054
Latin America	4.60E+03	0.184	4.60E+03	0.941	4.60E+03	1.72E+02	0.6192	0.027	0.037	0.033	0.032
Middle East	4.60E+03	0.184	4.60E+03	0.941	4.60E+03	1.72E+02	0.6192	0.123	0.081	0.071	0.064
ODA	4.60E+03	0.184	4.60E+03	0.941	4.60E+03	1.72E+02	0.6192	0.094	0.101	0.093	0.101
OECD Europe	4.60E+03	0.184	4.60E+03	0.941	4.60E+03	1.72E+02	0.6192	0.063	0.035	0.032	0.030
OECD North America	4.60E+03	0.184	4.60E+03	0.941	4.60E+03	1.72E+02	0.6192	0.069	0.062	0.054	0.043
OECD Pacific	4.60E+03	0.184	4.60E+03	0.941	4.60E+03	1.72E+02	0.6192	0.091	0.035	0.032	0.030
OETE	4.60E+03	0.184	4.60E+03	0.941	4.60E+03	1.72E+02	0.6192	0.074	0.066	0.061	0.058
Other OECD	4.60E+03	0.184	4.60E+03	0.941	4.60E+03	1.72E+02	0.6192	0.065	0.054	0.049	0.045
Others	4.60E+03	0.184	4.60E+03	0.941	4.60E+03	1.72E+02	0.6192	0.123	0.081	0.071	0.064
Russia	4.60E+03	0.184	4.60E+03	0.941	4.60E+03	1.72E+02	0.6192	0.062	0.065	0.067	0.066

Table 47. Truck manufacturing and WTW emission factors by fuel and region

	Gasoline		Diesel		Electric						
	Single truck manufacturing (kgCO2e)	WTW emission factor for gas (kgCO2e/ km)	Single truck manufacturing (kgCO2e)	WTW emission factor for diesel (kgCO2e/km)	Single truck manufacturing (kgCO2e)	WTW emission factor for electricity (Wh/km)	WTW emission factor for electricity (MJ/km)	2020 WTW emission factor for electricity (kgCO$_2$/km)	2030 WTW emission factor for electricity (kgCO$_2$/km)	2040 WTW emission factor for electricity (kgCO$_2$/km)	2050 WTW emission factor for electricity (kgCO$_2$/km)
Africa	1.60E+04	0.184	1.60E+04	0.941	1.60E+04	1.90E+03	6.84	1.360	0.759	0.428	0.357
ASEAN	1.60E+04	0.184	1.60E+04	0.941	1.60E+04	1.90E+03	6.84	1.034	1.117	1.025	1.120
ATE	1.60E+04	0.184	1.60E+04	0.941	1.60E+04	1.90E+03	6.84	0.818	0.734	0.674	0.637
China	1.60E+04	0.184	1.60E+04	0.941	1.60E+04	1.90E+03	6.84	1.034	0.963	0.835	0.752
EU 5	1.60E+04	0.184	1.60E+04	0.941	1.60E+04	1.90E+03	6.84	0.818	0.734	0.674	0.637
India	1.60E+04	0.184	1.60E+04	0.941	1.60E+04	1.90E+03	6.84	1.211	0.877	0.779	0.596
Latin America	1.60E+04	0.184	1.60E+04	0.941	1.60E+04	1.90E+03	6.84	0.301	0.411	0.360	0.358
Middle East	1.60E+04	0.184	1.60E+04	0.941	1.60E+04	1.90E+03	6.84	1.360	0.893	0.783	0.706
ODA	1.60E+04	0.184	1.60E+04	0.941	1.60E+04	1.90E+03	6.84	1.034	1.117	1.025	1.120
OECD Europe	1.60E+04	0.184	1.60E+04	0.941	1.60E+04	1.90E+03	6.84	0.694	0.382	0.356	0.330
OECD North America	1.60E+04	0.184	1.60E+04	0.941	1.60E+04	1.90E+03	6.84	0.760	0.681	0.595	0.477
OECD Pacific	1.60E+04	0.184	1.60E+04	0.941	1.60E+04	1.90E+03	6.84	1.009	0.382	0.356	0.330
OETE	1.60E+04	0.184	1.60E+04	0.941	1.60E+04	1.90E+03	6.84	0.818	0.734	0.674	0.637
Other OECD	1.60E+04	0.184	1.60E+04	0.941	1.60E+04	1.90E+03	6.84	0.721	0.592	0.545	0.495
Others	1.60E+04	0.184	1.60E+04	0.941	1.60E+04	1.90E+03	6.84	1.360	0.893	0.783	0.706
Russia	1.60E+04	0.184	1.60E+04	0.941	1.60E+04	1.90E+03	6.84	0.684	0.723	0.736	0.726

Appendix G: Equations

Table 48. Equations for quantifying GHG emissions

$$GWP_{build\ out} = GWP_{HMA\ cradle-to-laid} + GWP_{base\ material\ cradle-to-laid}$$

$$GWP_{HMA\ cradle-to-laid} = GWP_{asphalt\ plant} + GWP_{HMA\ materials\ +\ HMA\ transport\ +\ HMA\ construction}$$

$$GWP_{base\ cradle\ to\ laid} = GWP_{base\ materials\ +\ base\ transport\ +\ base\ construction}$$

$$\begin{aligned} GWP_{\text{build-out}} = {} & GWP_{asphalt\ plant} + GWP_{HMA\ materials\ +\ HMA\ transport\ +\ HMA\ construction} \\ & + GWP_{base\ materials\ +\ base\ transport\ +\ base\ construction} \end{aligned}$$

$$\begin{aligned} & GWP_{asphalt\ plant} \\ & \quad = Total\ road\ length\ (lane\ km) \times Quantity\ of\ HMA\ per\ lane\ km\ \left(\frac{kg\ of\ HMA}{lane\ km}\right) \\ & \quad \times Electricity\ and\ fuel_{emission\ factor}\left(\frac{kgco_2e}{kg\ of\ HMA}\right) \end{aligned}$$

$$\begin{aligned} & GWP_{HMA\ materials\ +\ HMA\ transport\ +\ HMA\ construction} \\ & \quad = Total\ road\ length\ (lane\ km) \times (Asphalt\ binder_{emission\ factor} + Crushed\ aggregate_{emission\ factor} \\ & \quad + HMA\ transport_{emission\ factor} + HMA\ Construction_{emission\ factor})\left(\frac{kgco_2e}{lane\ km}\right) \end{aligned}$$

$$\begin{aligned} & GWP_{base\ materials\ +\ base\ transport\ +\ base\ construction} \\ & \quad = Total\ road\ length\ (lane\ km) \times (Base\ material_{emission\ factor} + Base\ transport_{emission\ factor} \\ & \quad + Base\ construction_{emission\ factor})\left(\frac{kgco_2e}{lane\ km}\right) \end{aligned}$$

$$GWP_{road\ maintenance} = Total\ road\ length\ (lane\ km) \times Maintainance\ (Thin/medium\ HMA\ overlay)_{emission\ factor}\left(\frac{kgco_2e}{lane\ km}\right)$$

Appendix H: GHG emissions data

Table 49. GHG emissions from Model 1 road length prediction

Region	Decade	New road construction	Existing road M&R
Africa	2021 – 2030	2.12E+11	8.57E+10
ASEAN	2021 – 2030	2.06E+11	5.93E+10
ATE	2021 – 2030	1.65E+10	7.06E+09
China	2021 – 2030	3.00E+07	1.31E+11
EU 5	2021 – 2030	7.87E+09	4.93E+09
India	2021 – 2030	3.27E+11	1.76E+11
Latin America	2021 – 2030	6.26E+10	7.65E+10
Middle East	2021 – 2030	4.47E+10	1.78E+10
ODA	2021 – 2030	7.80E+10	3.35E+10
OECD Europe	2021 – 2030	1.39E+11	1.54E+11
OECD North America	2021 – 2030	4.02E+11	2.24E+11
OECD Pacific	2021 – 2030	7.14E+10	6.16E+10
OETE	2021 – 2030	1.73E+10	9.83E+09
Other OECD	2021 – 2030	4.87E+09	2.90E+09
Others	2021 – 2030	0.00E+00	1.78E+08
Russia	2021 – 2030	0.00E+00	3.92E+10
Africa	2031 – 2040	3.25E+11	1.16E+11
ASEAN	2031 – 2040	2.98E+11	8.82E+10
ATE	2031 – 2040	1.83E+10	1.09E+10
China	2031 – 2040	1.45E+07	1.31E+11
EU 5	2031 – 2040	1.01E+10	6.85E+09
India	2031 – 2040	4.72E+11	2.57E+11
Latin America	2031 – 2040	9.03E+10	9.28E+10
Middle East	2031 – 2040	5.76E+10	2.41E+10
ODA	2031 – 2040	1.09E+11	4.44E+10
OECD Europe	2031 – 2040	1.72E+11	1.87E+11
OECD North America	2031 – 2040	3.84E+11	3.19E+11
OECD Pacific	2031 – 2040	8.29E+10	7.92E+10
OETE	2031 – 2040	2.38E+10	1.41E+10
Other OECD	2031 – 2040	5.90E+09	4.07E+09
Others	2031 – 2040	0.00E+00	1.78E+08
Russia	2031 – 2040	0.00E+00	3.92E+10
Africa	2041 – 2050	4.52E+11	1.39E+11
ASEAN	2041 – 2050	3.47E+11	1.07E+11
ATE	2041 – 2050	1.55E+10	1.20E+10
China	2041 – 2050	0.00E+00	1.31E+11
EU 5	2041 – 2050	9.90E+09	7.70E+09
India	2041 – 2050	5.61E+11	3.10E+11
Latin America	2041 – 2050	1.08E+11	1.03E+11

Region	Decade	New road construction	Existing road M&R
Middle East	2041 – 2050	5.78E+10	2.69E+10
ODA	2041 – 2050	1.29E+11	5.08E+10
OECD Europe	2041 – 2050	1.65E+11	2.01E+11
OECD North America	2041 – 2050	3.21E+11	3.30E+11
OECD Pacific	2041 – 2050	8.32E+10	8.53E+10
OETE	2041 – 2050	2.31E+10	1.64E+10
Other OECD	2041 – 2050	6.08E+09	4.54E+09
Others	2041 – 2050	0.00E+00	1.78E+08
Russia	2041 – 2050	0.00E+00	3.92E+10

Table 50. GHG emissions from Model 2 road length prediction

Region	Decade	New road construction	Existing road M&R
Africa	2021 – 2030	1.04E+11	8.29E+10
ASEAN	2021 – 2030	3.74E+11	6.35E+10
ATE	2021 – 2030	3.77E+09	6.48E+09
China	2021 – 2030	9.74E+11	1.56E+11
EU 5	2021 – 2030	0.00E+00	4.58E+09
India	2021 – 2030	9.64E+11	2.04E+11
Latin America	2021 – 2030	6.14E+10	7.64E+10
Middle East	2021 – 2030	3.66E+10	1.76E+10
ODA	2021 – 2030	0.00E+00	3.16E+10
OECD Europe	2021 – 2030	7.36E+10	1.51E+11
OECD North America	2021 – 2030	1.82E+11	2.14E+11
OECD Pacific	2021 – 2030	2.49E+10	5.94E+10
OETE	2021 – 2030	0.00E+00	9.05E+09
Other OECD	2021 – 2030	1.63E+09	2.76E+09
Others	2021 – 2030	0.00E+00	1.78E+08
Russia	2021 – 2030	0.00E+00	3.92E+10
Africa	2031 – 2040	1.30E+11	9.70E+10
ASEAN	2031 – 2040	2.38E+11	1.08E+11
ATE	2031 – 2040	5.07E+09	7.41E+09
China	2031 – 2040	7.35E+10	2.59E+11
EU 5	2031 – 2040	0.00E+00	4.58E+09
India	2031 – 2040	8.29E+11	4.20E+11
Latin America	2031 – 2040	3.97E+10	9.01E+10
Middle East	2031 – 2040	3.23E+10	2.23E+10
ODA	2031 – 2040	1.43E+10	3.19E+10
OECD Europe	2031 – 2040	3.35E+10	1.66E+11
OECD North America	2031 – 2040	1.56E+11	2.56E+11
OECD Pacific	2031 – 2040	1.66E+09	6.43E+10
OETE	2031 – 2040	0.00E+00	9.05E+09

Region	Decade	New road construction	Existing road M&R
Other OECD	2031 – 2040	5.93E+08	3.09E+09
Others	2031 – 2040	0.00E+00	1.78E+08
Russia	2031 – 2040	2.57E+09	3.93E+10
Africa	2041 – 2050	1.61E+11	1.04E+11
ASEAN	2041 – 2050	2.05E+11	9.94E+10
ATE	2041 – 2050	4.26E+09	7.85E+09
China	2041 – 2050	2.08E+11	1.71E+11
EU 5	2041 – 2050	0.00E+00	4.58E+09
India	2041 – 2050	8.08E+11	4.32E+11
Latin America	2041 – 2050	4.20E+10	8.79E+10
Middle East	2041 – 2050	3.29E+10	2.27E+10
ODA	2041 – 2050	4.16E+10	3.45E+10
OECD Europe	2041 – 2050	3.89E+10	1.60E+11
OECD North America	2041 – 2050	1.57E+11	2.58E+11
OECD Pacific	2041 – 2050	1.30E+09	5.98E+10
OETE	2041 – 2050	8.51E+09	9.44E+09
Other OECD	2041 – 2050	1.01E+09	2.94E+09
Others	2041 – 2050	0.00E+00	1.78E+08
Russia	2041 – 2050	3.47E+09	4.00E+10

Table 51. GHG emissions from Model 3 road length prediction

Region	Decade	New road construction	Existing road M&R
Africa	2021 – 2030	1.89E+11	8.51E+10
ASEAN	2021 – 2030	7.22E+10	5.59E+10
ATE	2021 – 2030	5.77E+09	6.57E+09
China	2021 – 2030	1.39E+11	1.35E+11
EU 5	2021 – 2030	1.06E+09	4.63E+09
India	2021 – 2030	1.47E+11	1.67E+11
Latin America	2021 – 2030	4.21E+10	7.55E+10
Middle East	2021 – 2030	2.53E+10	1.73E+10
ODA	2021 – 2030	6.13E+10	3.31E+10
OECD Europe	2021 – 2030	3.17E+10	1.49E+11
OECD North America	2021 – 2030	7.14E+10	2.08E+11
OECD Pacific	2021 – 2030	1.29E+10	5.88E+10
OETE	2021 – 2030	1.02E+09	9.10E+09
Other OECD	2021 – 2030	1.37E+09	2.74E+09
Others	2021 – 2030	0.00E+00	1.78E+08
Russia	2021 – 2030	1.05E+10	3.97E+10
Africa	2031 – 2040	2.12E+11	1.10E+11
ASEAN	2031 – 2040	6.29E+10	6.50E+10
ATE	2031 – 2040	5.26E+09	7.88E+09

Region	Decade	New road construction	Existing road M&R
China	2031 – 2040	7.64E+10	1.51E+11
EU 5	2031 – 2040	7.19E+08	4.85E+09
India	2031 – 2040	1.41E+11	2.01E+11
Latin America	2031 – 2040	3.95E+10	8.55E+10
Middle East	2031 – 2040	2.37E+10	2.06E+10
ODA	2031 – 2040	6.47E+10	4.11E+10
OECD Europe	2031 – 2040	2.48E+10	1.56E+11
OECD North America	2031 – 2040	6.24E+10	2.25E+11
OECD Pacific	2031 – 2040	1.11E+10	6.18E+10
OETE	2031 – 2040	1.17E+09	9.34E+09
Other OECD	2031 – 2040	1.34E+09	3.06E+09
Others	2031 – 2040	0.00E+00	1.78E+08
Russia	2031 – 2040	7.55E+09	4.20E+10
Africa	2041 – 2050	2.16E+11	1.18E+11
ASEAN	2041 – 2050	4.46E+10	6.51E+10
ATE	2041 – 2050	4.41E+09	7.99E+09
China	2041 – 2050	1.74E+10	1.45E+11
EU 5	2041 – 2050	3.37E+08	4.81E+09
India	2041 – 2050	1.11E+11	2.05E+11
Latin America	2041 – 2050	3.04E+10	8.64E+10
Middle East	2041 – 2050	2.01E+10	2.10E+10
ODA	2041 – 2050	5.98E+10	4.30E+10
OECD Europe	2041 – 2050	1.68E+10	1.55E+11
OECD North America	2041 – 2050	4.28E+10	2.25E+11
OECD Pacific	2041 – 2050	9.39E+09	6.19E+10
OETE	2041 – 2050	2.14E+08	9.38E+09
Other OECD	2041 – 2050	9.82E+08	3.10E+09
Others	2041 – 2050	0.00E+00	1.78E+08
Russia	2041 – 2050	2.12E+09	4.15E+10

Table 52. Vehicle-related GHG emissions for all vehicle fuel types

Region	Decade	Vehicle manufacturing	Vehicle operation	Additional fuel from road roughness
Africa	2021 – 2030	2.80E+11	4.00E+12	4.53E+10
ASEAN	2021 – 2030	2.78E+11	4.33E+12	5.22E+10
ATE	2021 – 2030	3.56E+10	5.33E+11	6.34E+09
China	2021 – 2030	2.02E+12	8.45E+12	1.04E+11
EU 5	2021 – 2030	2.41E+10	5.90E+11	6.67E+09
India	2021 – 2030	2.59E+11	2.64E+12	3.10E+10
Latin America	2021 – 2030	3.89E+11	5.36E+12	6.08E+10
Middle East	2021 – 2030	2.35E+11	4.43E+12	5.22E+10

Region	Decade	Vehicle manufacturing	Vehicle operation	Additional fuel from road roughness
ODA	2021 – 2030	4.51E+10	2.34E+12	2.60E+10
OECD Europe	2021 – 2030	9.84E+11	1.77E+13	2.15E+11
OECD North America	2021 – 2030	1.28E+12	1.98E+13	2.49E+11
OECD Pacific	2021 – 2030	2.57E+11	5.57E+12	6.58E+10
OETE	2021 – 2030	6.34E+10	8.91E+11	1.02E+10
Other OECD	2021 – 2030	4.66E+10	1.41E+12	1.55E+10
Others	2021 – 2030	0.00E+00	0.00E+00	0.00E+00
Russia	2021 – 2030	1.21E+11	1.35E+12	1.69E+10
Africa	2031 – 2040	4.89E+11	4.81E+12	2.26E+11
ASEAN	2031 – 2040	3.85E+11	6.55E+12	3.43E+11
ATE	2031 – 2040	8.46E+10	6.89E+11	3.45E+10
China	2031 – 2040	1.39E+12	1.19E+13	6.88E+11
EU 5	2031 – 2040	2.53E+10	4.44E+11	2.34E+10
India	2031 – 2040	5.22E+11	5.02E+12	2.53E+11
Latin America	2031 – 2040	4.36E+11	5.85E+12	2.65E+11
Middle East	2031 – 2040	3.29E+11	5.04E+12	2.38E+11
ODA	2031 – 2040	1.28E+11	1.91E+12	9.92E+10
OECD Europe	2031 – 2040	7.93E+11	1.30E+13	6.79E+11
OECD North America	2031 – 2040	9.04E+11	1.73E+13	9.53E+11
OECD Pacific	2031 – 2040	3.38E+11	3.99E+12	2.00E+11
OETE	2031 – 2040	8.68E+10	7.65E+11	3.85E+10
Other OECD	2031 – 2040	3.43E+10	6.52E+11	3.26E+10
Others	2031 – 2040	0.00E+00	0.00E+00	0.00E+00
Russia	2031 – 2040	1.77E+11	1.18E+12	6.25E+10
Africa	2041 – 2050	4.96E+11	5.31E+12	6.13E+10
ASEAN	2041 – 2050	3.81E+11	6.62E+12	9.77E+10
ATE	2041 – 2050	4.20E+10	7.15E+11	8.31E+09
China	2041 – 2050	1.42E+12	9.27E+12	1.77E+11
EU 5	2041 – 2050	2.55E+10	3.00E+11	4.50E+09
India	2041 – 2050	6.62E+11	6.59E+12	9.37E+10
Latin America	2041 – 2050	3.28E+11	5.34E+12	5.87E+10
Middle East	2041 – 2050	2.60E+11	4.95E+12	5.54E+10
ODA	2041 – 2050	1.62E+11	2.21E+12	3.70E+10
OECD Europe	2041 – 2050	7.98E+11	7.11E+12	1.02E+11
OECD North America	2041 – 2050	9.74E+11	1.15E+13	1.73E+11
OECD Pacific	2041 – 2050	2.94E+11	2.44E+12	3.38E+10
OETE	2041 – 2050	6.78E+10	7.92E+11	9.13E+09
Other OECD	2041 – 2050	3.58E+10	5.04E+11	6.91E+09

Region	Decade	Vehicle manufacturing	Vehicle operation	Additional fuel from road roughness
Others	2041 – 2050	0.00E+00	0.00E+00	0.00E+00
Russia	2041 – 2050	1.35E+11	1.02E+12	1.32E+10

Table 53. Vehicle-related GHG emissions for gasoline vehicles

Region	Decade	Vehicle manufacturing	Vehicle operation	Additional fuel from road roughness
Africa	2021 – 2030	1.13E+11	1.32E+12	1.72E+10
ASEAN	2021 – 2030	1.38E+11	1.76E+12	2.26E+10
ATE	2021 – 2030	3.03E+10	3.35E+11	4.33E+09
China	2021 – 2030	1.41E+12	4.27E+12	5.99E+10
EU 5	2021 – 2030	8.40E+09	5.56E+10	7.67E+08
India	2021 – 2030	8.12E+10	4.70E+11	6.80E+09
Latin America	2021 – 2030	2.38E+11	2.14E+12	2.80E+10
Middle East	2021 – 2030	1.88E+11	2.82E+12	3.61E+10
ODA	2021 – 2030	2.21E+10	6.57E+11	8.22E+09
OECD Europe	2021 – 2030	3.75E+11	2.58E+12	3.77E+10
OECD North America	2021 – 2030	1.12E+12	1.42E+13	1.89E+11
OECD Pacific	2021 – 2030	1.07E+11	2.27E+12	3.05E+10
OETE	2021 – 2030	2.93E+10	2.64E+11	3.49E+09
Other OECD	2021 – 2030	2.26E+10	4.66E+11	5.71E+09
Others	2021 – 2030	0.00E+00	0.00E+00	0.00E+00
Russia	2021 – 2030	1.00E+11	8.77E+11	1.18E+10
Africa	2031 – 2040	2.00E+11	1.42E+12	8.36E+10
ASEAN	2031 – 2040	1.99E+11	2.51E+12	1.47E+11
ATE	2031 – 2040	7.16E+10	4.16E+11	2.34E+10
China	2031 – 2040	5.37E+11	6.34E+12	3.52E+11
EU 5	2031 – 2040	6.45E+09	6.93E+10	4.38E+09
India	2031 – 2040	2.29E+11	9.16E+11	5.89E+10
Latin America	2031 – 2040	2.77E+11	1.92E+12	1.06E+11
Middle East	2031 – 2040	2.48E+11	2.52E+12	1.37E+11
ODA	2031 – 2040	7.74E+10	7.79E+11	4.61E+10
OECD Europe	2031 – 2040	1.05E+11	2.12E+12	1.35E+11
OECD North America	2031 – 2040	4.62E+11	1.07E+13	6.17E+11
OECD Pacific	2031 – 2040	4.54E+10	9.06E+11	5.49E+10
OETE	2031 – 2040	4.21E+10	2.34E+11	1.49E+10
Other OECD	2031 – 2040	7.40E+09	1.81E+11	1.13E+10
Others	2031 – 2040	0.00E+00	0.00E+00	0.00E+00

Region	Decade	Vehicle manufacturing	Vehicle operation	Additional fuel from road roughness
Russia	2031 – 2040	1.43E+11	7.25E+11	4.23E+10
Africa	2041 – 2050	1.58E+11	1.52E+12	2.12E+10
ASEAN	2041 – 2050	6.00E+10	2.06E+12	2.91E+10
ATE	2041 – 2050	2.66E+10	3.68E+11	4.69E+09
China	2041 – 2050	2.20E+11	3.67E+12	4.50E+10
EU 5	2041 – 2050	1.68E+07	3.17E+10	4.67E+08
India	2041 – 2050	7.00E+10	1.26E+12	1.88E+10
Latin America	2041 – 2050	1.20E+11	1.35E+12	1.75E+10
Middle East	2041 – 2050	1.53E+11	1.97E+12	2.46E+10
ODA	2041 – 2050	3.11E+10	8.50E+11	1.18E+10
OECD Europe	2041 – 2050	6.61E+09	8.66E+11	1.27E+10
OECD North America	2041 – 2050	1.18E+11	4.46E+12	5.91E+10
OECD Pacific	2041 – 2050	2.55E+09	2.82E+11	4.09E+09
OETE	2041 – 2050	2.07E+10	1.93E+11	2.79E+09
Other OECD	2041 – 2050	1.91E+09	8.38E+10	1.20E+09
Others	2041 – 2050	0.00E+00	0.00E+00	0.00E+00
Russia	2041 – 2050	7.00E+10	5.47E+11	7.03E+09

Table 54. Vehicle-related GHG emissions for diesel vehicles

Region	Decade	Vehicle manufacturing	Vehicle operation	Additional fuel from road roughness
Africa	2021 – 2030	1.67E+11	2.68E+12	2.81E+10
ASEAN	2021 – 2030	1.39E+11	2.57E+12	2.97E+10
ATE	2021 – 2030	5.35E+09	1.98E+11	2.01E+09
China	2021 – 2030	5.60E+11	4.13E+12	4.19E+10
EU 5	2021 – 2030	1.55E+10	5.34E+11	5.90E+09
India	2021 – 2030	1.77E+11	2.17E+12	2.42E+10
Latin America	2021 – 2030	1.51E+11	3.22E+12	3.28E+10
Middle East	2021 – 2030	4.71E+10	1.61E+12	1.61E+10
ODA	2021 – 2030	2.30E+10	1.69E+12	1.78E+10
OECD Europe	2021 – 2030	5.60E+11	1.51E+13	1.76E+11
OECD North America	2021 – 2030	1.46E+11	5.63E+12	5.97E+10
OECD Pacific	2021 – 2030	1.38E+11	3.30E+12	3.52E+10
OETE	2021 – 2030	3.40E+10	6.27E+11	6.72E+09
Other OECD	2021 – 2030	2.40E+10	9.44E+11	9.77E+09
Others	2021 – 2030	0.00E+00	0.00E+00	0.00E+00
Russia	2021 – 2030	2.05E+10	4.78E+11	5.06E+09

Region	**Decade**	**Vehicle manufacturing**	**Vehicle operation**	**Additional fuel from road roughness**
Africa	2031 – 2040	2.69E+11	3.36E+12	1.39E+11
ASEAN	2031 – 2040	1.33E+11	3.94E+12	1.81E+11
ATE	2031 – 2040	1.25E+10	2.72E+11	1.11E+10
China	2031 – 2040	2.65E+11	4.63E+12	1.88E+11
EU 5	2031 – 2040	4.80E+09	3.53E+11	1.64E+10
India	2031 – 2040	1.35E+11	4.02E+12	1.78E+11
Latin America	2031 – 2040	1.45E+11	3.92E+12	1.58E+11
Middle East	2031 – 2040	7.96E+10	2.52E+12	1.01E+11
ODA	2031 – 2040	3.93E+10	1.12E+12	4.97E+10
OECD Europe	2031 – 2040	1.92E+11	1.04E+13	4.87E+11
OECD North America	2031 – 2040	1.24E+11	6.25E+12	2.58E+11
OECD Pacific	2031 – 2040	8.01E+10	2.94E+12	1.27E+11
OETE	2031 – 2040	4.42E+10	5.31E+11	2.35E+10
Other OECD	2031 – 2040	1.42E+10	4.55E+11	1.91E+10
Others	2031 – 2040	0.00E+00	0.00E+00	0.00E+00
Russia	2031 – 2040	2.32E+10	4.48E+11	1.90E+10
Africa	2041 – 2050	2.65E+11	3.72E+12	3.75E+10
ASEAN	2041 – 2050	1.28E+11	3.99E+12	4.20E+10
ATE	2041 – 2050	9.52E+09	3.44E+11	3.45E+09
China	2041 – 2050	2.06E+11	3.04E+12	3.05E+10
EU 5	2041 – 2050	2.37E+09	2.11E+11	2.24E+09
India	2041 – 2050	1.44E+11	4.92E+12	5.15E+10
Latin America	2041 – 2050	1.14E+11	3.94E+12	3.94E+10
Middle East	2041 – 2050	8.09E+10	2.96E+12	2.96E+10
ODA	2041 – 2050	2.50E+10	1.12E+12	1.17E+10
OECD Europe	2041 – 2050	8.30E+10	5.36E+12	5.69E+10
OECD North America	2041 – 2050	1.21E+11	5.88E+12	5.91E+10
OECD Pacific	2041 – 2050	4.23E+10	1.85E+12	1.89E+10
OETE	2041 – 2050	3.92E+10	5.96E+11	6.15E+09
Other OECD	2041 – 2050	6.95E+09	3.61E+11	3.65E+09
Others	2041 – 2050	0.00E+00	0.00E+00	0.00E+00
Russia	2041 – 2050	1.96E+10	4.44E+11	4.52E+09

Table 55. Vehicle-related GHG emissions for electric vehicles

Region	Decade	Vehicle manufacturing	Vehicle operation	Additional fuel from road roughness
Africa	2021 – 2030	2.49E+07	9.45E+07	2.16E+06
ASEAN	2021 – 2030	6.75E+07	7.89E+07	5.04E+06
ATE	2021 – 2030	3.57E-02	4.46E-01	9.75E-03
China	2021 – 2030	5.10E+10	4.67E+10	1.96E+09
EU 5	2021 – 2030	2.27E+08	4.93E+07	1.79E+06
India	2021 – 2030	8.41E+07	9.31E+07	5.94E+06
Latin America	2021 – 2030	6.02E+07	2.75E+07	1.12E+06
Middle East	2021 – 2030	2.39E-01	7.00E-01	1.55E-02
ODA	2021 – 2030	7.97E+05	3.28E+07	2.12E+06
OECD Europe	2021 – 2030	4.84E+10	1.45E+10	5.73E+08
OECD North America	2021 – 2030	1.26E+10	1.35E+10	8.47E+08
OECD Pacific	2021 – 2030	1.16E+10	3.60E+09	1.41E+08
OETE	2021 – 2030	6.34E-02	4.04E-01	8.73E-03
Other OECD	2021 – 2030	1.52E+07	1.25E+08	2.84E+06
Others	2021 – 2030	0.00E+00	0.00E+00	0.00E+00
Russia	2021 – 2030	1.38E+07	8.12E+06	5.24E+05
Africa	2031 – 2040	2.08E+10	2.45E+10	2.75E+09
ASEAN	2031 – 2040	5.26E+10	1.05E+11	1.52E+10
ATE	2031 – 2040	4.80E+08	2.25E+08	5.95E+07
China	2031 – 2040	5.89E+11	9.44E+11	1.48E+11
EU 5	2031 – 2040	1.40E+10	2.16E+10	2.59E+09
India	2031 – 2040	1.58E+11	7.89E+10	1.58E+10
Latin America	2031 – 2040	1.37E+10	7.03E+09	9.71E+08
Middle East	2031 – 2040	1.32E+09	1.11E+09	2.75E+08
ODA	2031 – 2040	1.13E+10	1.76E+10	3.45E+09
OECD Europe	2031 – 2040	4.95E+11	4.07E+11	5.77E+10
OECD North America	2031 – 2040	3.18E+11	4.00E+11	7.77E+10
OECD Pacific	2031 – 2040	2.13E+11	1.42E+11	1.86E+10
OETE	2031 – 2040	5.24E+08	3.00E+08	5.92E+07
Other OECD	2031 – 2040	1.27E+10	1.61E+10	2.19E+09
Others	2031 – 2040	0.00E+00	0.00E+00	0.00E+00
Russia	2031 – 2040	1.05E+10	4.49E+09	1.24E+09
Africa	2041 – 2050	7.26E+10	7.18E+10	2.56E+09
ASEAN	2041 – 2050	1.92E+11	5.76E+11	2.66E+10
ATE	2041 – 2050	5.95E+09	2.66E+09	1.66E+08
China	2041 – 2050	9.90E+11	2.56E+12	1.01E+11
EU 5	2041 – 2050	2.31E+10	5.74E+10	1.79E+09

Region	**Decade**	**Vehicle manufacturing**	**Vehicle operation**	**Additional fuel from road roughness**
India	2041 – 2050	4.47E+11	4.08E+11	2.34E+10
Latin America	2041 – 2050	9.40E+10	5.05E+10	1.80E+09
Middle East	2041 – 2050	2.63E+10	2.03E+10	1.18E+09
ODA	2041 – 2050	1.06E+11	2.36E+11	1.36E+10
OECD Europe	2041 – 2050	7.09E+11	8.89E+11	3.28E+10
OECD North America	2041 – 2050	7.36E+11	1.21E+12	5.51E+10
OECD Pacific	2041 – 2050	2.49E+11	3.09E+11	1.08E+10
OETE	2041 – 2050	7.93E+09	3.43E+09	1.91E+08
Other OECD	2041 – 2050	2.69E+10	5.98E+10	2.06E+09
Others	2041 – 2050	0.00E+00	0.00E+00	0.00E+00
Russia	2041 – 2050	4.51E+10	2.64E+10	1.68E+09