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India Transport Energy Outlook

Puneet Kamboj, Ankur Malyan, Harsimran Kaur, Himani Jain, and Vaibhav Chaturvedi

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Image: Alamy

Executive summary

The transport sector is a significant contributor to the global energy demand and associated emissions. Countries worldwide have been devising strategies to mitigate emissions from this sector. In India, although the transport sector accounts for less than a fifth of India's final energy use and almost 11 per cent of India's energy sector related carbon dioxide emissions, its emissions are growing at a faster rate compared to other sectors. As India's economic growth accelerates, emissions from this sector are expected to grow at an even faster pace.

India's transportation services are crucial to its future growth, given its close linkage to infrastructure development and manufacturing. Hence, to continue

its developmental trajectory while balancing its climate goals, India needs policies that emphasise a sustainable and low-carbon transport sector.

This transport sector outlook reveals the following insights:

- **With economic development, an exponential increase in four-wheelers will drive the future growth of passenger transport.** In the next three decades, we estimate four-wheeler ownership to grow by nine times whereas ownership of two-wheelers will saturate with rising income levels.

- **The shift to four-wheelers will significantly impact the transport sector's energy demand and emissions.** However, the falling cost of electric vehicles could lead to their faster adoption if the necessary support infrastructure is developed in parallel. Electric vehicles reduce direct emissions from the transport sector and shift emissions to the electricity generation sector where they can be reduced cost effectively. In addition, they are highly energy efficient. If the central and state governments commit to developing electric charging infrastructure rapidly, electric cars could account for 30 per cent of sales in 2030 and 75 per cent of sales in 2050.

- **The rapid growth of private passenger vehicles implies that the share of public transport will continue to decline,** a matter of concern for policymakers. This will also have implications for congestion and transport infrastructure development.

- **With rising income levels, the demand for domestic air travel will continue to increase at a fast pace for the next few decades,** which will result in a significant increase in this sector's share of emissions due to the high carbon intensity of air travel. Domestic aviation will be the 'hard to abate' sector within passenger transport.

- **The dominance of trucks in India's freight transport segment means that this transport segment would be the most challenging one for India to tackle from a decarbonisation perspective due to the limited availability of sustainable alternatives.** While natural gas uptake is expected to significantly increase in the next three decades, uptake of electric trucks will require a considerable improvement in battery densities. Other fuel options such as hydrogen and synthetic fuels are at a very early stage of innovation and need more time for full-scale deployment.

Specifically, as per our assessment, policymakers need to be aware of the following challenges and prepare well in advance to address them effectively:

- The decline in the share of public transport

- Air travel emerging as a challenge to mitigation in the transport sector in the next three decades

- The slow pace of electric vehicle charging infrastructure development impeding the pace of electric vehicle penetration

- **Overall, our outlook indicates that in the next couple of decades, India's transport sector is set to witness deep structural changes, driven by market forces. Policymaking has to intervene in specific niches to support and accelerate this transition while avoiding the pitfalls of unsustainable mobility behaviours driven by higher disposable incomes.**

1. Introduction

India is one of the world's fastest-growing economies and is home to around 1.4 billion people. With an average economic growth rate of 7 per cent in the last 20 years (Chakraborty 2021), the need to transport goods and people to meet the compounding demands of its vast population is also growing exponentially (NITI Aayog, RMI and RMI India 2021). The transport sector accounts for about 50 per cent of the oil demand in India (IEA 2021). Transport accounts for a significant share of the total energy in demand in India, with only three other countries dedicating a larger share of their energy to transport – the US, China, and Russia (IEA 2016). While the growth of transport energy demand in the US, China, and Russia is declining, India's transport demand is set to increase, given that it is currently a growing economy with a low per capita energy consumption for transport (IEA 2021). The demand for transport will continue to grow in parallel with accelerating economic growth, making the transport sector in India critical from an energy use and decarbonisation perspective. Technology choices and policy decisions made today will decide the energy use and carbon emissions from this sector in the decades to come. **The objective of India Transport Energy Outlook is to understand what India's transport energy use and associated carbon emissions will look like in a business-as-usual (BAU) scenario over the next 30 years.**

> **India's transport sector emissions are growing at a faster rate compared to other sectors.**

2. Evolution of India's transport sector

2.1 Historical demand for passenger transport in India

In recent years, India's motorised passenger travel demand has mostly been fulfilled by road, rail and a small share by air travel[1]. Passenger travel by water, which is the least-used mode (almost negligible) is limited to a few coastal states (Nag 2021). Indians primarily use two-wheelers and four-wheelers as personal vehicles to meet their mobility requirements.

With rising income levels, the vehicle fleet in India has seen significant growth, driven by the rapid increase in the number of two-wheelers (Anup and Yang 2020). India's total motorised passenger activity increased from roughly 1,700 billion passenger-kilometres[2] (pkm) in 2005 to 3,833 billion pkm in 2020. Apart from motorised travel, a significant portion of mobility needs in India is met by non-motorised modes of transport (walking and cycling). The demand for non-motorised modes is far below its potential due to the lack of support infrastructure (Kaur and Ghosh 2021), although it is noticeably higher than in other developed countries (ITF 2021).

Figure 1 A significant portion of passenger mobility needs in India is met by non-motorised modes of transport
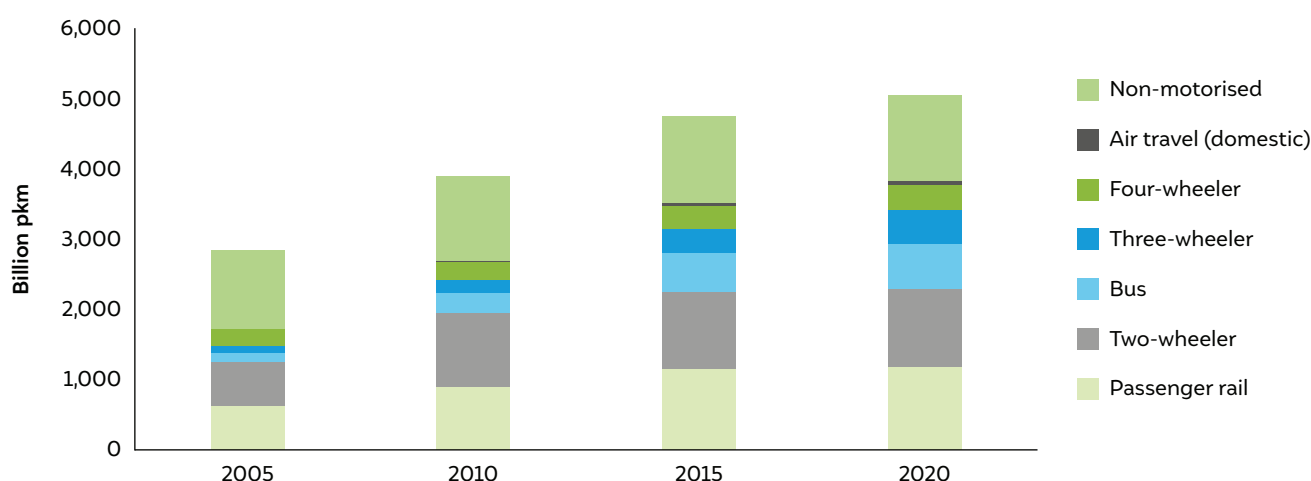
Source: Authors' analysis based on GCAM-CEEW

Note: The passenger activity for various modes is estimated based on CEEW's assumptions for load factors, annual vehicle kilometres, and survival curve assumptions for vehicle stock on the road (Soman et al. 2020). LDV_4W, LDV_2W and LDV_3W refer to motorised four-wheelers, two-wheelers, and three-wheelers.

Indian Railways (IR) is the most used mode of passenger transport by Indians, especially for long-distance travel. Its vast network stretching 67,956 km connects the length and breadth of the country (Railway Board 2020). This extensive railway system carries the most number of passengers among railway systems globally (UIC 2020). In the last decade, the railways accounted for around 30 per cent of the motorised passenger travel demand (Figure 1). For a sizeable Indian population, the railways remain the most affordable mode of transportation as passenger fares are cross-subsidised by overcharging freight traffic (Kamboj and Tongia 2018). However, the share of railways in overall motorised modes fell from

36 per cent in 2005 to 31 per cent in 2020, largely due to the increasing share of personal modes of travel.

Two-wheelers are the preferred mode of personal transport for the majority of the population. India is one of the biggest and fastest-growing markets for two-wheelers (Doval 2017; Anup and Yang 2020). For many households in India, a two-wheeler is the primary mode of personal mobility. One of the dominant factors for the rise of two-wheelers in the Indian vehicle stock is their high fuel economy (Bansal et al. 2021). Many Indian cities are highly congested, making two-wheelers the preferred mode of travel to avoid getting stuck in traffic (Jha 2020). Two-wheelers

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1   As India lacks granular data on passenger and freight movements across various modes, the historical trends presented in the outlook are as per the authors' analysis based on a CEEW-tailored version of the Global Change Analysis Model developed for India-specific assumptions (GCAM-CEEW) and the literature review.

2   Passenger-kilometre is a unit of measure of passenger traffic corresponding to the movement of one person over a distance of one kilometer.

are more popular in tier-1 and tier-2 cities compared to metropolitan cities, particularly due to the lack of adequate public transport (Soman et al. 2019). The booming e-commerce industry in India has also contributed to the increase due to the use of two-wheelers to make last-mile deliveries.

Intermediate public transport (IPT), which mainly comprises three-wheelers and e-rickshaws, is an essential mode of urban travel. IPT plays a significant role in providing transport services in smaller towns and as feeder modes in larger cities that lack adequate public transport infrastructure (Gadepalli 2016). In India, three-wheelers are mainly used as a shared mobility service and support the insufficient public transport infrastructure in Indian cities (IEA 2021). Buses are also widely used by large sections of the population, mainly for intercity travel, and limited intracity services in a few cities. In 2020, three-wheelers and buses (public and private) contributed to 13 per cent and 17 per cent of motorised passenger activity, respectively.

Four-wheelers contributed to roughly 9 per cent of the total passenger traffic in 2020. The low share of four-wheelers in the overall passenger movement is due to low ownership rates compared to developed countries (ITF 2021). However, with rising income levels, the share of four-wheelers is rising exponentially in the Indian vehicle stock (MoRTH 2017). The growing market for app-based on-demand mobility services has also contributed to the rising number of four-wheelers in

India (ITF 2021). Domestic aviation accounts for the lowest share in passenger service demand, but it has been growing consistently over the years.

2.2 Historical demand for freight transport

With the rapid growth of the Indian economy, freight activity has increased significantly. The growth in freight demand primarily comes from the road sector. Freight movement in India has doubled to 2,250 billion tonne-kilometres[3] (tkm) in 2020, compared to 2005 levels. According to the *India Transport Report* by the National Transport Development Committee, the increase in freight demand has been accompanied by the sub-optimal development of the rail–road share (National Transport Development Policy Committee 2014).

Trucks dominate the freight modal share, accounting for 65 per cent of freight movement in 2020. Over the past two decades, India has invested significantly in strengthening road infrastructure by expanding and constructing new national and state highways (IEA 2021). This improved road infrastructure has helped increase the average distance across which commodities are transported by trucks. The Indian trucking fleet, which hauls freight over long distances, is mainly comprised of medium-sized trucks with a gross vehicle weight between 3.5 tonnes–12 tonnes (ITF 2021) resulting in relatively lower tonnes carried for a unit of energy consumed.

Figure 2 Trucks dominate India's freight movement and are growing consistently
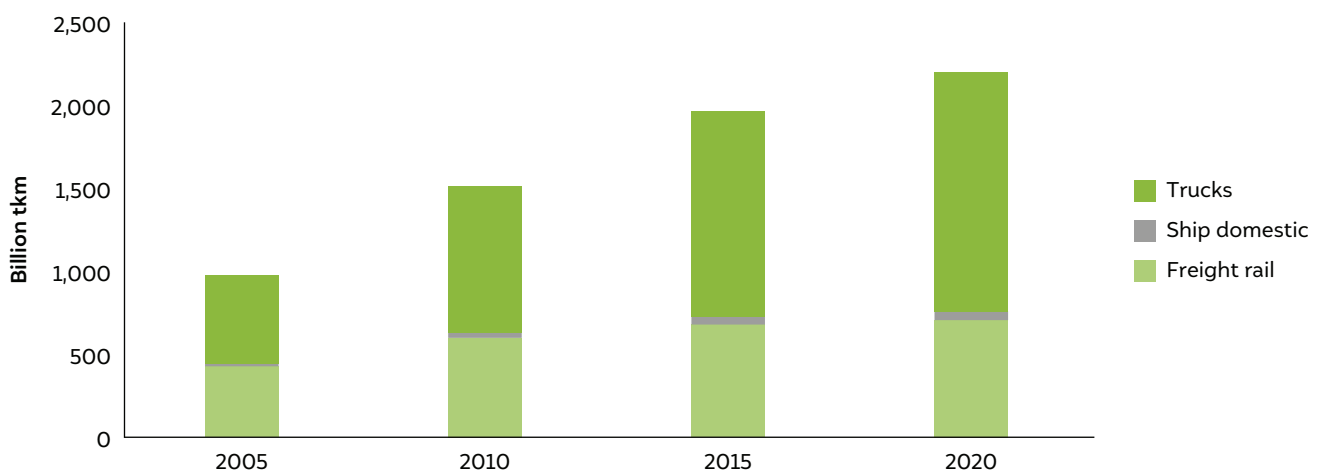
Source: Authors' analysis based on GCAM-CEEW

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3   Tonne-kilometres is a unit of measure of freight traffic corresponding to the move of one tonne of freight over a distance of one kilometer.

IR has consistently lost its share in freight movement to roads due to an inability to add capacity and respond to market needs (National Transport Development Policy Committee 2014). IR carries a significant amount of freight, but its modal share has been declining over the years. Among the many reasons that have led to its declining share, two stand out— the high cost of carrying freight and congestion on the railway network (Kamboj and Tongia 2018). IR overcharges freight services to cross-subsidise passenger services, which makes it the most expensive railway system in the world to carry payload when compared to equivalent railway networks of other countries (Kamboj and Tongia 2018). Also, IR operates both passenger and freight traffic on highly congested and over-utilised shared tracks, where passenger traffic is always prioritised. This prioritisation policy has resulted in very long turn-around times for railway rake with no guarantee on delivery times. IR's commodity basket is limited to a few bulk commodities, e.g., out of the total revenue-earning freight carried by it, around 45 per cent is attributed to coal (Kamboj and Tongia 2018). This high dependence on limited

> **India's transport sector consumes almost one-fifth of India's final energy use.**

commodities for its revenue and inability to expand its commodity basket has resulted in a loss of business opportunities (National Transport Development Policy Committee 2014). Domestic shipping, which includes coastal shipping and inland waterways, remains highly underdeveloped and accounts for a negligible share in overall freight movement.

2.3 Historical energy consumption and carbon emissions

The transport sector has been a significant consumer of energy in India, especially oil. In 2020, the transport sector consumed around 4 EJ of energy, which was 19 per cent of the final energy consumed by India.[4] While overall the transport sector accounts for a relatively small share in India's final energy consumption, it accounted for just about 50 per cent (IEA 2020) of India's oil consumption.

Figure 3 Energy consumed by various modes of passenger and freight transport from 2005 to 2020
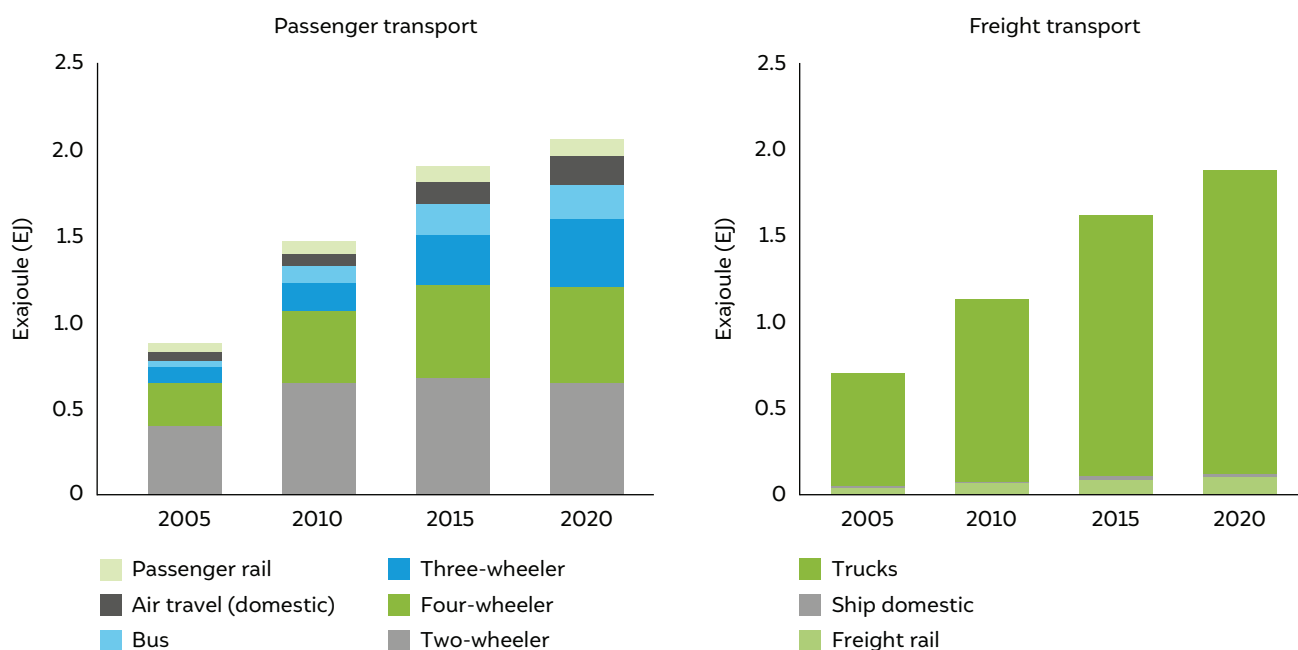
Source: Authors' analysis based on GCAM-CEEW

In 2020, two-wheelers consumed 31 per cent of the total passenger energy, more than any other mode. Buses and three-wheelers combined consumed 29 per cent of the total passenger transport energy. Four-wheelers accounted for 27 per cent of the total passenger energy despite having a lower share in the

total passenger transport activity due to the low fuel efficiency of four-wheelers compared to other modes per passenger. Domestic aviation was also an energy-intensive mode, where a 2 per cent share in passenger activity contributed to an 8 per cent share in total energy consumption.

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4 Authors' analysis based on GCAM-CEEW.

> **Market forces will continue to impact the evolution of both passenger and freight transport in the absence of a dedicated policy push to promote any particular mode or technology.**

The railways is the most energy-efficient mode for both passenger and freight transport. IR contributes to around 30 per cent of passenger and freight activities individually but consumes only 5 per cent of the total energy consumed by each transport service. The relatively higher share of the electrified rail network in India makes IR more energy-efficient than the rail systems in other countries. Recently, IR announced that it will electrify 100 per cent of its network by 2023, which will make it the most energy-efficient railway network in the world (Ministry of Railways 2020).

Trucks account for the largest share of energy consumption in freight transport. Between 2005 and 2020, the energy consumed by trucks grew faster than their respective share in freight activity. The gap in growth rates is mainly due to the low fuel efficiency of Indian trucking fleets. India's slow progress in implementing stringent fuel efficiency standards, especially for heavy-duty vehicles, has also contributed

to this gap (Garg and Sharpe 2017). The Indian trucking fleet is characterised by individually owned, medium-sized diesel trucks with lower fuel efficiencies compared to those in other developed countries. Another characteristic that defines the Indian vehicle fleet, especially trucks, is the high share of used vehicles. India has a booming secondary market for used vehicles. Often, trucks that have already been used for several years and are depreciated are sold in the used vehicles' market at a significantly lower price. These vehicles are then again used for many years, mainly for short intracity trips, despite their abysmal fuel efficiency and emissions, before they are finally retired.

The emissions produced by the transport sector reflect the energy used by various modes of both passenger and freight transport. In 2020, direct emissions (tailpipe emissions) by the transport sector (excluding international aviation and international shipping) stood at 272 million tonnes of CO_2 ($MtCO_2$). The road sector, including passenger and freight, dominate transport emissions, accounting for a share of more than 92 per cent. It also significantly contributes to India's air pollution problem. Emissions produced by road transport are growing faster than in any other sector and are expected to be a significant challenge to decarbonising India's energy sector.

Figure 4 Carbon emissions produced by the transport sector in 2020
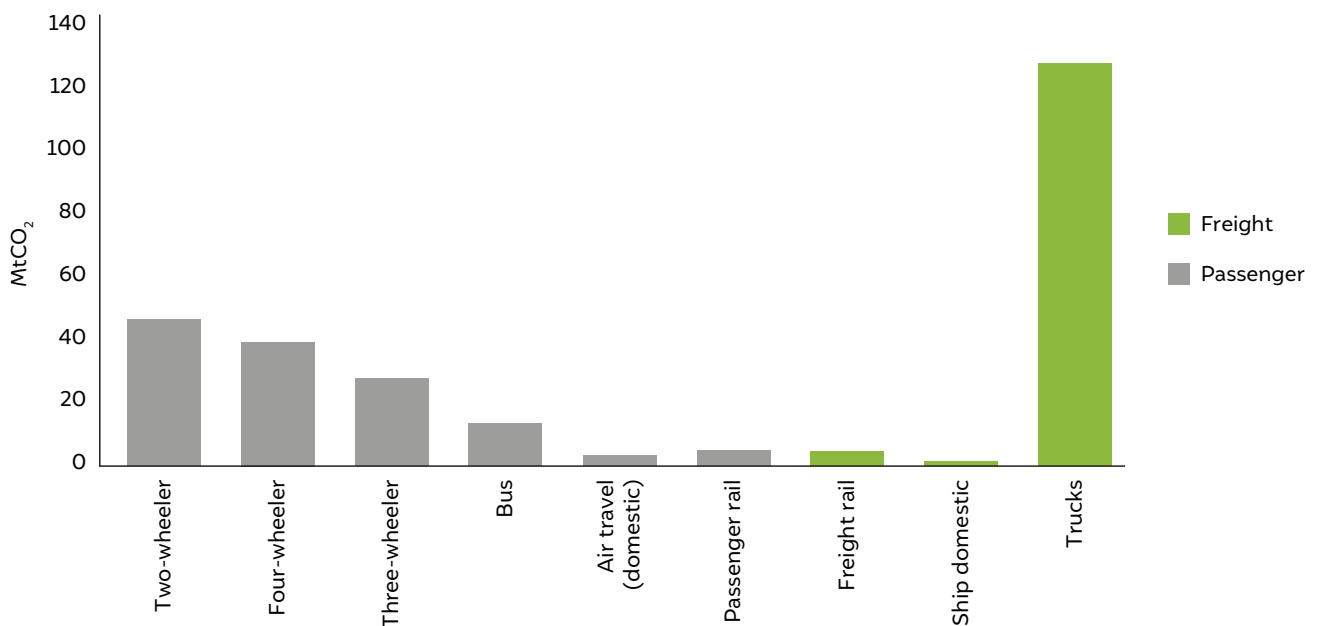
Source: Authors' analysis based on GCAM-CEEW

3. The future of India's transport sector

Our outlook provides insights into what India's transport sector might look like in the next few decades. In this section, we will highlight the key characteristics of the future growth of India's transport sector. Our analysis assumes that market forces will continue to impact the evolution of both passenger and freight transport in the absence of a dedicated policy push to promote any particular mode or technology. We also assume that the cost of oil and gas-based internal combustion engines (ICE) across all modes will follow historical trends. A crucial assumption of the BAU scenario is that the cost of electric vehicles across all modes of transport will continue to decline. We have assumed that by 2030, electric four-wheelers will reach cost parity with the ICE in terms of capital cost. For other modes, the rate of decline will differ since the share of battery costs differs for each mode.

> By 2030, we expect that electric four wheelers will reach cost parity with ICE four wheelers.

The detailed assumptions for the transport sector are discussed in Annexure 1 of the document. The following are the key insights from our assessment.

3.1 Future passenger service demand will be driven by four-wheelers

A growing economy and rapid urbanisation have increased the mobility needs of a relatively young and ambitious population (Kapoor and Sinha 2020). Our outlook for passenger travel highlights that the demand for motorised transport will double in the next three decades from nearly 4,000 billion pkms in 2020 to more than 8,000 billion pkms (Figure 5). However, there will be a substantial change in the modal share of motorised passenger transport.

Figure 5 Four-wheelers will drive the demand for passenger transport in the future
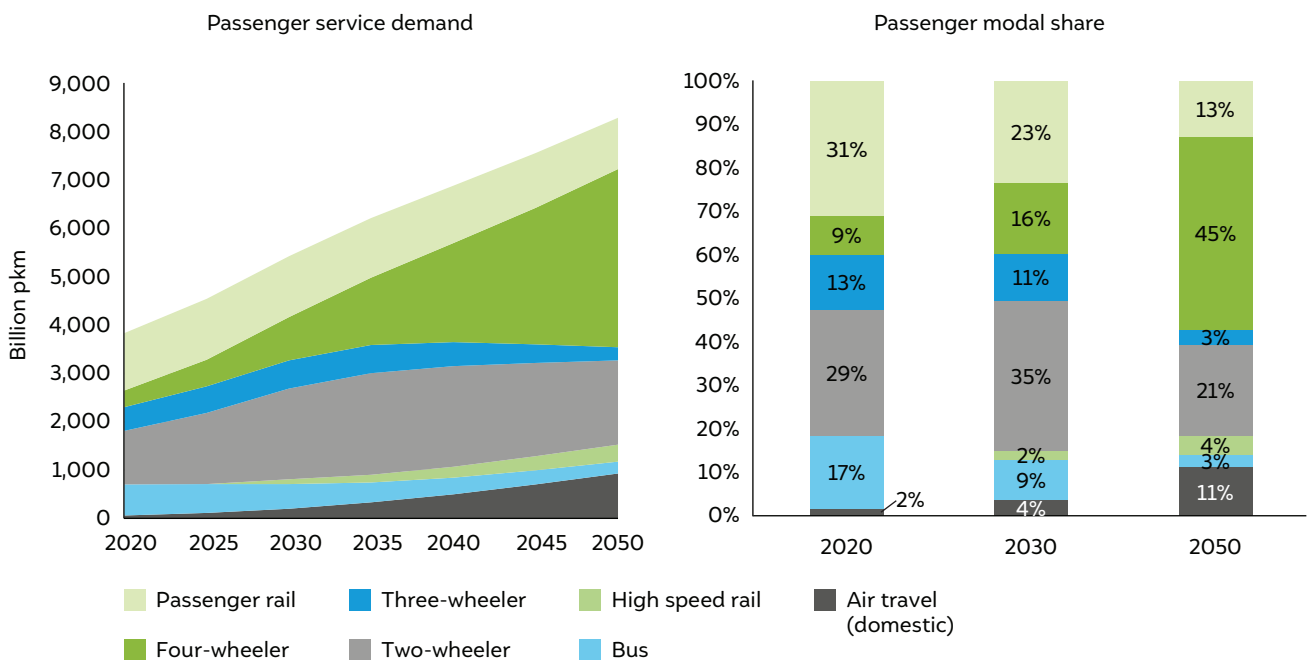
Source: Authors' analysis based on GCAM-CEEW

Historically, the railways and two-wheelers have dominated India's passenger demand (Figure 1), but this may not be the case in the future. We estimate that with rising income levels, four-wheelers will drive passenger service demand in the next three decades. The modal share of four-wheelers in motorised passenger service will increase from 9 per cent in 2020 to a staggering 45 per cent in 2050, mainly driven

by the desire to own a personal four-wheeler with increasing income levels as well as the growth of on-demand mobility services (such as Ola and Uber). This enormous gain, from 2 per cent in 2020 to 11 per cent in 2050, in the modal share of four-wheelers comes at the cost of the reduced shares of other modes like two-wheelers and public transport. There will be a substantial reduction in the percentage share of public transport modes such as the railways, buses, and three-wheelers. The increasing number of four-wheelers and reduced share of mass transportation will significantly impact the future of India's transport sector from an energy use and emissions point of view as well as drive up congestion and infrastructure requirements.

Two-wheelers will remain a significant mode of travel. While its modal share will peak initially, the segment will eventually see a decline. We predict that the two-wheeler service demand will peak around 2040 and then decline. Other countries, like China, have observed the peaking of two-wheeler ownership rates[5] at similar GDP per capita levels that India will achieve in 2035 (ITF 2015). Figure 6 shows the estimated ownership rates of two-wheelers and four-wheelers in India. According to these estimates, the ownership rate of two-wheelers will peak around per capita income levels of 2015 USD 5000 while the ownership rate for four-wheelers will see a continuously increasing trend.

Figure 6 The ownership rate for two-wheelers will peak around GDP per capita of 2015 USD 5000 while the ownership rate for four-wheelers will substantially increase
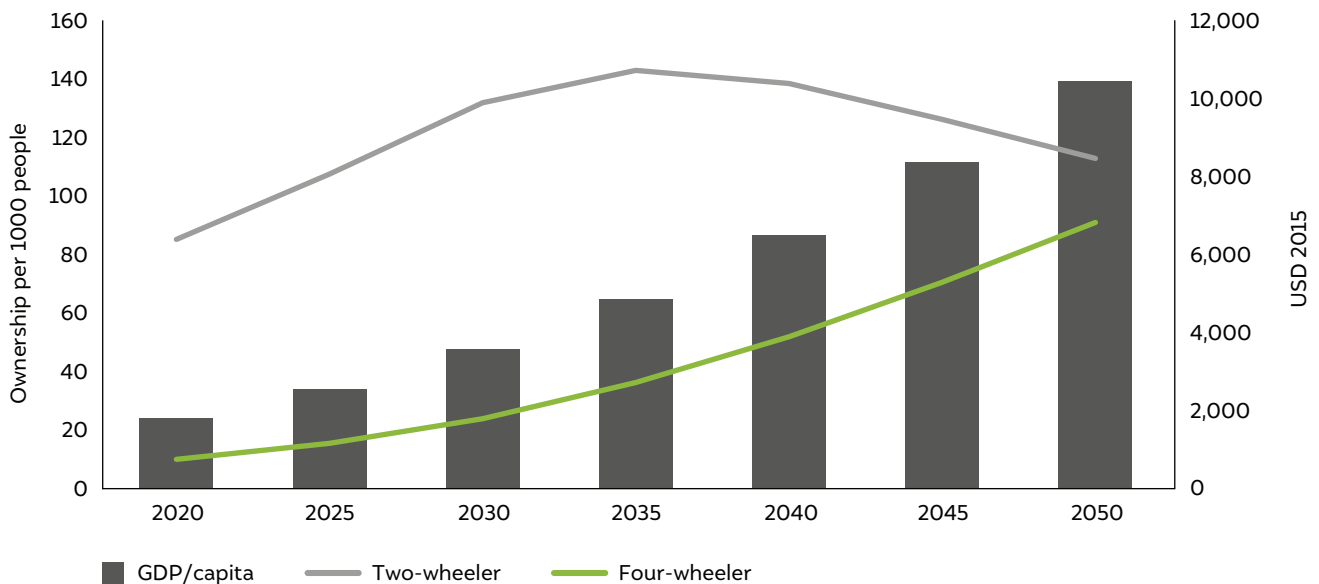
Source: Authors' calculations.

Note: The ownership rates for the future are estimated using the model output of future service demand, which incorporates the survival curves for both technologies. We have assumed that the load factors and annual vehicle kilometre (VKM) for two-wheelers and four-wheelers will remain constant in the future, but this may not necessarily be the case. We have considered a load factor of 1.5 and an annual VKM of 6,300 kilometres for two-wheelers, a load factor of 2.14 and an annual VKM of 11,560 kilometres for four-wheelers (Soman et al. 2020).

3.2 Private passenger vehicle space is set for a disruption due to electric vehicles, the bus segment will need policy support

Our assessment emphasises the importance of creating the charging infrastructure and support ecosystem required for electric vehicles across the country rapidly to take full advantage of the declining cost. As per our estimates, with dedicated efforts in the right direction, by starting in the first decade till 2030 and increasing

the pace for the next 20 years, we can achieve a high share of electric vehicles across all vehicle categories. Our outlook highlights that around one-third of the four-wheelers and half of the two-wheelers sold in 2030 could be electric, and that this share could increase up to 75 per cent and 90 per cent, respectively, by 2050. We

We see a slower uptake of electric buses in the near term due to high upfront capital costs.

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5   Ownership rates are defined as vehicles owned per 1,000 people.

foresee a relatively slower uptake of electric buses in the first decade due to high upfront capital costs and charging infrastructure requirements. Increasing the uptake of electric buses will require a focused policy effort to increase the share of buses in public transport, which could address the challenge of high upfront costs. Measures such as demand aggregation, or other interventions that seek to reduce the upfront cost borne by states and municipalities, will be critical for the electrification of this segment.

Figure 7 Electric vehicles will significantly gain share in new vehicles, especially in the two and three-wheeler segment
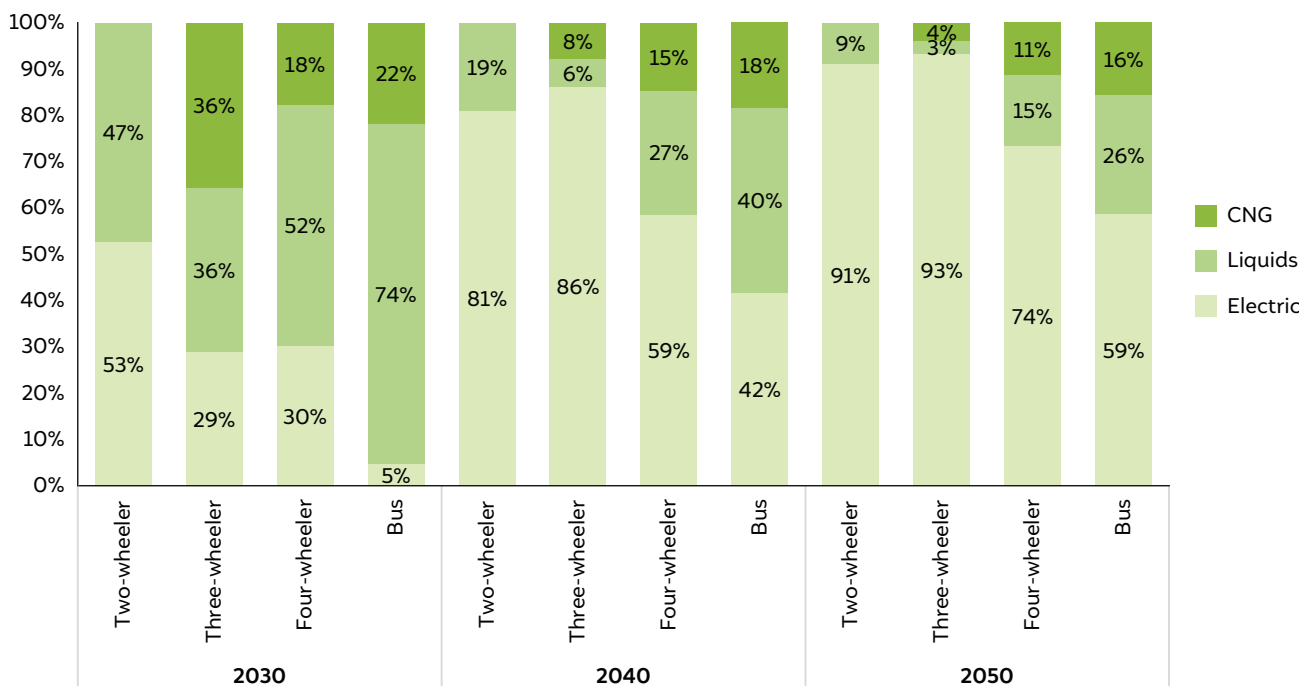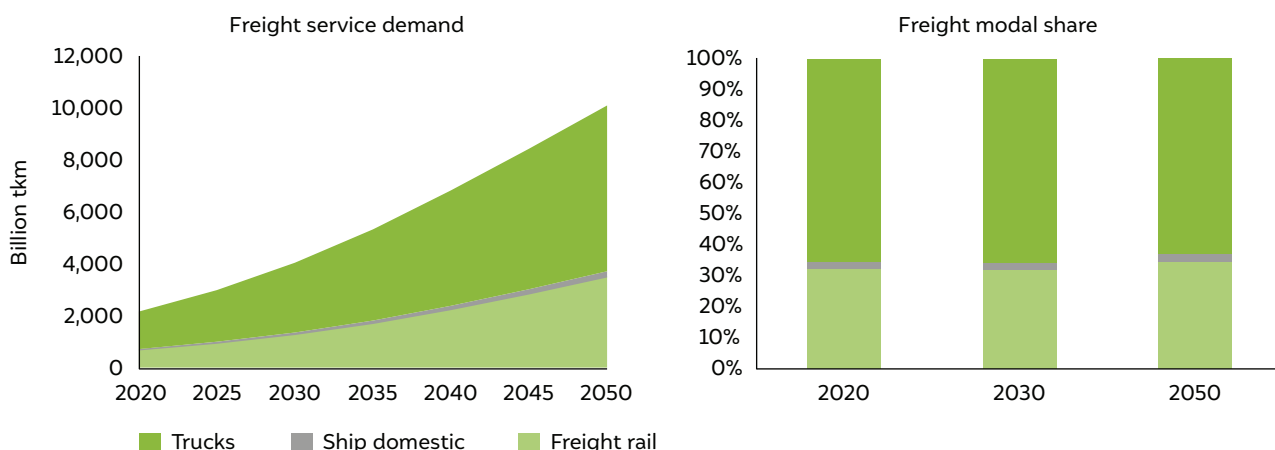

Source: Authors' estimates

Note: The uptake of electric vehicles across different modes is contingent on our assumptions that their price decline will continue in the future and that the rate of decrease will vary by mode as the share of battery cost varies across modes. We also assume that all the non-economic barriers, such as the availability of electric vehicles, charging stations, and other required infrastructure, will disappear by 2050.

3.3 Trucks will continue to dominate freight service demand

Economic development fuels the growth of freight transport and associated logistical services. India's future economic growth will involve significant infrastructure development, which will require the expansion of its freight transport activities. Our outlook for freight transport shows that freight service demand will grow five times from nearly 2,000 billion tkm in 2020 to more than 10,000 billion tkm by 2050. However, unlike passenger transport, we do not estimate any significant change in the modal share of freight transport in the future. Although we see that the total freight carried by the railways will continue to increase in absolute terms, we do not see any significant change in the modal share. Trucks will continue to dominate the freight business. We see only a slight uptake in domestic shipping in a BAU scenario.

Figure 8 Freight demand to grow by over five times in the next three decades

Freight service demand

Freight modal share

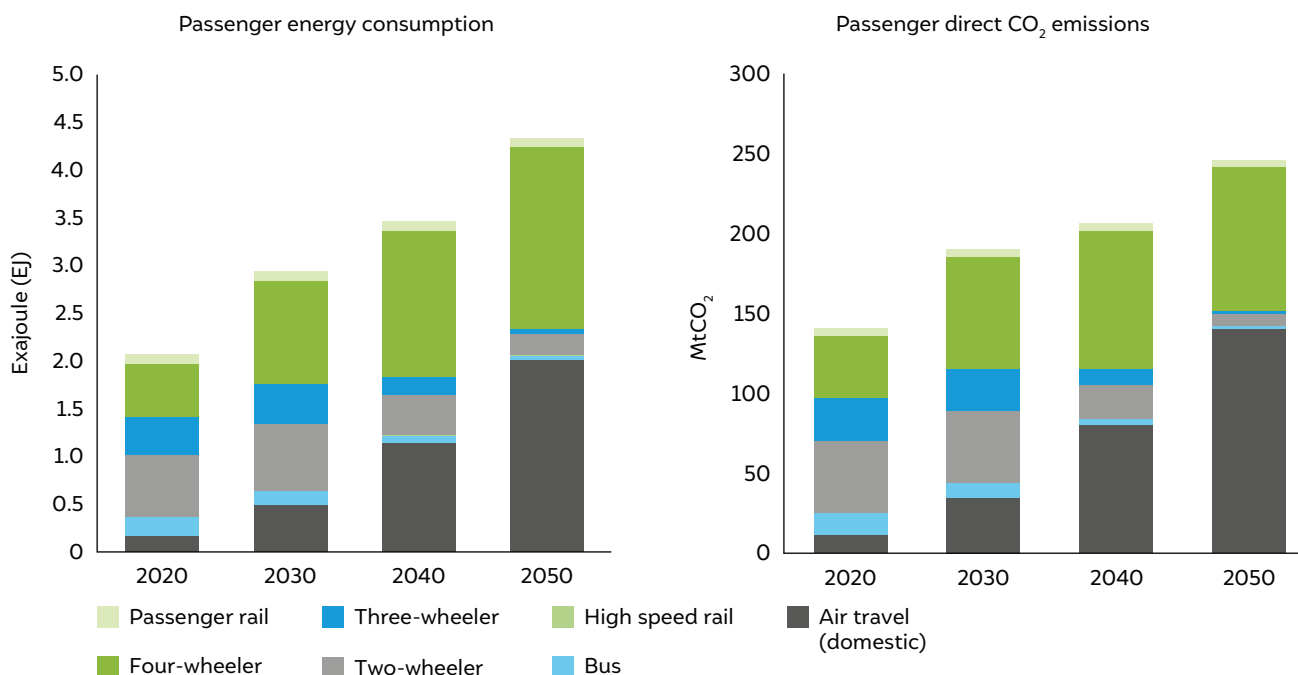Trucks   Ship domestic   Freight rail

Source: Authors' analysis based on GCAM-CEEW

3.4 Aviation will increase its share in transport energy use and emissions

Historically, oil dominates the Indian transport sector's energy use; our outlook shows that this will not be the case in the future. With growing energy demand, the sector's energy mix will also diversify. The transport energy demand is expected to grow by more than three times from nearly 4 EJ in 2020 to more than 13 EJ in 2050, and the share of oil in the total transport energy consumed will reduce from 95 per cent in 2020 to 66 per cent in 2050. The shift in the fuel mix will come from the increase in the share of natural gas (from 3 per cent to 25 per cent) and electricity (from 2 per cent to 9 per cent). Most of the oil consumption will be by domestic aviation in the passenger segment and trucks in the freight segment.

Domestic aviation, a marginal source of emissions in 2020, will become highly critical for the decarbonisation of the Indian transport sector. By 2050, the share of domestic aviation in energy use and emission will grow significantly to almost half of the energy use and an even higher percentage of passenger transport emissions. This is not just because of the high emission intensity of air travel but also due to the zero direct emissions and low energy intensity of the electrified road transport sector, which is expected to expand rapidly in the decades to come. The air travel sector in India has been growing consistently over the years, and this is likely to accelerate with rising income levels. Our outlook highlights that domestic air travel will significantly impact the sector's energy use and decarbonisation efforts due to the relatively poor fuel efficiencies of air travel compared to other modes of transport.

Figure 9 Fast electrification of passenger transport means that the share of airlines in energy use and emissions will significantly increase by 2050

Passenger energy consumption

Passenger direct CO_2 emissions

Legend:
- Passenger rail
- Four-wheeler
- Three-wheeler
- Two-wheeler
- High speed rail
- Bus
- Air travel (domestic)

Source: Authors' analysis based on GCAM-CEEW

3.5 Passenger vehicle growth will have significant implications for congestion

There is significant potential for limiting and reducing the energy used and emissions produced by the transport sector by electrifying the passenger fleet. Investing in support infrastructure could contribute to reducing a substantial amount of energy use and emissions. As per this study, because of rapid electrification and the peaking of two-wheeler service demand, the share of CO_2 emissions by two-wheelers in passenger transport will decline from 32 per cent in 2020 to just 3 per cent by 2050. The rapid uptake of electric vehicles in the four-wheeler segment will nullify

the negative impact of their exponential growth and modal shift away from energy-efficient modes. However, the increasing number of on-road four-wheelers will have significant implications for congestion and infrastructure requirements.

3.6 Natural gas will have significant penetration in the truck segment

Trucks will continue to dominate energy consumption and CO_2 emissions in the freight sector (Figure 10). Emissions from trucks will grow slower than their respective energy consumption due to the increasing share of natural gas and a slight increase in the uptake of electric trucks in the last decade (Figure 11).

Figure 10 Transport energy consumption will be heavily dominated by trucks

Freight energy demand

Freight direct CO$_2$ emisions
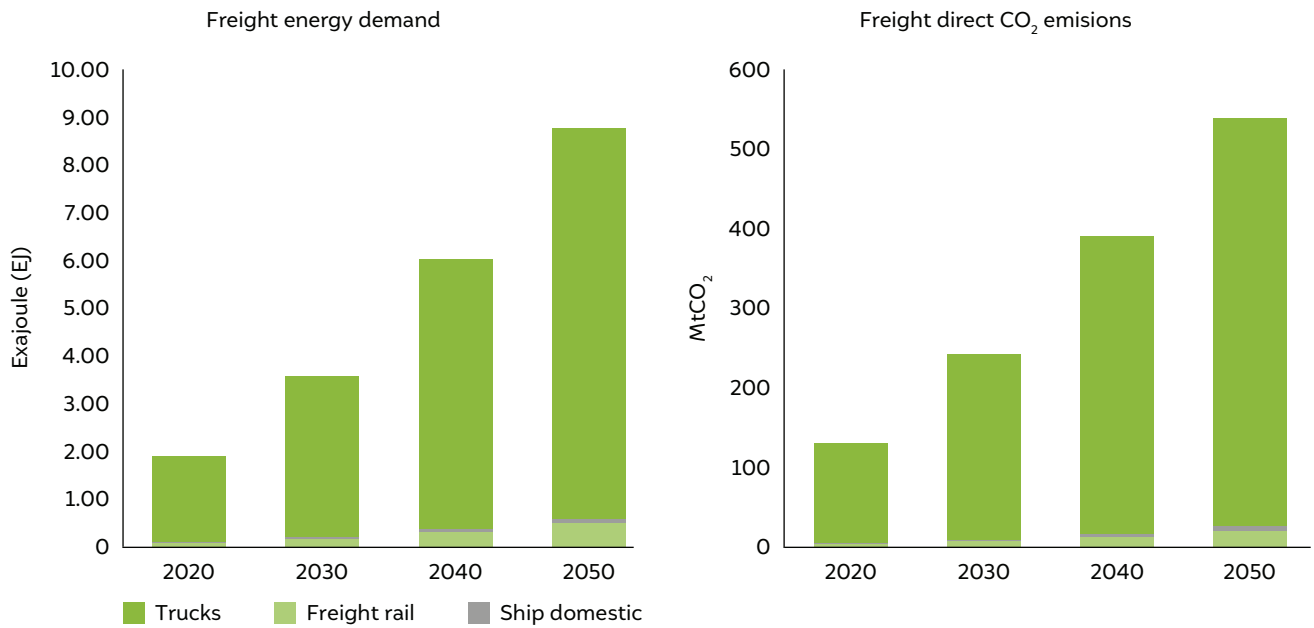
Source: Authors' analysis based on GCAM-CEEW

Even with low gas prices, we do not expect any immediate increase in the share of natural gas in trucks' fuel mix due to infrastructure bottlenecks. It will take a decade to build the required pipelines and infrastructure to see any meaningful gain in the share of natural gas.[6] However, in the last two decades, natural gas will gain a significant percentage of the trucking fuel mix. By 2050, natural gas is expected to account for 35 per of trucks' fuel mix. We estimate the slow uptake of electric trucks from 2030. The unavailability of equivalent electric trucks, in terms of the required range and upfront cost, remains the key bottleneck.

Figure 11 Liquid fuels and natural gas will become the two primary fuels for the trucks
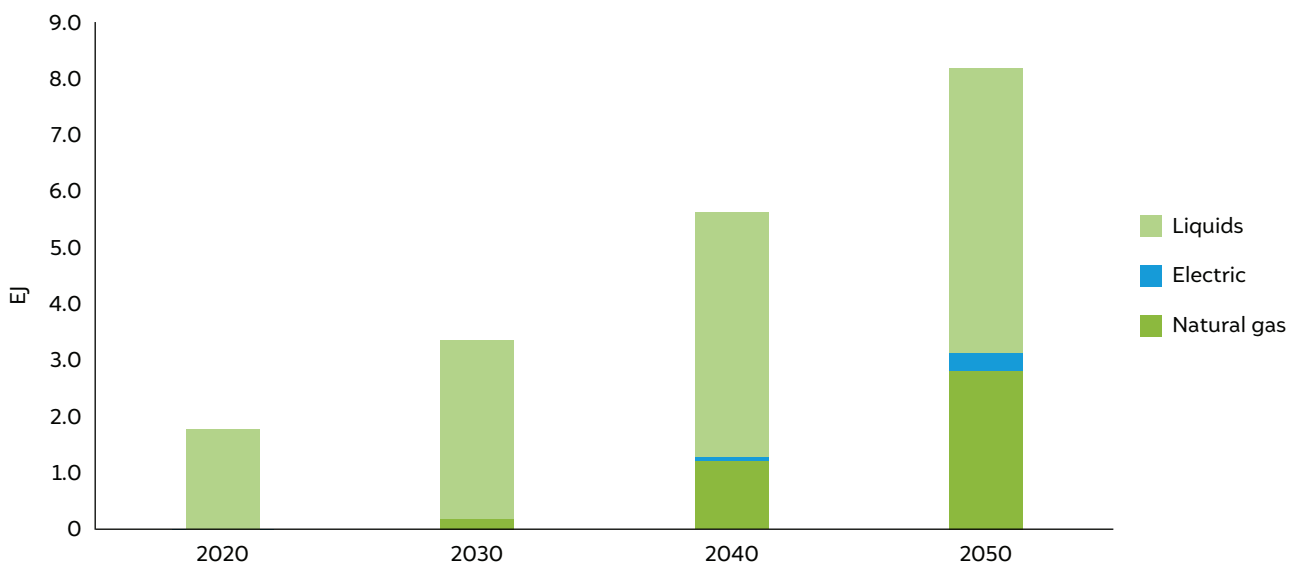
Source: Authors' analysis based on GCAM-CEEW

6 Government of India is building LNG fuelling stations along the golden quadrilateral – major highways across India (Ministry of Petroleum & Natural Gas 2020) – and is seeking comments for the inclusion of hydrogen-enriched compressed natural gas (HCNG) as an automotive fuel (Ministry of Road Transport & Highways 2020).

4. Conclusion

India's passenger and freight transport demand is growing at a fast pace with increasing per capita incomes. Along with growth, the sector is witnessing many path-defining changes that will have a significant impact on its evolution. Policymakers need to ensure that this transition, while increasing social welfare, does not impact society and the environment negatively. The sustainability implications of the impending structural changes, hence, have to be understood in a systematic way. Our transport outlook seeks to understand the impact of market forces on the evolution of India's transport sector and subsequently its energy use and emissions. We highlight the structural shifts that this sector will witness in the next three decades to inform policymakers as well as industry stakeholders. Policy has to intervene in specific niches to support and accelerate this transition while avoiding the pitfalls of unsustainable mobility behaviours driven by higher disposable incomes. We analyse conditions in the BAU scenario and do not explore the impact of a net-zero scenario. However, our results do reveal that pointed efforts, particularly in the freight and aviation sectors, are required to ensure that the transport sector is on course to realise a net-zero future and contributes to the objectives of jobs, growth, and sustainability of the Indian economy.

Annexure 1 Methodology and assumptions

Modelling framework – the Global Change Analysis Model (GCAM)

We use GCAM modelling framework, the CEEW version, for our analysis. GCAM has a detailed energy-sector module and a land-use module.

Figure A1 represents the schematic for GCAM. GCAM is housed at the Joint Global Change Research Institute (USA) and models 32 regions of the world with India as a separate region. The GCAM-CEEW version is an updated version of GCAM with changes in assumptions across sectors, as well as structural changes related to buildings and the transport sector. The electricity generation sector is modelled in detail in GCAM. GCAM-CEEW also captures a detailed representation of the building and transportation sectors and aggregate representation of the industrial sector. GCAM has been an important part of IPCC assessments on modelling-related literature and has been used extensively for national and international exercises for over three decades. Modelling analysis based on GCAM has been extensively published in high impact international journals. GCAM does not model the impact of energy and climate systems on economic variables like GDP, investments, etc. Currently, GCAM-CEEW is one of the in-house models of CEEW, India.

Figure A1 Schematic representation of the Global Change Analysis Model (GCAM)
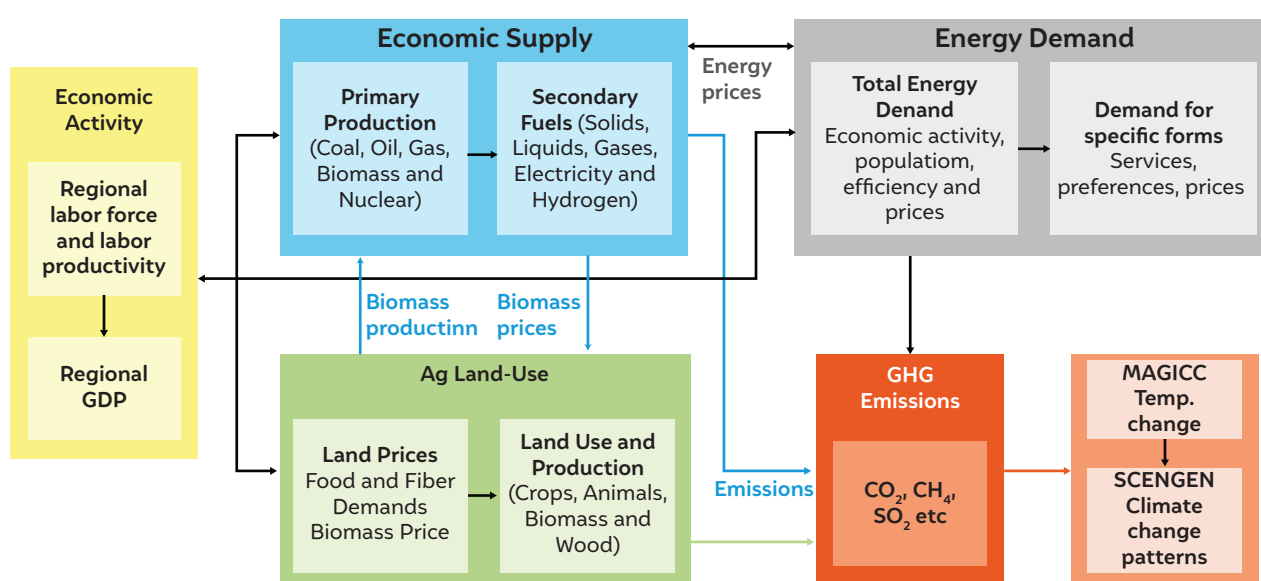
Source: Reproduced from the Joint Global Change Research Institute/Pacific Northwest National Laboratory, USA

Modelling transport as an end-use sector

The energy demand in the transportation sector is modelled for passenger transport (road, rail, and aviation), freight transport (road and rail), and international shipping, with the demand for each service being driven by per capita GDP and population. Each type of service demand is met by a range of competing modes. For passenger transport, two-wheelers, three-wheelers, cars, buses, railways, and aviation compete with each other for providing passenger services. Changes in modal shares in the future depending on the relative costs of the different options is modelled using a logit choice formulation. Costs in the passenger sector include the time value of transportation, which tends to drive a shift towards faster modes of transport (light-duty vehicles, aviation) as incomes increase.

In the core GCAM (global version available for the research community's use), many of the modes (including light-duty vehicles) include competition between different vehicle types, which also uses a logit choice mechanism that is calibrated to base-year shares; for example, in GCAM, the passenger car segment comprises four types of cars. In GCAM-CEEW, the structure has been simplified to represent only one type of car with different fuels. GCAM incorporates the impact of non-economic barriers, such as infrastructural constraints for new and emerging technologies (such as electric or hydrogen vehicles). It does not place hard constraints on the uptake of any technology. In GCAM-CEEW, population and per capita income are the exogenous drivers of passenger service demand expressed in passenger-kilometres (pkm), while GDP is the driver of freight demand.

Further, in GCAM-CEEW, passenger service demand by mode is estimated endogenously, based on the total travel costs (monetary cost per passenger kilometre, e.g., INR/pkm) by mode, fuel, technology, and time cost of travel, which is a function of the average hourly wage rate of the employed population, the mode-specific value of travel time (VTT), and travel speed. The passenger service demand (D_p) in region r and future time-period t is represented as follows:

$$D_p^{r,t} = \sigma^r \left(Y_i^{r,t}\right)^{\alpha} \left(P_i^{r,t}\right)^{\beta} \left(N_i^{r,t}\right)$$

where σ is the base year (2010), calibration parameter Y_i is the index for income in the form of per-capita GDP (defined on PPP basis) at time "t", divided by the per capita GDP in the base year. P_i is the index of the price of transportation (or generalised user cost) aggregated across all modes, size classes, and technologies and calculated as the ratio of price in time "t" to the price in the base year. N_i is the population in region r and time t. α and β are income and price elasticities, respectively, concerning per capita passenger demand.

Freight service demand is calculated based on simple functions of population, GDP, and fuel prices in the GCAM-CEEW. Freight trucks (five categories in the global version, while one representative category is used in the GCAM-CEEW version) and railways compete for servicing freight demand in the GCAM-CEEW. The rate of efficiency improvement of each represented vehicle technology is exogenous in the GCAM-CEEW. Details related to transportation in the GCAM can be found in Kyle and Kim (2011) and Mishra et al. (2013). A brief explanation is given below. The freight transportation demand (D_F) in region r and future time period t is estimated similarly:

$$D_f^{r,t} = \sigma^r \left(GDP_i^{r,t}\right)^{\alpha'} \left(P_i^{r,t}\right)^{\beta'}$$

where α' and β' are the income and price elasticities for the freight demand.

The total cost of any passenger/freight mode (P_i) in the region r and time period t is estimated as follows:

$$P_{i,r,t} = \frac{(FP_{i,r,t})(I_{i,r,t}) + NFP_{i,r,t}}{LF_{i,r,t}} + \frac{W_{r,t}}{S_{i,r,t}}$$

where FP is the fuel price, I is the vehicle fuel intensity, NFP is the vehicle non-fuel price, LF is the load factor (persons per vehicle), W is the wage rate, and S is the vehicle speed.

Fuel prices are endogenous and include the impact of emissions penalties (e.g., carbon price) depending on the scenario. All other variables are exogenously specified for each technology and time period. The fuel intensity and non-fuel costs of any single technology in the GCAM are exogenous. Future technological improvements and cost declines assumed for any technology may therefore be attributable to a variety

of sources that are not disaggregated explicitly in the model. The non-fuel cost includes the capital cost, maintenance costs, insurance and registration, and a variety of other costs, discounted and levelised per vehicle kilometre. The load factor represents the average number of passengers in each vehicle. The wage rate is calculated as the per-capita GDP divided by the number of working hours in the year. Vehicle speed represents the average door-to-door speed for the mode.

The market share of individual modes is determined endogenously in the model based on the following formulation:

$$S_{i,r,t} = \frac{(SW_{i,r})(P_{i,r,t})^{\lambda}}{\sum_{i}^{n}(SW_{i,r})(P_{i,r,t})^{\lambda}}$$

where *SW* is the share weight, *P*i is the cost of transport service, *λ* is a cost distribution parameter, and *n* is the number of modes in the given sector. The share weight is a calibration parameter, and the cost distribution parameter regulates the degree to which future price changes will be reflected in modal shifts.

Socio-economic and demographic assumptions

GDP and population are the two underlying drivers that influence energy demand from all energy-consuming sectors and hence impact overall greenhouse gas (GHG) emissions. These are the primary variables that determine passenger and freight mobility demand (LBNL 2009; Paladugula et al. 2018; Keramidas et al. 2017). They are the key exogenous variables in our analysis as well for driving overall passenger service and car demand.

Population projections are in a similar line with the UN population projections (medium variant) for India. India's population is assumed to reach 1.5 billion in 2030 and 1.6 billion by mid-century. Our GDP assumption represents a high growth scenario for India and per capita income growth from thousand 2015 USD 1.6 to thousand 2015 USD 10.5 in 2050. However, we have considered the impact of the COVID-19 pandemic, which resulted in a negative growth rate in 2020 and a V-shaped recovery in the next year as estimated by the Government of India (MoF 2021).

Table A1 Socio-economic and demographic assumptions

	2015	2020	2030	2040	2050	Units
GDP	2118	2505	5375	10363	17143	Billion 2015 USD
GDP CAGR*	6.8%	3.4%	7.7%	6.5%	4.7%	Per centage
Population	1310	1380	1504	1593	1639	Million
Per capita income	1617	1815	3574	6506	10458	2015 USD
Urbanisation rate	32.7%		39.9%		50.7%	Per centage

Source: Authors' compilation

*Note: The CAGR presented in the table is also a five-year time step variable. For instance, the growth rate shown in the column 2030 is the rate between 2025 and 2030. In the GCAM-CEEW's assessment, 2015 implies calendar year 2015.

Assumptions on the cost of transport technologies

Each technology's passenger service demand is determined by the model based on the total cost of the technology, including non-energy and energy costs. The energy cost of the technology is calculated endogenously by the model, based on fuel efficiencies. The non-energy cost, which includes the upfront capital cost and maintenance cost, is given exogenously to the model. We have tried to reflect real-world consumer behaviours while estimating the non-energy cost.

Following are the assumptions for calculating the non-energy cost for various technologies:

- Commercial vehicles (four-wheelers, three-wheelers, and buses) and economical two-wheelers (engine capacity up to 120 cc) represent the total cost of ownership across the vehicle's lifetime.

- Private four-wheelers and premium two-wheelers (engine capacity greater than 120 cc) cost represent upfront capital cost.

- As the model does not differentiate between commercially- and privately-owned cars and economic two-wheelers and premium two-wheelers,

we have taken a weighted average cost to reflect the above two assumptions in the model. The weighted average is calculated for four-wheelers based on the average hiftorical share of commercial four-wheelers registered in India in the last ten years. However, the weighted average for two-wheelers is calculated based on the sales data for various two-wheeler models in the past ten years.

- The capital cost for all vehicle categories reflects the latest market prices.

- The natural gas (NG) price regime reflects the increase in global supply following the US shale gas discovery.

Table A2 Assumptions on vehicle efficiency improvement

Vehicle Category	Fuel	CAGR		
		2020-2030	2030-2040	2040-2050
Four-wheeler (4W)	ICE - Oil	0.69%	0.67%	0.65%
	ICE - CNG	0.66%	0.64%	0.62%
	BEV	0.20%	0.20%	0.20%
Two-wheeler (2W)	ICE - Oil	0.30%	0.30%	0.30%
	BEV	0.61%	0.61%	0.61%
Three-wheeler (3W)	ICE - Oil	0.69%	0.67%	0.65%
	ICE - CNG	0.30%	0.30%	0.30%
	BEV	0.40%	0.40%	0.40%
Buses	ICE - Oil	0.82%	0.82%	0.82%
	ICE - CNG	0.82%	0.82%	0.82%
	BEV	0.93%	0.93%	0.93%
Trucks	ICE - Oil	0.16%	0.16%	0.16%
	ICE - CNG	0.16%	0.16%	0.16%
	BEV	0.16%	0.16%	0.16%
Freight Rail	Oil	0.02%	0.03%	0.03%
	Electric	0.02%	0.03%	0.03%
Passenger Rail	Oil	0.02%	0.03%	0.03%
	Electric	0.02%	0.02%	0.03%
Air travel (Domestic)	Oil	0.69%	0.56%	0.40%
International Aviation	Oil	0.69%	0.56%	0.40%

Source: Authors' compilation

Annexure 2 Modelled transport service demand

Table A3 Passenger transport service demand (billion pkm)

Category	2020	2025	2030	2035	2040	2045	2050
Air travel (Domestic)	61	113	198	329	497	700	927
Bus	641	599	509	416	346	293	246
HSR	-	-	101	158	224	291	350
2W	1,112	1,470	1,876	2,102	2,086	1,936	1,751
3W	489	548	590	582	498	382	271
4W	343	556	890	1,397	2,049	2,833	3,692
Passenger Rail	1,186	1,259	1,267	1,237	1,192	1,129	1,056
Non-motorised	1,216	1,061	924	813	727	654	590

Source: Authors' compilation

Table A4 Passenger transport service demand by vehicle type and fuel (billion pkm)

Vehicle type	Fuel	2020	2025	2030	2035	2040	2045	2050
4W	BEV	2	31	179	533	1,062	1,753	2,564
	ICE-Oil	329	456	564	632	673	689	679
	ICE-CNG	13	69	147	232	314	390	450
2W	BEV	38	185	781	1,249	1,565	1,609	1,556
	ICE-Oil	1,073	1,285	1,095	853	522	326	194
3W	BEV	2	12	71	204	287	293	235
	ICE-Oil	404	388	322	208	106	42	16
	ICE-CNG	83	149	197	170	104	47	20
Bus	BEV	0	1	10	52	101	128	131
	ICE-Oil	561	524	407	279	177	113	75
	ICE-CNG	81	73	91	85	68	53	41

Source: Authors' compilation

Table A5: Freight transport service demand (billion tkm)

Category	2020	2025	2030	2035	2040	2045	2050
Freight Rail	708	965	1,297	1,721	2,253	2,860	3,510
Ship Domestic	54	77	103	133	168	204	246
Trucks	1,443	1,983	2,682	3,510	4,435	5,400	6,368

Source: Authors' compilation

Table A6: Freight transport service demand by vehicle type and fuel (billion tkm)

Vehicle type	Fuel	2020	2025	2030	2035	2040	2045	2050
	BEV	0	1	4	14	43	111	218
Trucks	ICE-Oil	1,443	1,982	2,553	3,128	3,556	3,885	4,201
	ICE-CNG/LNG	-	-	125	368	837	1,404	1,949

Source: Authors' compilation

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The authors

Puneet Kamboj
pnt.kmbj@gmail.com

Ankur Malyan
malyanankur@gmail.com

Harsimran Kaur
h.kaur@theicct.org

Himani Jain
himani.jain@ceew.in

Vaibhav Chaturvedi
vaibhav.chaturvedi@ceew.in
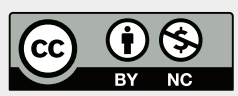
🐦 @puneetkmbj   🐦 @ankur_malyan   🐦 @harsimrankaur09   🐦 @Dr_VaibhavCh

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Peer reviewers:

Dr Ahm Mehbub Anwar, Senior Research Associate, King Abdullah Petroleum Studies and Research Center (KAPSARC), Saudi Arabia; Megha Kumar, Consultant, International Council on Clean Transportation (ICCT), India; and Vaibhav Pratap Singh, Programme Lead, CEEW, India.

Publications team:

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