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DECARBONIZING INDIA'S ROAD TRANSPORT: A META-ANALYSIS OF ROAD TRANSPORT EMISSIONS MODELS

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EXECUTIVE SUMMARY

In India, 90% of carbon dioxide (CO_2) emissions from transportation come from the road sector. Setting a precise goal for road transport decarbonization is thus important for helping to steer India closer to its overall climate commitment, and decarbonization offers significant co-benefits like cleaner air and related health and wellbeing gains. With this in mind, we undertook a meta-analysis of India's key road transport energy and emissions models and paid particular attention to the Business-As-Usual (BAU) and High Ambition scenarios. The information about energy use and emissions in this paper is intended as a starting point from which to draft a policy roadmap and a strong decarbonization target.

Significant variations were identified in the assumptions and estimations in the eight leading models reviewed, even in the BAU scenarios. Differences exist across models in 2020 baseline numbers and in all future years. Still, all models predicted a rapid growth in vehicle activity, varying from 4,000 to over 10,000 vehicle kilometers per year. On average, BAU scenarios predict energy consumption and CO_2 emissions will be 3.5–5 times higher in 2050 when compared with the level in 2020. In the High Ambition scenarios, even though energy use and emissions drop significantly when compared to BAU, only a few models expect emissions to peak within a decade or two. However, there was general consensus among models that significant electrification would take place across passenger vehicles, including in cars and buses, and that freight vehicles would be harder to electrify.

We also evaluated the impacts of COVID-19 on emissions and energy using ICCT's in-house model. The pandemic made a severe dent on vehicle sales and travel demand in India, and that shifted the energy and emissions trajectory of the road transport sector. The study explored additional policy efforts in an Aggressive Policy scenario, to estimate the extent to which the emissions curve could be bent down further. Results show that policy efforts could help India reach 45%–50% cumulative reduction in CO_2 emissions between 2021 and 2050, as compared to BAU. This could be achieved through efforts like mode shift and deeper grid decarbonization. Further, as shown in Figure ES-1, in the post-COVID situation, it is possible to achieve peak emissions of approximately 300 Mt CO_2 by 2030 under both the High Ambition and the Aggressive Policy scenarios.

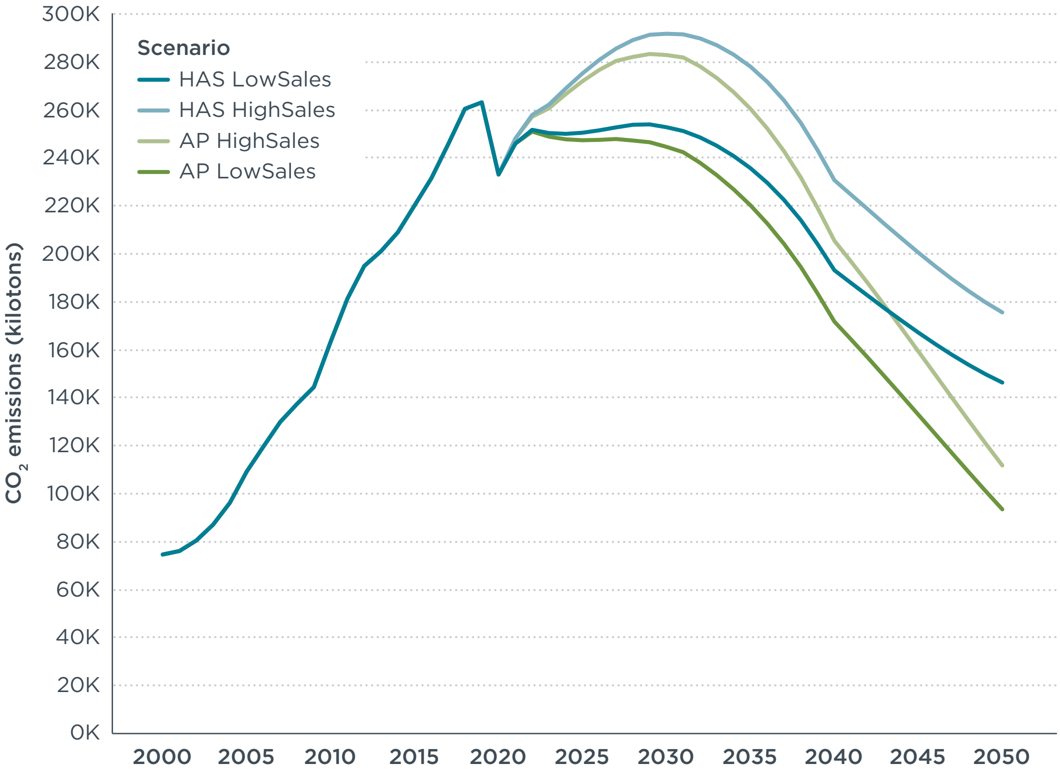

Figure ES-1. CO_2 emissions trajectory under alternate scenarios.
Note: HAS: High Ambition Scenario; AP: Aggressive Policy scenario

Based on these potential reductions, India should set a target of lowering emissions from road transport by 25%–50% below the 2020 level by 2050. Additionally, given the variations we found in the models, there is a need to institutionalize data collection for the transport sector. The data collection effort could be done by government bodies and include conducting periodic national-level travel surveys and an annual greenhouse gas inventory. These would be quite valuable because they would provide a better understanding of travel behavior, energy consumption, and emissions from the sector.

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INTRODUCTION

Transport is a key contributor to carbon dioxide (CO_2) emissions in India. It is 14% of energy-related direct (Scope 1) CO_2 emissions and one of the fastest growing emissions sectors in the country, along with industry (Godinho & Coetzee, 2020; International Energy Agency, 2020a). Within the transport sector, road transport is responsible for 90% of total energy consumption (Hagemann et al., 2020).

India's motor vehicle fleet has grown rapidly in recent years, and before the COVID-19 pandemic, the on-road vehicle stock was expected to almost double to over 200 million by 2030. At present, the energy used in road transport is mostly from petroleum, and the majority of that is imported (Bansal & Bandivadekar, 2013). Additionally, in its Nationally Determined Contribution (NDC) under the Paris Agreement, India has committed to reduce the emissions intensity of its gross domestic product (GDP) by 33% to 35% below 2005 levels by 2030 (Climate Action Tracker, 2020). While the government has accordingly defined economy-wide emissions reduction targets, thus far there are not any sector-specific targets for high-emitting sectors like industry and transport.

A policy roadmap and a strong decarbonization target for the road sector would steer India closer to its climate commitment, and decarbonization offers significant co-benefits like cleaner air and related health and wellbeing gains. Such a roadmap would need both strong ambition and to be accompanied by a feasible action plan. However, the data about energy use and emissions that could provide the groundwork for such a roadmap is still lacking.

With this in mind, we undertook a meta-analysis of India's key road transport energy and emissions models. The models analyzed were developed by research organizations and use well-established modeling frameworks. This work fills a gap, as currently there are few studies that attempt to compare modeling frameworks and energy and emissions projections across different models of India's transport sector (Paladugula et al., 2018; Srinivasan et al., 2019). This paper additionally goes beyond the scope of earlier work by providing a comprehensive evaluation of the baseline and mitigation scenarios in the models, and by comparing key assumptions, energy use, and emissions by vehicle and fuel type from a large number of models. We further include the impact of the COVID-19 pandemic on the energy and emissions trajectory in India and answer the critical question of how much emissions reduction could be achieved from the road transport sector through aggressive policy efforts.

SCOPE AND METHODS

This study is confined to the road transport sector, excluding railways, and compares key inputs, assumptions, and outputs across the eight models shown in Table 1. Given the significant differences in data availability across models, we present the trends across three key parameters—vehicle activity, energy consumption (final energy), and CO_2 emissions, the latter of which are tailpipe emissions only in most cases—between 2010 and 2050 at decadal intervals. These trends are further disaggregated by vehicle and fuel type wherever such data was available.

Table 1. Details of the models analyzed.

Research group	Model name	Baseline year[a]	Source of data
Council on Energy, Environment and Water (CEEW)	Global Change Analysis Model (GCAM)-CEEW version	2010	Compiled data received from Sustainable Growth Working Group (SGWG)[d]
Center for Study of Science, Technology and Policy (CSTEP)	Transport activity wise India Multi-region Demand Model	2015	Compiled data received from Sustainable Growth Working Group (SGWG)[d]
Pacific Northwest National Laboratory (PNNL)	GCAM	2015	Compiled data received from Sustainable Growth Working Group (SGWG)[d]
Integrated Research and Action for Development (IRADe)	Activity Analysis Model	2010	Compiled data received from Sustainable Growth Working Group (SGWG)[d]
The Energy & Resources Institute (TERI)	Transport Demand Model	2015	Compiled data received from Sustainable Growth Working Group (SGWG)[d]
International Energy Agency (IEA)	Mobility Model (MoMo)	2020[b]	India Energy Outlook 2021
International Transport Forum (ITF)	ITF	2015[b]	ITF Transport Outlook 2019 and data received from ITF pertaining to 2019
International Council on Clean Transportation (ICCT)	India Emissions Model (IEM)	2018[c]	Based on IEM

[a] Baseline year was estimated using CO_2 emissions trajectories from alternate scenarios. The year from where trajectories for alternate scenarios diverged was considered to be the baseline year.
[b] There is limited data available for the IEA and ITF models. The discussion in this paper is based on data received from ITF pertaining to year 2019 and from ITF (2019). Most of the data for IEA is derived from IEA (2021).
[c] The pre-COVID analysis is based on IEM's 2018 baseline year.
[d] Under the SGWG, five modeling teams (CEEW, CSTEP, PNNL, IRADe, and TERI) worked together on an inter-model comparison study under the aegis of NITI Aayog. Hence, their modeling inputs and outputs were compiled together.

The models analyzed used a variety of approaches to estimate energy and emissions from road transport: some were top-down in approach, while others used bottom-up estimates. Both top-down and bottom-up models are useful in certain applications (Nursimulu, 2015). Generally, top-down models are used to conduct economy-wide energy analysis with the help of macroeconomic data. Such models focus on the interaction between the economy and the energy sector and include feedback effects. These are generally considered better for understanding the effect of different economic scenarios on energy and the environment. Bottom-up models, meanwhile, depend on end-use energy consumption, data that is generally difficult to obtain but provides a better level of detail and spatial resolution for each specific sector. They typically do not capture the impacts of structural changes in the economy and such models are preferred for conducting detailed energy planning at the sectoral or sub-sectoral level. Table 2 provides an overview of key attributes of the different models analyzed in this study.

Table 2. Overview of the approaches of the models analyzed.

Organization	CEEW	CSTEP	PNNL	IRADe	TERI	IEA	ITF	ICCT
Model name	GCAM-CEEW	Transport activity wise India Multi-region Demand Model	GCAM	Activity Analysis Model	MARKAL Transport Demand Model	Mobility Model	ITF modeling framework	India Emissions Model
Modeling approach	Top-down	Bottom-up	Top-down	Top-down	Bottom-up	Bottom-up	Bottom-up	Bottom-up
Model tool	Logit choice model	Excel-based model	Logit choice model	Linear programming model	Excel-based national macro transport model	Excel-based transport model	Excel-based model	Python

In terms of modeling tools, CEEW and PNNL use the Global Change Assessment Model (GCAM). In this model, energy use and emissions are estimated using passenger and freight transport demand that is itself assessed using GDP and population projections for future years. Mode share and fuel share are typically estimated using probabilistic cost curves and S-curves are used to determine the lifetime of different technologies.

IRADe relies on an Activity Analysis model based on the input-output framework which uses a social accounting matrix. CSTEP uses The Integrated MARKAL EFOM System (TIMES) model to assess economy-wide energy use. However, transport is considered a separate demand-side sector module and is soft linked to the TIMES model such that transport energy demand feeds into the TIMES model. CSTEP's is an accounting model based on IEA's activity-structure-intensity-fuel carbon (ASIF) framework built on Excel (IEA, 2017). It is also soft linked to the TIMES model. The ASIF framework uses Activity (passenger or freight travel, including vehicle travel and load factors), Structure (mode split), and energy Intensity (Fuel consumption per unit km of vehicles, combined with load factors) to estimate energy and emissions. The activity level in these models is usually calculated as a function of population growth and GDP growth. In CSTEP's model, assumptions related to mode and fuel shares and fuel intensities are borrowed from the business-as-usual (BAU) scenario of NITI Aayog's India Energy Security Scenarios, 2047 (IESS) calculator (NITI Aayog, 2015). TERI, IEA, ITF, and ICCT also use the bottom-up ASIF framework to estimate energy and emissions from the transport sector (Qamar, 2021; IEA, 2020b; ITF, 2021; ICCT, n.d.). While TERI and IEA rely on an Excel-based tool, ICCT uses a Python interface.

Description of scenarios evaluated

Our analysis includes each model's BAU and mitigation scenarios, and the latter group typically includes scenarios being characterized as Moderate and High Ambition. For the most part, the BAU scenarios reflect the extension of current trends without considering any new policy intervention or considering only limited new policy intervention. Meanwhile, the Moderate and the High Ambition scenarios consider that policy improvements in the future will reduce emissions intensity. The Moderate scenarios consider that existing policies are achieved to some degree and, in some cases, also incorporate ambitions that have not yet been implemented. Broadly, this could be assumed to be a moderate-effort scenario. The High Ambition scenarios are the highest effort and assume that existing policy targets would be far exceeded. The table below describes the scope of the mitigation scenarios, as defined by different modeling teams.

Table 3. Description of mitigation scenarios

Modeling team	Moderate Ambition	High Ambition
Sustainable Growth Working Group (SGWG)[a]: CEEW, PNNL, IRADe, CSTEP, and TERI	Supposes that policy targets, as already announced by the Government of India, are fully effective (called New Policy scenario)	Considers success far exceeding that envisioned in policy targets set by the Government of India
IEA	Incorporates policy ambitions and targets that have been legislated for or announced by the Government of India and by other governments around the world (called Stated Policies scenario)	Under this scenario, India is on track to reach net-zero emissions in the mid-2060s (called Sustainable Development scenario)
ITF[b]	—	This scenario incorporates more ambitious decarbonization policies
ICCT	Includes moderate effort above and beyond existing adopted policies	Incorporates ambitious decarbonization policies aligned with state-of-the-art policies adopted around the world

[a] The five modeling teams worked together on an inter-model comparison study organized as part of the SGWG under the aegis of NITI Aayog. Hence, these teams share some of their assumptions and interventions. The findings of this work were released in 2019.
[b] ITF does not have a Moderate scenario

Also, not all models analyzed incorporated a BAU, Moderate Ambition, and High Ambition scenario. We analyzed all three scenarios for CEEW, CSTEP, IRADe, PNNL, TERI, and ICCT, but only had access to Moderate and High Ambition scenarios for IEA and only the BAU and High Ambition scenarios for ITF. Further, because the goal of this work is to identify decarbonization targets for the road transport sector, after a brief review of BAU scenarios, this paper mostly focuses on the High Ambition scenarios, which align closer with a 1.5° C path.

PRE-COVID-19 ANALYSIS – ALL MODELS

BAU SCENARIOS

For the most part, the BAU scenarios project energy and CO_2 emissions considering only current trends and policies and no further policy improvements. There are exceptions, however, and the assumptions were not entirely consistent across models. Some models incorporated a degree of efficiency improvement or accounted for near-term policies that have been legislated but not yet implemented. For instance, no efficiency improvements were considered in IRADe's BAU scenario, but fairly large efficiency improvements were built in by CSTEP, CEEW, and PNNL for all years till 2050. Additionally, in ICCT's BAU scenario, near-term fuel efficiency improvements as adopted by the Government of India until 2022 were incorporated.

There were also variations across BAU scenarios in terms of assumptions regarding alternate fuel technologies and mode share. Some models built in incremental change in these assumptions, but others kept these assumptions rather static. Despite these variations, the comparison under BAU scenarios broadly presents the expectation of energy consumption and CO_2 emissions growth in India with minimal policy interventions.

Vehicle activity under the BAU scenario

Most of the models have vehicle activity increasing 3 to 3.5 times between 2020 and 2050, from 1,800 billion vehicle kilometers traveled per year (vkt/year) on average in 2020 to an average of approximately 5,000 billion vkt/year in 2050 (Figure 1). However, CSTEP and IRADe expected much higher vehicle activity, close to 10,000 billion vkt/year in 2050. CSTEP's high estimates might come from its GDP assumptions, which were the highest among all the models across all years. As vehicle activity is estimated as a function of economic growth, a high GDP assumption directly translates to a high vehicle activity level (Paladugula et al., 2018). An exceptionally high eight-fold increase in vehicle activity for IRADe is likely a result of a massive increase in car use and a decline in public transport use. While this type of trend is mostly present across models, in IRADe's case, the shift from buses to cars is extremely pronounced.

Across models, about 80%–90% of vehicle activity was from passenger transport and the rest was from freight. As we segregated vehicle activity by modes, we found large differences among different vehicle categories and these differences not only existed for future years but also for baseline years. Irrespective of these variations, what stood out was that two-wheelers and passenger cars contributed to around 65% of vehicle activity both in 2020 and 2050, which implies huge dependence on personal vehicles. However, in most cases where data are available, the share of cars and two-wheelers reversed by 2050; while it was around 40% for two-wheelers in 2020, it became 20% or lower in 2050 whereas the contribution of cars on an average increased from around 30% in 2020 to 50% in 2050. Still, CSTEP and ICCT expected the share of cars and two-wheelers to remain similar in 2050 as in 2020.

Models mostly expected the share of buses in vehicle activity to drop from an average of 14% to a mere 2%. The only exception was ICCT's model, which expected the share of buses to grow marginally from 7% to 8%, which seems to be an optimistic assumption for the BAU scenario. Most models also expected vehicle activity from two-wheelers and three-wheelers to slow down after 2040. Here, too, the only exception was ICCT, which expected two-wheelers to continue growing at the same pace between 2040 and 2050 as in the previous decade.

Most of the models show freight activity growing at a faster rate between 2020 and 2050 than passenger activity, and this slightly increases the future contribution of freight activity to overall road transport activity.

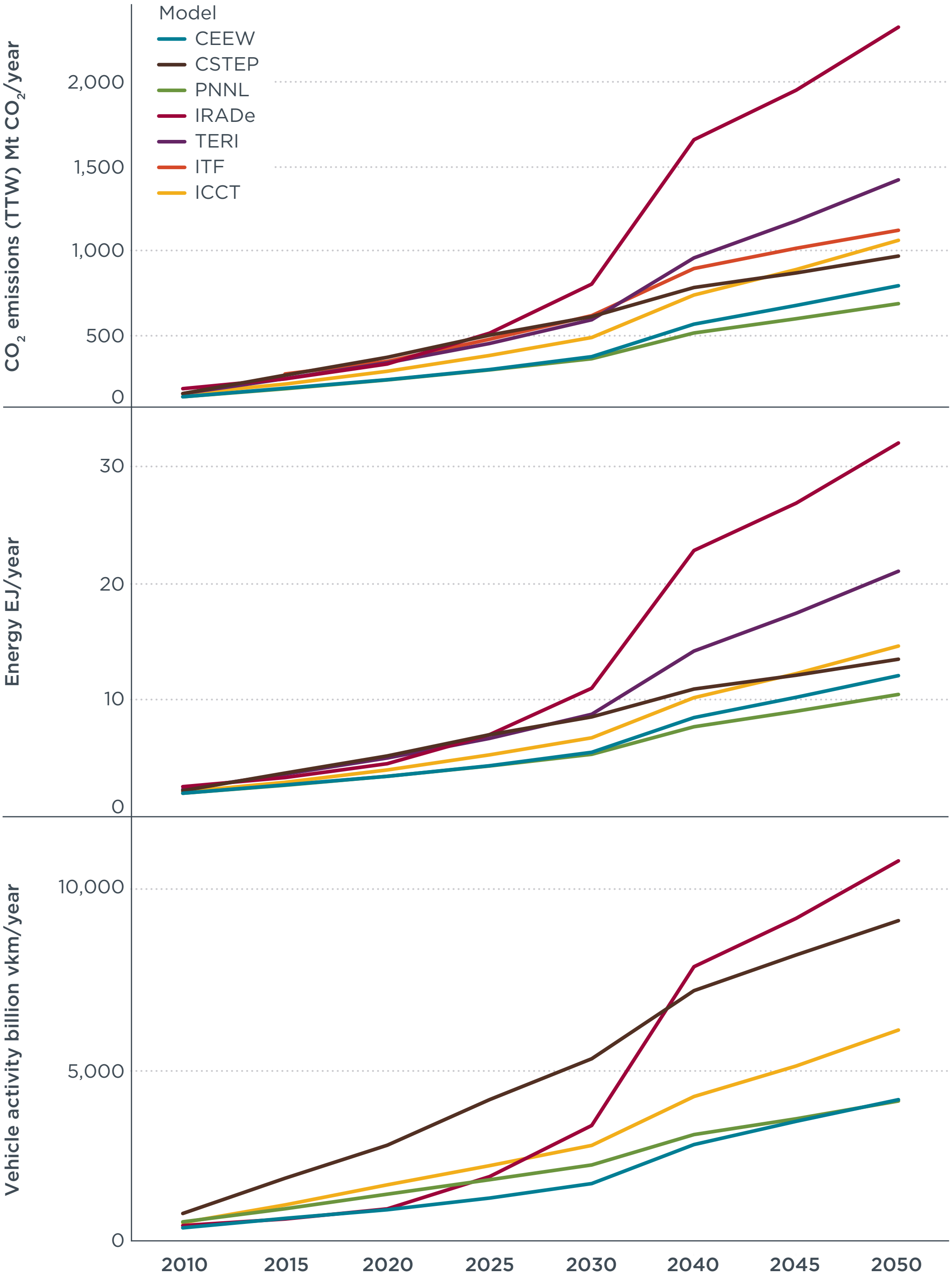

Figure 1. Key trends under BAU scenarios for India's road transport sector, as estimated by the different models.

Note: No BAU scenario was available from IEA.

Energy consumption under the BAU scenario

Significant increase in energy consumption between 2020 and 2050 was observed in the BAU scenarios. On average, the models expect energy consumption to rise from about 3.5–5 exajoules per year (EJ/year) in 2020 to 11–13 EJ/year by 2050. TERI and IRADe's models are outliers, and in those models energy consumption is 20–30 EJ/year by 2050. As can be seen from Figure 1, IRADe is the highest in 2050 and it is primarily due to high vehicle activity and high energy intensity assumption. The second highest energy consumption estimates for TERI can also be attributed to its high energy intensity and high vehicle activity assumptions for future years. Though vehicle activity estimates were not available for TERI, we did have passenger and freight activity estimates for TERI and some of the other models. Both passenger-kilometer (pkm) and tonne-kilometer (tkm) estimates were higher for TERI than for PNNL, CEEW, CSTEP, and IRADe. TERI's estimate of freight activity was especially steep—double the estimated tkm by IRADe, which had the second highest estimate in the group at 9,000 billion tkm per year in 2050. CSTEP and ITF had freight activity projections in a similar range as IRADe. CSTEP, PNNL, and CEEW had the lowest energy consumption projections for 2050 as these models assumed higher efficiency improvements or lower energy intensity for vehicle activity.

All of the models predict that the share of energy consumed by heavy-duty trucks (HDTs) will rise the most between 2020 and 2050, by 5%–10%, across most of the models. The only exception is IRADe's, where the rise in the share of cars is greater than the growth in energy consumption of any other mode.

In the majority of the models under the BAU scenario, petroleum remains the dominant source of energy for the road transport sector and it meets 90%–98% of energy needs in 2050 (Figure 2). CEEW, PNNL, and ICCT expect slight diversification of energy sources by 2050, but only compressed natural gas (CNG) is expected to play any significant role among the alternate fuel options; CNG could be catering to 30%, or to 10% or even less, of energy needs by 2050. Models show CNG mostly used to fuel three-wheelers, buses, and passenger light-duty vehicles. IRADe and PNNL expect the highest penetration of electricity, and it meets 1.5% of road transport's energy demand by mid-century.

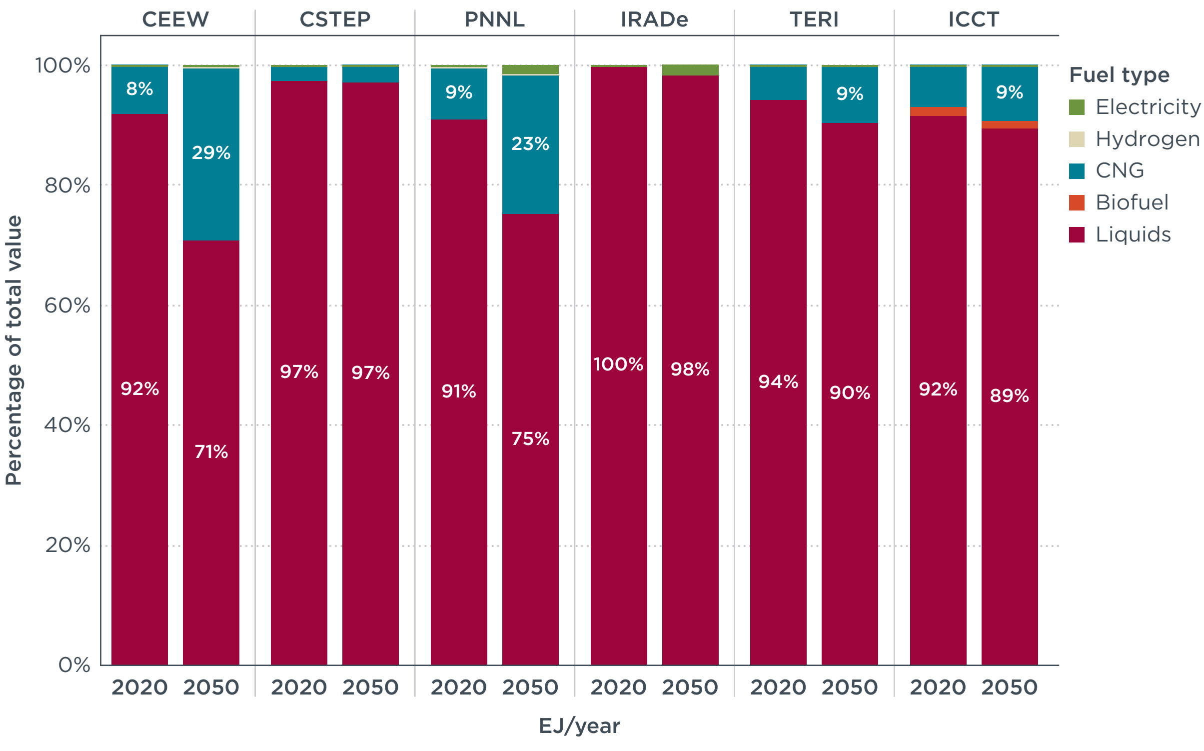

Figure 2. Energy consumption by fuel type in 2020 and 2050 in the BAU scenarios where such data was available.

Note that, in our analysis, "liquids" denotes fuels like gasoline, diesel, and liquid petroleum gas. In some cases, gasoline and diesel also include some percentage of biofuel. Due to the difficulty in separating these different fuel types across models, we merged them into a single category.

CO_2 emissions under the BAU scenario

CO_2 emissions would likely quadruple by mid-century in the BAU scenarios. Total CO_2 emissions from the road transport sector are mostly tank-to-wheel (TTW) emissions, and the only exception is ICCT's model, which includes electricity grid emissions for electric vehicles. CO_2 emissions are estimated to be around 300 million tonnes (Mt) in 2020 and, on average across the models, they reach 1,000 Mt by 2050. IRADe, however, projected emissions to be as high as 2,300 Mt in 2050 and this is due to its assumption of high energy consumption.

The contribution of freight transport to CO_2 emissions in 2050 is disproportionately high at 40%–50% or more, compared to its 10%–20% share of vehicle activity in 2020 (Figure 3).

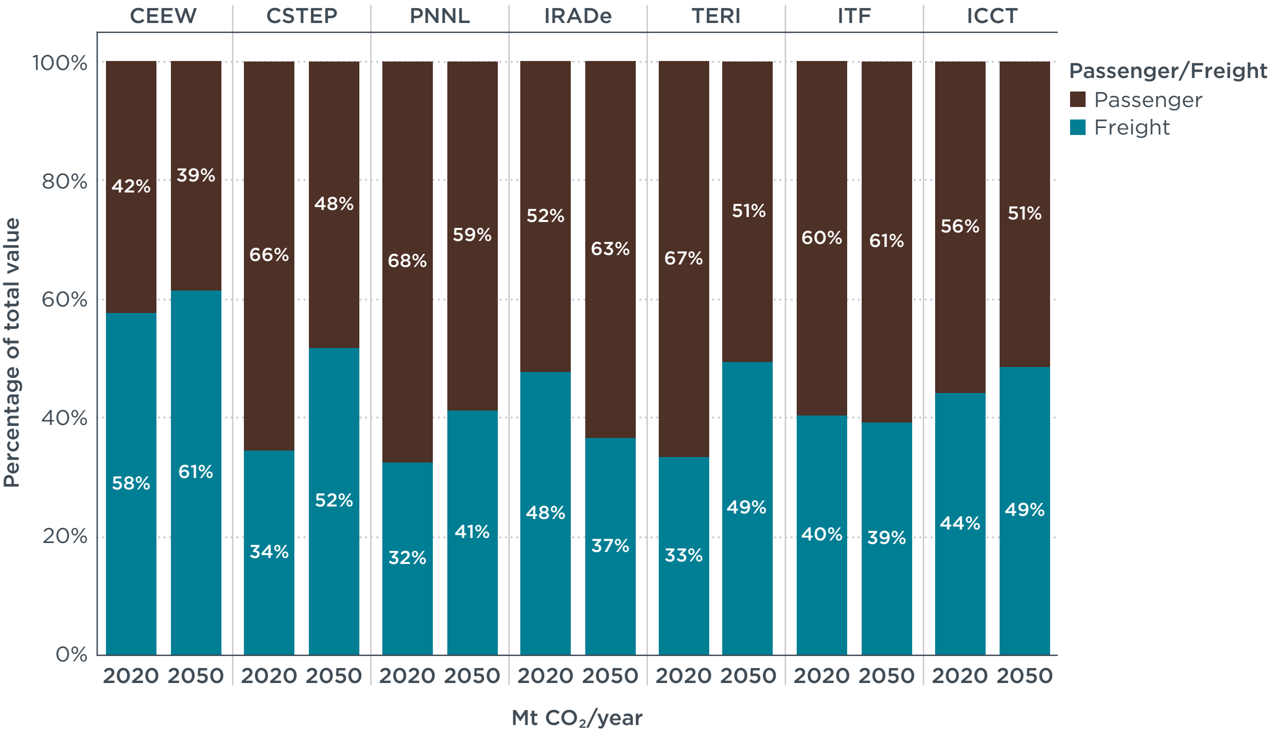

Figure 3. Contribution of passenger and freight transport modes to road transport CO_2 emissions in 2020 and 2050 under the BAU scenarios.

In terms of vehicle categories, HDTs and cars contributed almost 60% of total road transport emissions on an average, and most of the models expected these modes to remain the leading sources of emissions in 2050. In the absence of any intervention, the emissions share of these vehicles could increase to over 70% by mid-century. In ICCT's model, though, while the emissions from HDTs rise, emissions from cars and HDTs together remain around 60% in both 2020 and 2050.

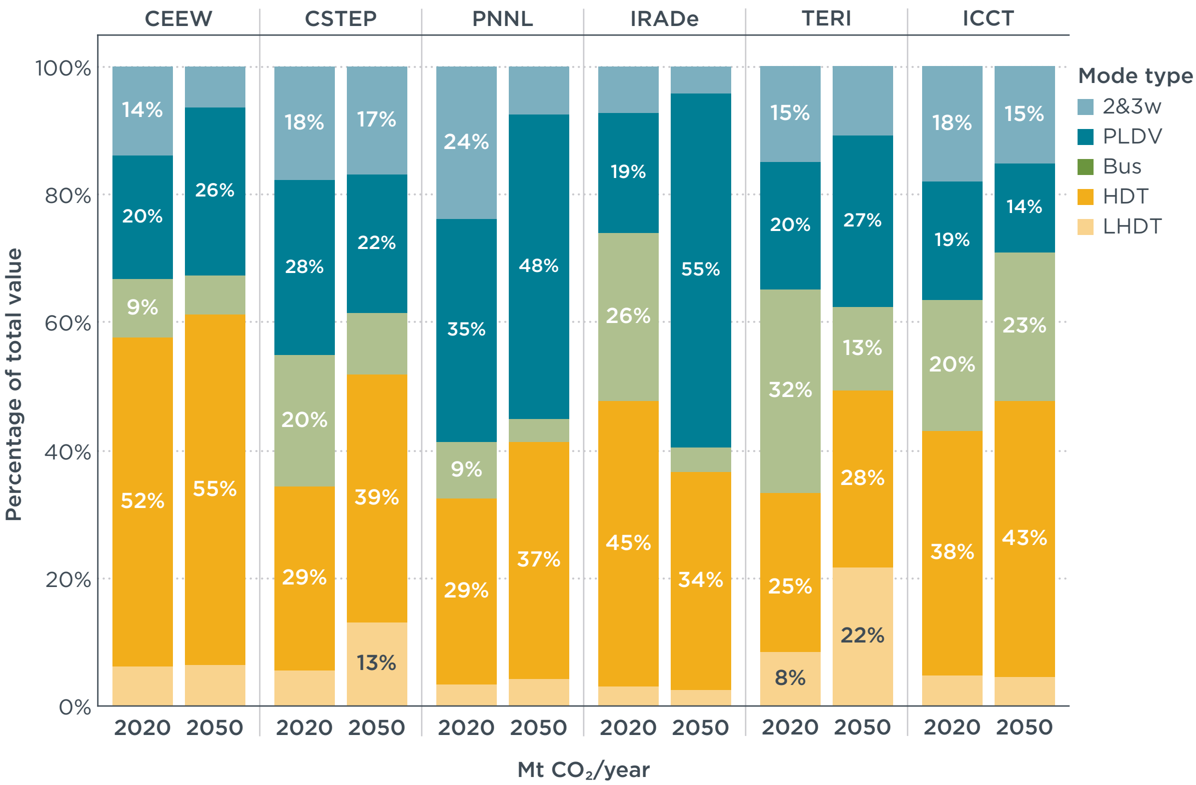

Figure 4. Contribution of different vehicle categories to CO_2 emissions in 2020 and 2050 in the BAU scenarios where such data was available.

Other challenges

It is clear from above that significant differences exist across models, and not just in future projections but also in baseline numbers. This points to a gap in terms of data on actual travel behavior, energy consumption, and emissions from the transport sector. Lack of understanding about these variables makes model validation challenging. Thus, if India were to develop an annual greenhouse gas (GHG) inventory of the road transport sector, it would be extremely useful.[1] Similarly, tracking energy consumption by sector by collecting end-use petroleum consumption data would also be valuable. Additionally, conducting periodic national-level travel surveys would provide a better understanding of people's travel behavior and how it changes with time.[2] It would be important to also institutionalize the data collection process so that such exercises become a mandate for an identified authority and are conducted periodically.

Key takeaways

Despite variations in assumptions and construct, the BAU scenarios all indicate an unabated rise in vehicle activity. The growth in vehicle activity is characterized by large dependence on personal vehicles, especially cars, and a decline in the share of buses. To meet increasing demand for mobility from the road transport sector, energy consumption in the BAU scenarios is expected to grow by three times or more between 2020 and 2050. Commensurate with the current trend, this transport demand is expected to be fulfilled largely by petroleum, with limited hope of alternate fuel technologies playing any significant role by 2050. Together these trends are likely to increase CO_2 emissions from road transport by at least three to four times by mid-

1 Such an exercise could be conducted along the same lines as the U.S. effort to estimate GHG emissions from various sectors. The Unites States Environmental Protection Agency has been undertaking an economy-wide exercise for the past two decades and tracks its GHG emissions and sinks by source, sector, and type of gas.

2 Many countries undertake similar surveys at regular intervals and these include the United Kingdom, Germany, and Australia. This is useful because official data can be used to validate a given model's baseline; in contrast, in the absence of official data, any such modeling work will be inherently limited.

century. The share of freight transport in vehicle activity, which contributed 30%–50% of CO_2 emissions in 2020, is expected to grow faster relative to passenger activity and could be contributing to 40%–60% of road transport CO_2 emissions by 2050.

HIGH AMBITION SCENARIOS

High Ambition scenarios in the models we analyzed include key interventions such as improvements in fuel efficiency, vehicle electrification, higher penetration of alternative fuels, and moderation of travel demand. Assumptions about how different policies would take shape in the future varied immensely across models and Table 4 provides an overview of the different interventions taken into account in the various High Ambition scenarios. Information concerning the assumptions in ITF's High Ambition scenario was not available.

Table 4. Interventions considered in the High Ambition scenarios (for 2050, unless otherwise specified).

Intervention	SGWG[a]	IEA (all for 2040)[b]	ICCT
Vehicle fuel efficiency			
Annual improvement	1.8%–2.7% between 2021 and 2030	Not available	1%–3% between 2021 and 2050
Electric vehicle share of new vehicle sales			
2W	80%	Not available	100%
3W	100%	Not available	100%
Cars	30%	90%	100%
Bus	40%	Not available	95%
Light-duty truck	0%	Not available	100%
Medium-duty truck	0%	Not available	90%
Heavy-duty truck	0%	Not available	90%
All	Not available	86%	~100%
Biofuel blending targets			
Bioethanol in gasoline	20%	Not available	20%
Biodiesel in diesel	5%	Not available	5%
Alternative fuel			
Fuels diversity	Electricity, compressed natural gas (CNG), biofuels, liquefied petroleum gas (LPG)	Electricity, CNG, biofuels, hydrogen	Electricity, CNG, biofuels
Other interventions			
	Reduction in vehicle activity (vkm): -5% to -10% in 2030; -15% to -20% in 2050 in comparison to BAU	—	Electricity grid decarbonisation: 2020: 613 gCO_2/kwh; 2050: 84 gCO_2/kwh

[a] The policy interventions for CEEW, PNNL, CSTEP, TERI, and IRADe were formulated under the SGWG. These assumptions only represent the highest ambition and not all interventions were adopted across all of the models. For instance, no electrification was considered by CEEW and CSTEP under their High Ambition scenarios.
[b] Data for IEA is derived from IEA (2021)

Note that some of the models with conservative electrification assumptions framed these scenarios some years ago, mostly under the SGWG exercise in FY 2018–19 or earlier. It is expected that many of the assumptions would be updated if reviewed today. The expectation with respect to electrification could especially rise across models in the wake of the positive developments in battery price reduction, the introduction of multiple electric vehicle models in the market, the emergence of new business models, and the launch of both central and state electric vehicle subsidies and incentive policies in India.

Also note that only IEA's numbers are recent enough to incorporate the COVID-19 pandemic. It is very likely that many of the models would now incorporate higher optimism with respect to policies like travel demand reduction and higher mode share for public transport. With respect to public transport, the opposite assumption is also possible. While higher public transport use might sound counterintuitive in the backdrop of the ongoing pandemic, it is possible that people might not wish to own private vehicles if they no longer need to commute daily, and this could induce a shift toward public transport, especially among the younger population. These revised assumptions would certainly further reduce energy and emissions from the sector.

One thing that stands out in Table 4 is how efficiency improvement assumptions for internal combustion engine (ICE) vehicles varied across models. While ICCT assumed efficiency improvements to continue until mid-century and at a greater pace, at 1%–3%, depending on vehicle category, CEEW, PNNL, CSTEP, TERI, and IRADe presumed that efficiency improvements of 1.8%–2.7% would cease after 2030.

IEA and ICCT assumed the highest levels of electrification across both passenger and freight vehicles, and the SGWG models had more conservative assumptions, especially regarding electrification of freight vehicles. As shown in Figure 5, most of the models considered the two- and three-wheeler segments as the frontrunners in vehicle electrification. ICCT and IEA's High Ambition scenarios expected cars to electrify following two-wheelers and three-wheelers. The SGWG models, meanwhile, expected higher electrification of buses than of cars. This is consistent with the government's strong policies in support of bus electrification under the Faster Adoption and Manufacturing of Electric Vehicles (FAME) scheme and also international experience pointing in the same direction (Dallmann et al., 2021; Heid et al., 2018). Similarly, while some of the models had almost no expectations for the electrification of freight vehicles, ICCT and IEA were positive on it and expected high electric truck uptake by mid-century, not only in the light-duty segment but also in the medium- and heavy truck segments. ICCT expected around 90% of light-duty trucks and over 60% of medium and HDTs could be electrified by 2050; exact values were not available for IEA.

Figure 5. Energy consumption by different vehicle categories by fuel type, where such data was available.

Note: Information for IEA was not available

Biofuel blending also played a role. ICCT and SGWG models assumed that India would meet a 20% bioethanol and 5% biodiesel blending target in 2050. However, biofuels are only a fraction of total gasoline and diesel consumption, and the use of both is expected to decline over time, anyway; for that reason, biofuels are not especially significant by 2050, when they are catering to less than 2% of road transport demand.

In terms of fuel diversification, most models consider that only electricity and CNG play any noteworthy role. Other fuels like hydrogen and liquefied petroleum gas (LPG) would remain almost inconspicuous in consumption. However, the latest projections by IEA under the India Energy Outlook 2021 expected CNG, electric hybrid, electric, and hydrogen fuel cell electric vehicles to constitute around 50% of the freight vehicle stock by 2040; the other half would still be diesel. As per ICCT's model, 36% of the freight vehicle stock would be electric and 2% would be CNG in 2040. By 2050, ICCT projected that around 70% of the freight vehicle stock would be electric.[3]

Other strategies adopted for decarbonization included moderation of travel demand and grid decarbonization. Some of the SGWG models considered a reduction of 15%–20% in travel demand by 2050 in comparison to the BAU scenario. In the case of ICCT, decarbonization of the grid was considered a critical strategy in addition to vehicle electrification. The carbon intensity of electricity was assumed to fall from the current 613 gCO_2/kwh to 84 gCO_2/kwh by 2050. This reduction is based on the assumption that by 2050, 89% of the electricity would be generated from renewable energy sources (Sen et al., 2021).

3 Sales share information for IEA was not available. ICCT assumed that 100% of new light-duty truck sales and 90% of medium and heavy-duty truck sales would be electric in 2050.

Vehicle electrification would undoubtedly yield the greatest emissions reduction benefits if the vehicles were powered by a low-carbon grid. However, we observed significant differences across models in terms of their recommendation regarding when India should start aggressive vehicle electrification. Some of the modeling teams suggested that India should place higher policy priority on strategies like mode shift and delay electrification of the road transport sector until India's grid becomes cleaner. However, Bieker (2021) estimated that well-to-wheel CO_2 emissions of average medium-size electric cars registered in India in 2021 will be lower over their lifetimes than their ICE counterparts, even though a substantial portion of India's electricity is currently generated from coal. Moreover, India is deploying renewables at a healthy rate and has set a target in its Nationally Determined Contribution (NDC) to have 40% of installed capacity of electric power in 2030 be from non-fossil sources (Climate Action Tracker, 2021). The benefits of vehicle electrification in India would be maximized if efforts are undertaken without any delay (Sen et al., 2021).

Further, that models are continuously updated to reflect the latest policy efforts and technological advancements has significant implications for the High Ambition scenarios. Recall from Table 1 that while some of the models are a bit dated, others have been updated recently. That might explain some of the variations in expected level of adoption of different policies. These differences are clearly visible in assumptions like the level of electrification expected, especially across freight vehicles. Models like IEA and ICCT, which have been updated more recently, have a more positive outlook on this.

Vehicle activity under the High Ambition scenario

As mentioned in Table 4, some of the models consider travel demand reduction. CEEW and PNNL considered a moderate level of reduction (-17%) in vehicle kilometers traveled under their High Ambition scenarios in 2050 as compared to their BAU scenarios (Figure 6). This reduction was much smaller (-12%) in case of IRADe. ICCT did not incorporate any travel demand reduction in its High Ambition scenario and hence its vehicle activity is the same for the BAU and High Ambition scenarios. Data on vehicle activity was not available for other models.

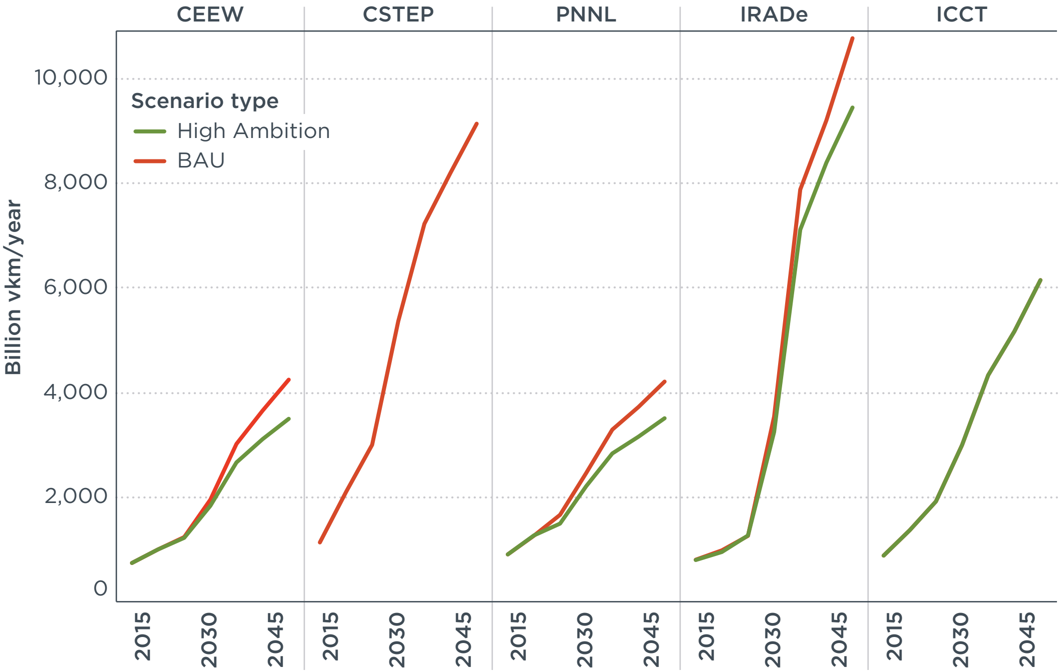

Figure 6. Travel demand reduction assumed under the High Ambition scenarios in models where the data was available.

Note: Vehicle activity data for CSTEP's High Ambition Scenario is not available.

Energy consumption under the High Ambition scenario

Under the High Ambition scenarios, energy consumption is expected to roughly double between 2020 and 2050. This is less than in the BAU scenarios, where it was almost tripling or even quadrupling over the same time period. The average energy consumption across models in the High Ambition scenario was down to about 6–7 EJ by 2050 (Figure 7). Models with conservative electrification and efficiency improvements expect gasoline and diesel to remain the primary energy source for road transport. Meanwhile, models with aggressive electrification expect that electricity could meet as much as 40% to 70% of the energy requirement of the sector by mid-century. As per most of the models, CNG was the other prominent fuel and it could be catering to 20%–25% of energy demand in 2050, mostly to be used by buses.

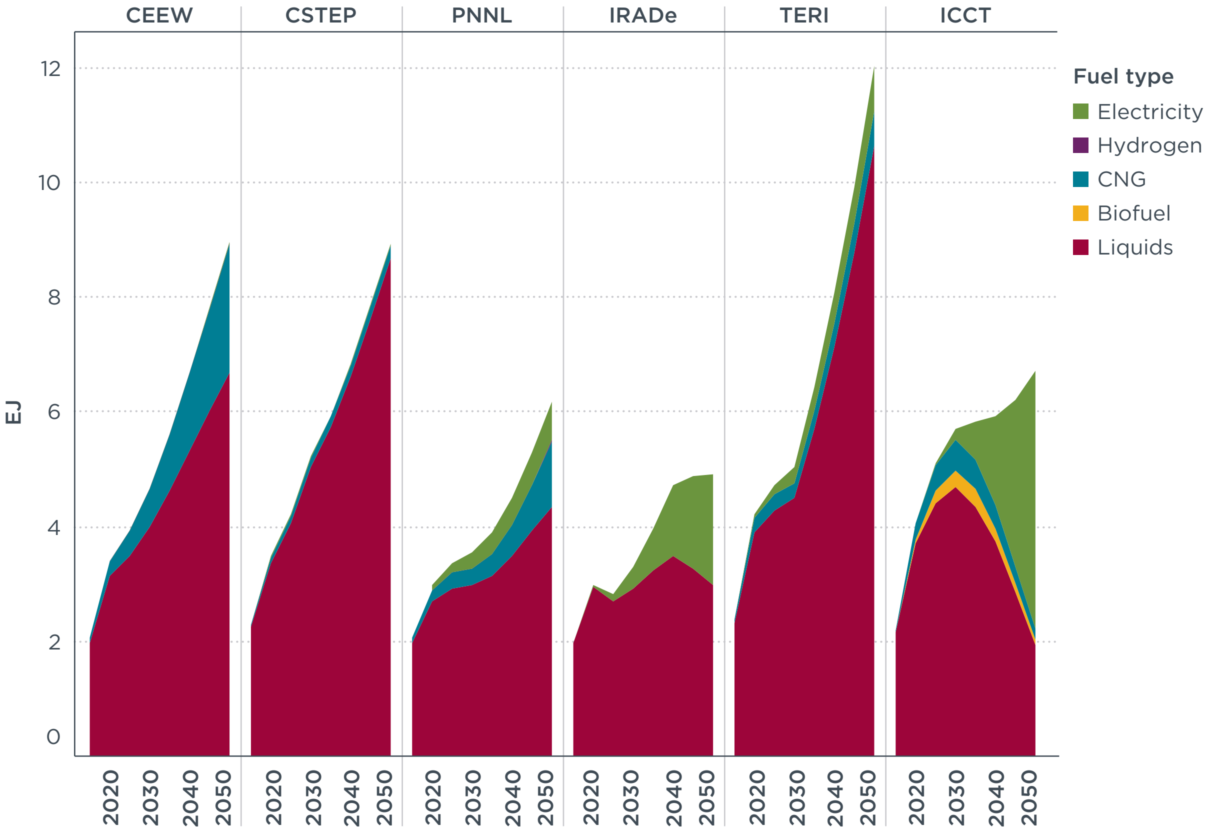

Figure 7. Energy consumption by fuel under the High Ambition scenarios across models where data was available.

Note: In models other than ICCT, the liquids fuel category may include some degree of biofuel blending in liquid petroleum.

CO_2 emissions under the High Ambition scenario

Two types of emissions pathways were identified across models within the High Ambition scenarios. In one, emissions continue to grow until mid-century, although at a slower pace than in the BAU scenario. This pathway is found in models from CEEW, PNNL, TERI, and CSTEP. Figure 8 shows that emissions could reach beyond 600 Mt under such a pathway. In the second pathway, CO_2 emissions peak before mid-century and then drop.

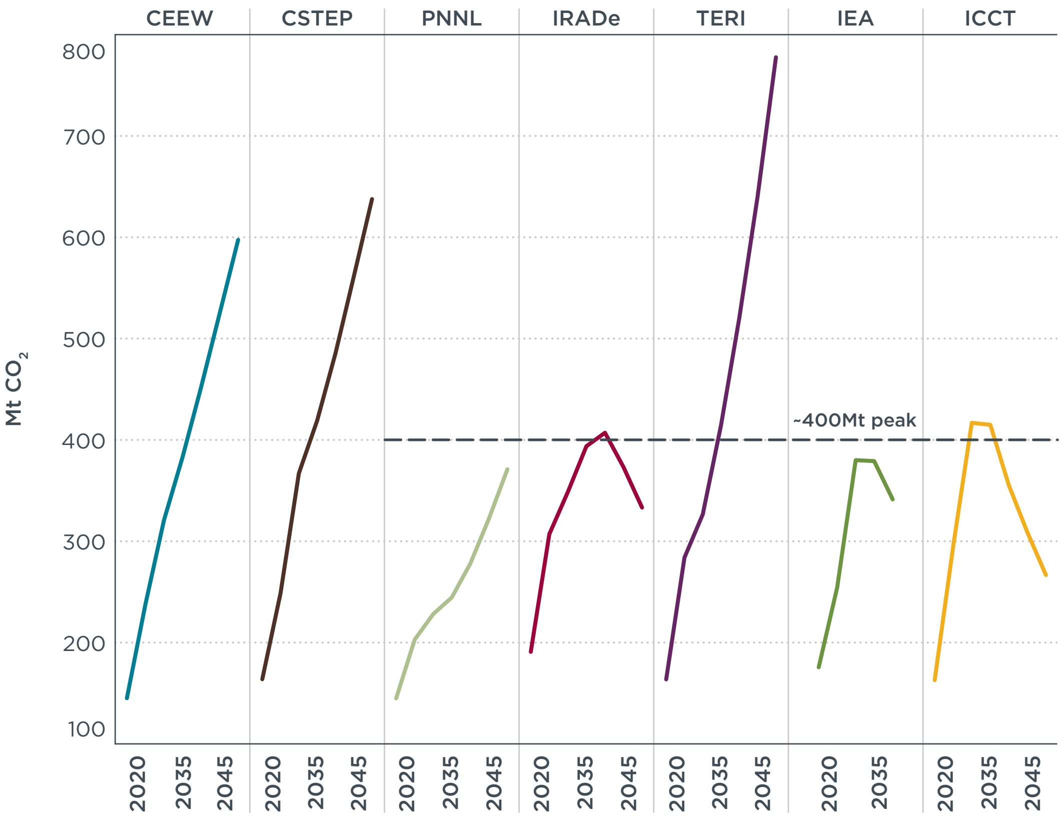

Figure 8. CO_2 emissions trajectories for the models with a High Ambition scenario.

Models like ICCT and IEA expect emissions to peak by 2030. IRADe's scenario also expects peaking to happen, but a decade later. These show that reversal of increasing emissions in the road transport sector is possible with an already identified set of decarbonization strategies. In ICCT's model, CO_2 emissions could be reduced to approximately 250 Mt in 2050. Each of the models with a reversal of emissions trends assumes aggressive electrification along with continued efficiency improvements till 2050. Also, none of the CO_2 emissions trajectories under the High Ambition scenario reach close to zero by 2050.

As shown in Figure 9, the share of emissions from freight vehicles is higher in the High Ambition scenarios than in the BAU scenarios across all models. Further, HDTs could be responsible for over half the emissions in 2050, followed by cars at around 20% of road transport emissions. On the other hand, owing to electrification, emissions from two-wheelers and three-wheelers would become negligible, contributing just 1%–7% in 2050.

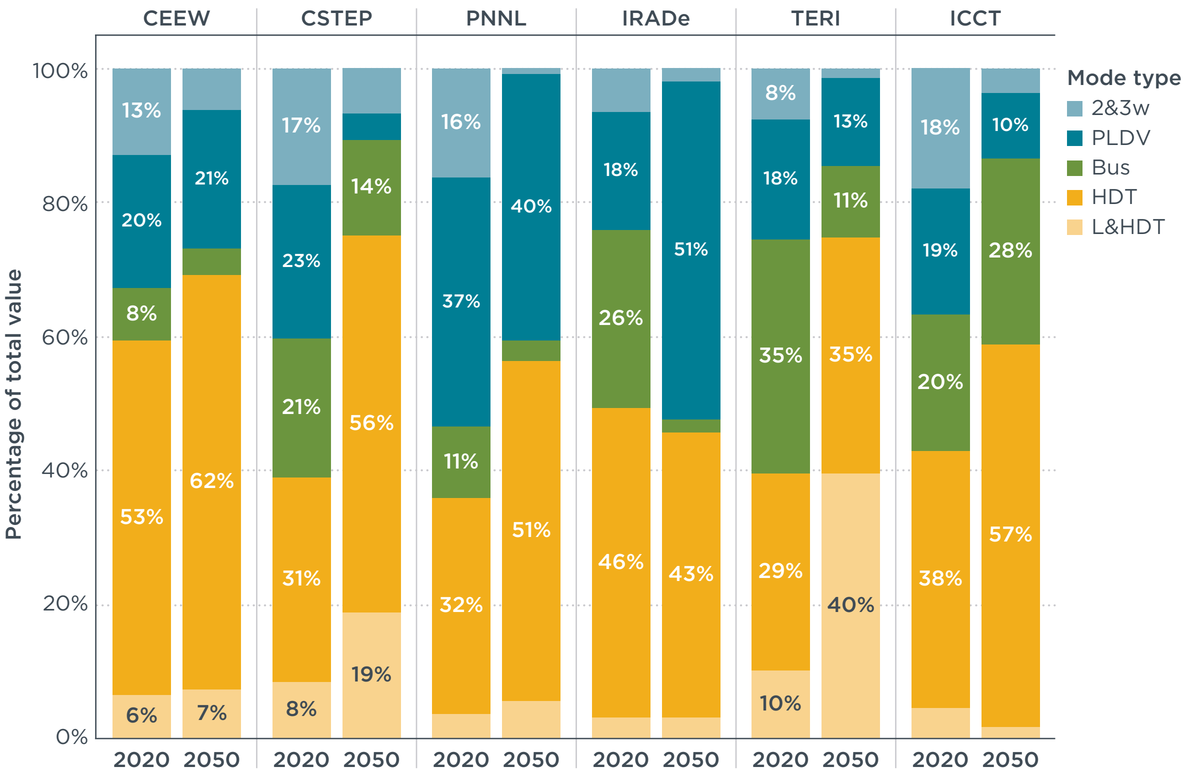

Figure 9. Contribution of different vehicle categories to CO_2 emissions in 2020 and 2050 under the High Ambition scenarios.

Further details of the estimates of vehicle activity, energy consumption, and CO_2 emissions under the BAU and the High Ambition scenarios for 2020 and 2050 are in the Appendix.

Key takeaway

In the High Ambition scenarios, even though energy use and emissions drop significantly in comparison to the BAU scenario, only a few models expect emissions to peak within a decade or two. Other models expect the emissions to double between 2020 and 2050. A reversal of the current emissions trend is only seen in models that assume aggressive electrification along with continued efficiency improvements till 2050. There was also general consensus among models that significant electrification would take place across passenger vehicles, including in cars and buses, while freight vehicles would be harder to electrify.

The analysis of various emissions models shows that there are many policy avenues that remain unexplored from a decarbonization perspective. Many of the models do not incorporate the entire set of emission reduction strategies already commonly employed, and thus the High Ambition scenarios in no way set a boundary as far as what India can achieve. For instance, ICCT's High Ambition scenario relies primarily on a few decarbonization strategies: fuel efficiency improvement, electrification, and alternative fuels like biofuel. Incorporating just a few strategies means leaving out measures that could offer higher emissions reduction. Clearly, a more aggressive approach could result in greater decarbonization.

CONSIDERING THE IMPACT OF COVID-19 USING ICCT'S ENERGY AND EMISSIONS TRAJECTORIES

The COVID-19 pandemic significantly affected vehicle sales and travel demand due to the widespread economic disruption it caused and stay-at-home orders. In ICCT's pre-COVID estimates, vehicle sales were expected to grow from 26.2 million in 2018 to 27.2 million in 2019 and 28.2 million in 2020, and then to more than 40 million by 2030 and nearly 80 million by mid-century.[4] However, vehicle sales instead shrank at 21.5 million in 2019 and to 18.6 million in 2020, reductions from the prior year of approximately 18% and 14%, respectively. Data on travel demand reduction during the pandemic was not available. However, we estimated that the likely reduction in travel demand could have been at least 11% in 2020 compared to 2019, based on data on end use consumption of petroleum in India (Petroleum Planning & Analysis Cell, 2021). This reduction could likely be higher, though.

Future sales scenarios

To explore the impact of the pandemic on emissions, we consider two future sales scenarios—one high and one low.[5] In the high-sales scenario, we expect the sales to rebound quickly. This is owing to India's large, young population and fast-growing economy, both of which suggest that the demand for automobiles is more likely to remain high. Under this scenario, the recovery in sales starts in 2021 and reaches 2018's level by 2024.

In a low-sales scenario, vehicle sales would remain low for almost a decade. Governments would follow a "green recovery" pathway that makes significantly higher investments in improving and expanding public transport and non-motorized transport infrastructure while also imposing severe vehicle use restraint measures, especially on vehicles that have poor efficiency. Such a scenario is possible only if central, state, and city governments work aggressively and in tandem with each other to formulate policies that strengthen decarbonization efforts. Several of the strategies that different levels of government could implement to realize a low-sales scenario are listed in Table 5. We consider this low-sales scenario because in the past, countries like Brazil and Indonesia have experienced a similar slump in vehicle sales solely as a consequence of economic slowdown (Indonesia Investments, 2014; MarkLines Automotive Industry Portal, 2015; Trading Economics, 2021).

4 The previous estimates pertain to 2018 baseline year which was a pre-COVID-19 and pre-2019 economic slowdown period

5 Both our low and high sales scenarios are conservative in their assumption with respect to future vehicle sales projection.

Table 5. Actions available to different levels of government for realization of a low-sales scenario.

Central	State	City
• Policies and investments for public transport improvement and expansion • Improving railway's freight capacity and competitiveness to promote mode shift from road to rail freight • Stringent fuel efficiency standards for all vehicle categories • Stringent emission standards for all vehicle categories* • Policies that support the adoption of electric vehicles (EVs) and other zero-emission vehicle technologies	• Policies encouraging deployment of clean vehicles like battery EVs • Policies and investments for public transport improvement and expansion • Measure to retire high-polluting vehicles*	• Urban planning – compact cities, transit-oriented development • Vehicle use and ownership restraint measures • Better parking and traffic management • Pedestrian and cycling friendly cities • EV-ready by-laws • Ultra-low and low-emission zones that allow only non-polluting vehicles

* Not a decarbonization measure, but critical to lower road transport-related air pollution levels.

The vehicle sales expected under both high- and low-sales scenarios are significantly lower than the sales projected under the pre-COVID BAU scenario. In the high-sales scenario, vehicle sales would cross the 30 million mark by 2028 and reach over 65 million by 2050. Under the low-sales scenario, sales would cross 30 million only in 2032 and reach around 57 million by 2050. As shown in Figure 10, these contrast with the 30 million vehicle sales that would have been expected by 2022 under the pre-COVID (and pre-2019 economic slowdown) baseline.

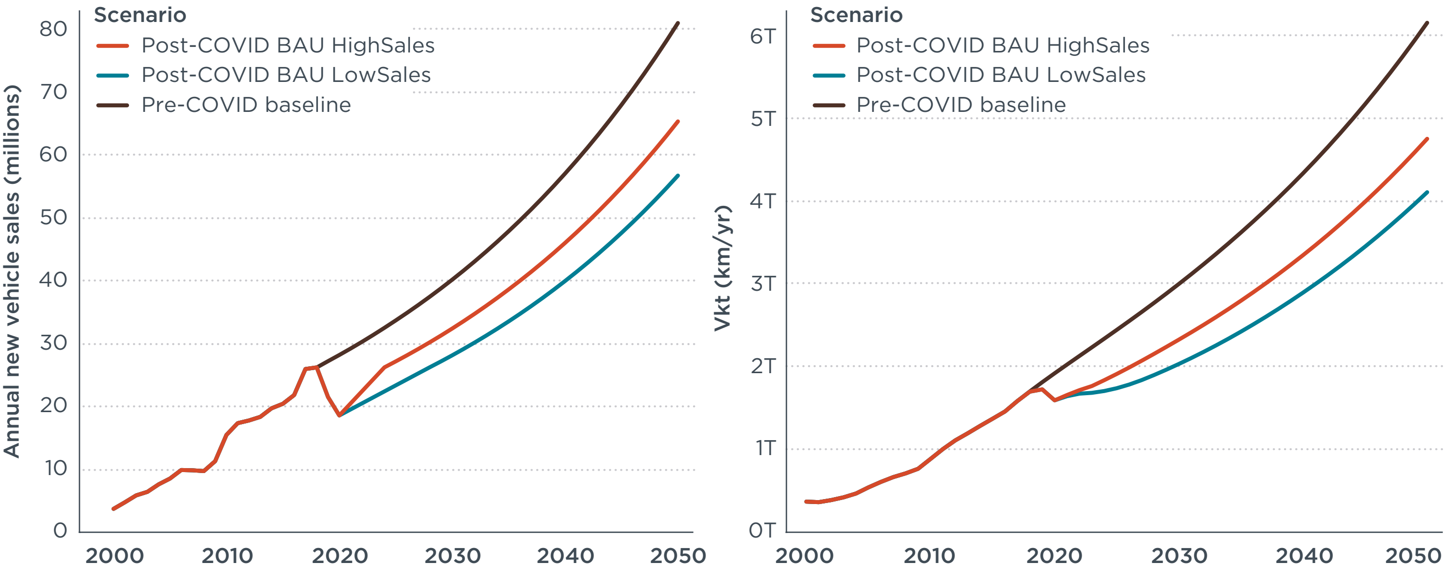

Figure 10. Vehicle sales and vehicle activity under pre- and post-COVID-19 BAU scenarios.

In terms of the energy and emissions impact, the high- and low-sales trajectories both contain notable reductions compared to the pre-COVID-19 baseline, and emissions in 2020 were 20% lower than expected. The post-COVID-19 high-sales scenario projects 30% lower CO_2 emissions in 2050 and under the low-sales scenario, the reduction would be more substantial, around 42% in 2050. The savings in oil and gas consumption would be in a similar range—30% and 42%, respectively—in 2050 under the post-COVID-19 high- and low-sales scenarios.

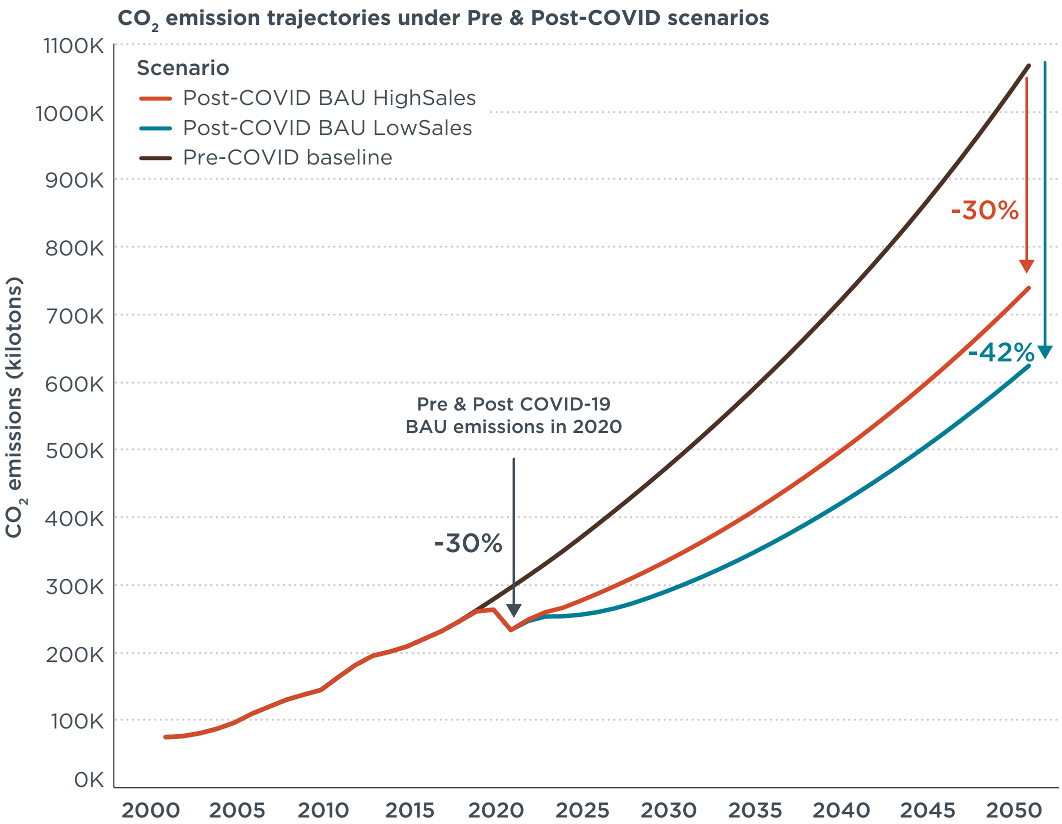

Figure 11. CO_2 emissions from different post-COVID-19 trajectories as compared to pre-COVID-19 baseline

HIGH AMBITION AND AGGRESSIVE POLICY SCENARIOS

Assumptions in our Aggressive Policy scenario

To explore the potential of further reducing emissions and energy use, we propose an Aggressive Policy scenario. In addition to the interventions incorporated in the High Ambition scenario, the Aggressive Policy scenario includes passenger mode shift from cars and two-wheelers to buses, freight mode shift from road to rail, and deeper electricity grid decarbonization, as described below. Otherwise, the assumptions related to fuel efficiency improvements, vehicle electrification, and the use of alternate fuels under the Aggressive Policy scenario are the same as in the High Ambition scenario.

Mode shift from cars and two-wheelers to buses: In the Aggressive Policy Scenario, we assume a gradual shift of passenger demand from private cars and two-wheelers to buses, starting in 2022. A shift of 10% of car and two-wheeler activity to buses is expected by 2030, and this increases to 20% by 2040 and then remains at that level until 2050. To accommodate the additional demand on bus systems, an additional 40% of new bus sales would be required in 2025 and this would gradually be increased to 46% and 50% by 2030 and 2050, respectively (considering an average load factor of 38 passengers per bus). However, if the average passenger load of the buses improves by 25% to 48 passengers per bus, the additional new bus requirement could be brought down to 30% and 40%, respectively, in 2030 and 2050.

Maintaining and further improving the share of buses will be critical to decarbonizing passenger road transport in India, but studies have found that improving the quality of public transport is not enough to push users out of their cars and two-wheelers (Broaddus et al., 2009; Vassallo & Bueno, 2019). Therefore, it is likely that a mix of push and pull strategies implemented in tandem with each other would be required. Hence, improving and expanding public transport in cities, along with implementing strategies like car and two-wheeler ownership and use restraint would play an important role. Stringent parking norms, low-emission zones, vehicle mileage tax, and car license plate lottery policies are some of the measures that could be employed as vehicle use and ownership restraint measures.

Freight mode shift from road to rail: A gradual mode shift is assumed to take place from HDTs to railway starting in 2025. The shift will reach 10% of freight activity (in the unit of billion tonne kilometers) by 2030, 20% by 2040, and remain at 20% till 2050.

Shifting freight demand from road to electric rail is a widely adopted strategy for decarbonizing the transport sector (Sustainable Mobility for All, 2021). In India, the share of road in freight movement has been constantly increasing owing to an improved highway system and the cost-competitiveness of the road sector; meanwhile, the share continues to decline steeply for the railways. Limited capacity for operating freight trains, lack of reliability (freight trains do not even have a timetable), and high freight charges are some of the issues that plague the railways. However, many efforts have been taken by Indian Railways to improve capacity, reliability, and the tariff structure, and these have brought improving railway infrastructure and service quality.

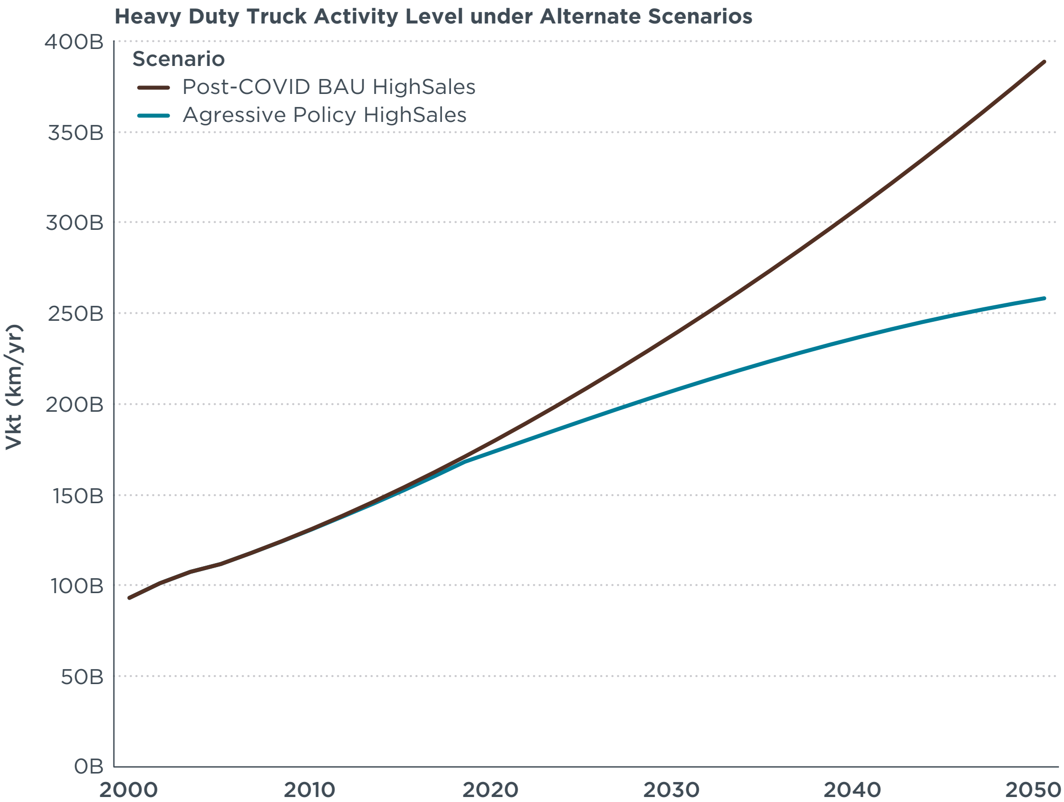

Figure 12. Freight demand in vehicle kilometers catered by heavy duty trucks under BAU/High Ambition and Aggressive Policy scenarios.

Note: The activity level for HDTs is similar under the BAU and High Ambition scenarios.

***Grid decarbonization*:** Under the High Ambition scenario, the carbon intensity of the grid was assumed to reduce from 613 gCO_2/kWh in 2020 to 84 gCO_2/kWh in 2040 and then remain at the same 2040 level till 2050. This was because we considered that any further decarbonization would be challenging. In the Aggressive Policy scenario, however, we expect that deeper decarbonisation of the grid would be possible beyond 2040 because of India's high rate of renewable energy deployment and global pressure to retire coal power plants. In this scenario, the carbon intensity of the grid is assumed to reach 50 gCO_2/kwh in 2050.

Vehicle activity and energy consumption under the High Ambition and Aggressive Policy scenarios

Estimates for vehicle activity and energy consumption in the post-COVID-19 High Ambition and Aggressive Policy scenarios for both high- and low-sales projections are shown in Figure 13. Even under the Aggressive Policy scenario, vehicle activity more than doubles, but this is a 17% reduction compared to the High Ambition scenario, for both high- and low-sales vehicle projections.

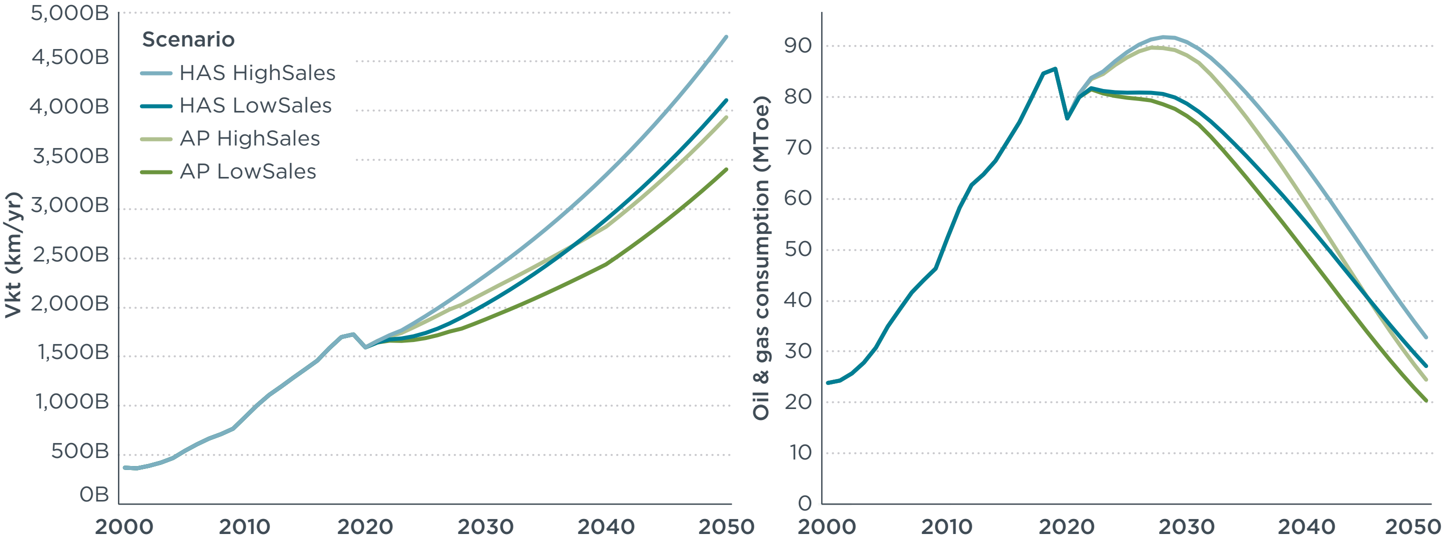

Figure 13. Vehicle activity and energy consumption under High Ambition and Aggressive Policy scenarios.

A similar reduction is also seen in petroleum consumption across the Aggressive Policy scenario. The consumption of petroleum drops by 19.3% in the high-sales Aggressive Policy scenario in comparison to the high-sales High Ambition scenario, and the savings are somewhat more modest, 14%, in the case of the low-sales Aggressive Policy scenario. Table 6 provides details of vehicle activity level and energy consumption under the High Ambition and Aggressive Policy scenarios for high and low sales scenarios.

Table 6. Projected vehicle activity and petroleum consumption under different post-COVID scenarios.

Scenarios	High sales		Low sales	
	High Ambition	Aggressive Policy	High Ambition	Aggressive Policy
Vehicle activity (billion vkm)				
2020	1,596.3			
2050	4,753.7	3,935.5	4,108.7	3,405.7
Petroleum consumption (Mtoe)				
2020	75.9			
2050	32.8	24.5	27.2	20.4

Emissions trend under High Ambition and Aggressive Policy scenario

As can be seen from Figure 14, the Aggressive Policy scenario offers substantial emissions reduction over the High Ambition scenario. In the high-sales Aggressive Policy scenario, CO_2 emissions from the road transport sector are expected to reach 111.8 Mt in 2050—that is on par with 2006's level. Combining the Aggressive Policy scenario with the low-sales scenario results in even lower CO_2 emissions, 93.5 Mt in 2050, and that is same as 2004's level. Results show the Aggressive Policy scenario offers a 36% reduction in emissions over the High Ambition scenario (111.8 Mt vs. 175.6 Mt under the high-sales scenario and 93.5 Mt vs. 146.4 Mt in the low-sales scenario). Also, it is clear from Figure 14 that in the post-COVID context, whether India follows an Aggressive Policy or High Ambition path, emissions would likely peak by 2030.

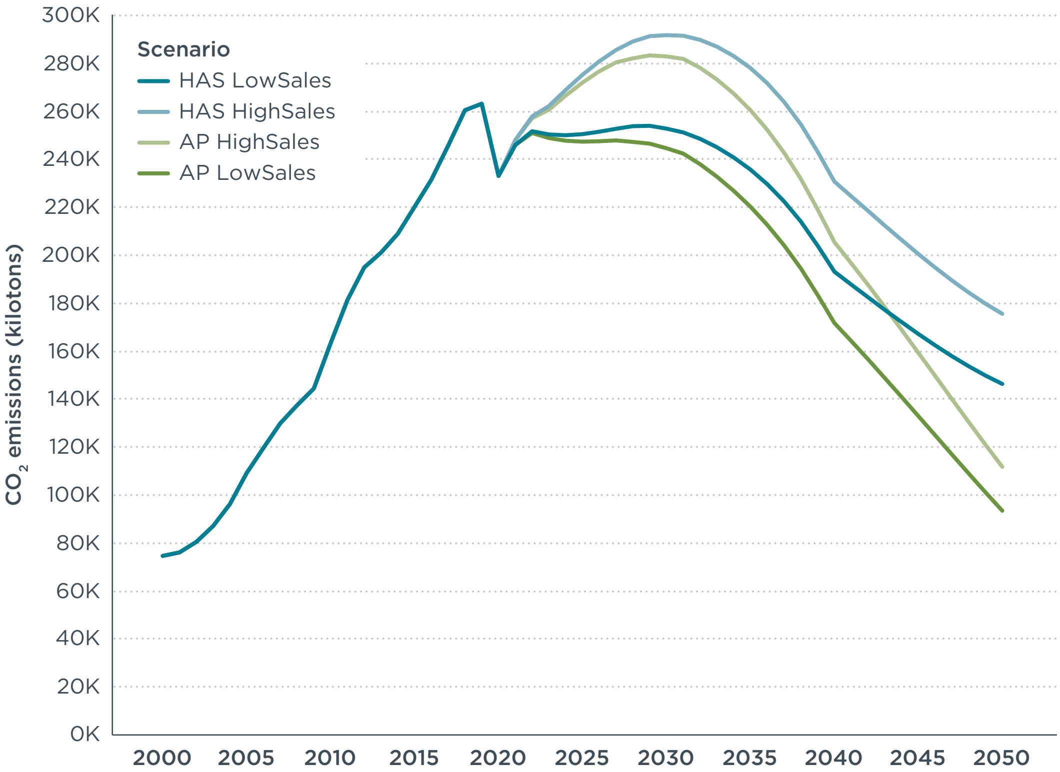

Figure 14. CO_2 emissions trajectory under alternate scenarios.
Note: HAS: High Ambition Scenario; AP: Aggressive Policy scenario

The results indicate that India could lower its cumulative road transport CO_2 emissions between 2021 and 2050 by almost 45%–50% when compared with the BAU scenario. The 45% savings come in the High Ambition scenario and 50% savings are realized in the Aggressive Policy scenario, both compared to BAU. In terms of annual CO_2 savings, these could be as high as 80% in 2050 (76% in the case of High Ambition and 85% in the case of Aggressive Policy, compared to a BAU scenario).

Table 7. Annual CO_2 emissions under different scenarios.

	High-sales scenario			Low-sales scenario		
Scenarios	**BAU**	**High Ambition**	**Aggressive Policy**	**BAU**	**High Ambition**	**Aggressive Policy**
Annual CO_2 emissions (Mt) in 2020	233.1					
Annual CO_2 emissions (Mt) in 2050	739.2	175.6	111.8	624.0	146.4	93.5
2050 emissions in comparison to 2020 level (%)	217%	-25%	-52%	168%	-37%	-60%
2050 emissions in terms of past level of emissions	3.2 times the 2020 level	2011 level	2006 level	2.7 times the 2020 level	2010 level	2004 level

Table 7 shows that even under high sales, annual emissions in 2050 under the Aggressive Policy and High Ambition scenarios would be 50% and 25% below the 2020 level of emissions, respectively. Therefore India's next NDC could set a target to lower emissions from its road transport sector by at least 25% to 50% by 2050 in comparison to 2020. This analysis shows that achieving such emissions reduction is possible through a known set of interventions and requires a high-to-aggressive level of effort.

The contribution of specific interventions to the emissions reductions in the Aggressive Policy, high-sales scenario is shown in Figure 15. Fuel efficiency improvement in ICE vehicles offers 38.4% reduction from the BAU scenario. Along with vehicle electrification and grid decarbonization, the emissions reduction becomes as high as 80.3%. These interventions combine with mode shift from private vehicles to public transport and freight mode shift from road to electric rail to offer a total emissions reduction of 85% in 2050.

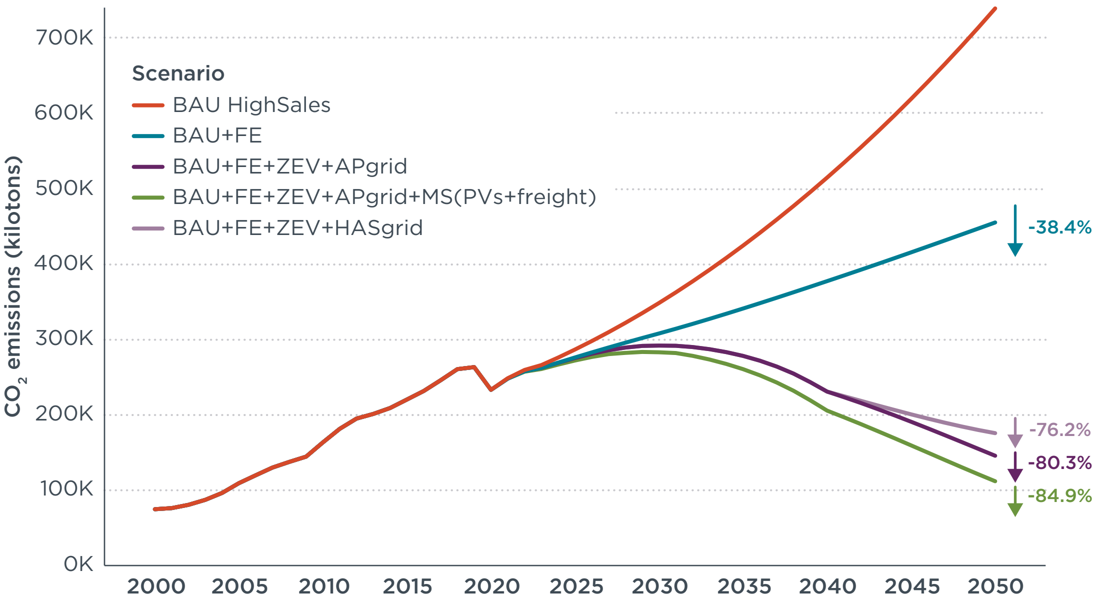

Figure 15. CO_2 emissions reduction offered by different policy interventions in an Aggressive Policy scenario under high sales.

Note: AP: Aggressive Policy scenario; HAS: High Ambition Scenario, FE: ICE vehicle fuel efficiency improvement, ZEV+grid: Vehicle electrification along with grid decarbonisation; MS (PVs+freight): Mode shift (Private vehicles to buses and HDT to electric rail)

CONCLUSION AND RECOMMENDATIONS

This work offered a view of India's transport sector by examining eight major road transport models. We explored both the potential of efforts to reduce emissions and the impacts of the COVID-19 pandemic. Even though the analysis was conducted on a high level, there are some conclusions that can be drawn and recommendations that stem from them:

» **A data gap exists in the understanding of India's road transport activity and its implications for future energy use and emissions.**
Large differences exist in estimates of key variables in the road transport sector such as vehicle activity level, its distribution among different modes, energy used by the sector, use of different fuels by different vehicle categories, and emissions emanating from different modes. Not only do these differences exist for the future, but also for the baseline year. This points to gap that exists in our understanding of the actual travel pattern and how it has been changing over time, and this can be addressed if the central and regional governments collect this data and publish it.

» **India will face a continued rise in energy use and CO_2 emissions in a business-as-usual future with no additional policy intervention or with limited new intervention**.
Despite their differences, the models expected 3–4 times rise in energy consumption and CO_2 emissions between 2020 and 2050. This translates to an increase in energy consumption from an average of 4 EJ in 2020 to 17 EJ by 2050 and a rise in CO_2 emissions of 300 Mt to 1,200 Mt between 2020 and 2050. The BAU scenario across models was characterised by unabated rise in vehicular activity with increasing dependence on personal vehicles and higher growth for freight activity with continuous reliance on petroleum.

» **High Ambition scenarios highlight the potential for a reversal of the current CO_2 emissions trend.**
Interventions like fuel efficiency improvements in ICE vehicles, vehicle electrification, increased use of alternative fuels, and restraining travel demand could limit or even reverse the growth trend CO_2 emissions from the transport sector. Any significant impact in terms of peaking and a subsequent reversal of the emissions trend would only be possible if aggressive vehicle electrification is undertaken along with continued efficiency improvements in ICE vehicles till 2050. Thus, the need for stronger action to decarbonize the road transport sector is clear as even efforts under the High Ambition scenarios fail to achieve carbon neutrality by mid-century. The **Aggressive Policy scenario could help abate 45%–50% cumulative CO_2 emissions between 2021 and 2050** using additional decarbonization efforts like mode shift and deeper grid decarbonization.

» **COVID-19 has made a severe dent on vehicle sales and travel demand.**
Our estimates show road transport travel demand reduced by at least 11% in 2020 as compared to 2019, and vehicle sales shrank from 21.5 million in 2019 to 18.6 million in 2020, a reduction of 14%. This was in addition to the 18% annual reduction in vehicles sales in 2019 due to the economic slowdown. In a future low-sales scenario, sales are expected to return to 2018 levels only by 2028 and **the low-sales trajectory might offer significant emissions reduction benefits.**

POLICY RECOMMENDATIONS

» **India should institutionalize data collection for the transport sector**. The data collection effort could include conducting periodic national-level travel surveys and an annual GHG inventory. Both would enable better understanding of travel behaviour, energy consumption, and emissions from the sector.

- **India should set a target of lowering emissions from road transport by 25%–50% below the 2020 level by 2050**. This is possible and would help accelerate India's achievement of climate goals.
- **India should develop a road transport policy roadmap that includes short-, medium-, and long-term goals** and policy support that would be offered toward transport sector decarbonization. Such a policy roadmap should include a combination of strategies to achieve highest CO_2 emissions savings. Interventions like fuel efficiency improvements in ICE vehicles, vehicle electrification with a low-carbon grid, increased use of alternative fuels, mode shift from private vehicles to public transport, and freight mode shift from road to electric rail, offer substantial emissions savings and ought to be considered in the policy roadmap.
- **India should prioritize vehicle electrification, electricity grid decarbonization, and stringent fuel efficiency standards**. Results from all models and post-COVID-19 analysis confirmed the effectiveness of these strategies in reducing petroleum reliance and CO_2 emissions. Vehicles such as two-wheelers and passengers cars can be prioritized due to lower technology barriers for electrification and their high share of total emissions.

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APPENDIX

Table A1. Estimates of vehicle activity, energy consumption, and CO_2 emissions under the BAU and the High Ambition scenarios for different models for 2020 and 2050.

BAU scenario			High Ambition scenario		
Vehicle activity (billion vkm/year)			**Vehicle activity (billion vkm/year)**		
Model	2020	2050	Model	2020	2050
CEEW	1,242.14	4,251.28	CEEW	1,228.26	3,503.34
CSTEP	3,005.76	9,144.16	CSTEP	—	—
PNNL	1,667.56	4,214.49	PNNL	1,500.11	3,513.92
IRADe	1,265.93	10,778.36	IRADe	1,272.74	9,453.23
ICCT	1,923.02	6,154.23	ICCT	1,923.02	6,154.23
Energy consumption (EJ/year)			**Energy consumption (EJ/year)**		
Model	2020	2050	Model	2020	2050
CEEW	3.50	12.13	CEEW	3.38	8.95
CSTEP	5.25	13.54	CSTEP	3.47	8.93
PNNL	3.50	10.52	PNNL	2.96	6.18
IRADe	4.58	32.08	IRADe	2.97	4.9
TERI	5.07	21.08	TERI	4.21	12.02
ICCT	4.04	14.67	ICCT	4.04	6.71
TTW CO_2 emissions (Mt CO_2/year)			**TTW CO_2 emissions (Mt CO_2/year)**		
Model	2020	2050	Model	2020	2050
CEEW	246.02	800.23	CEEW	238.18	597.87
CSTEP	378.23	975.1	CSTEP	249.28	638.09
PNNL	244.79	694.47	PNNL	203.34	371.47
IRADe	338.73	2324.81	IRADe	307.48	333.68
TERI	345.89	1424.47	TERI	284.33	778.08
ICCT	295.85	1067.95	ICCT	295.77	267.04