REPORT

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INDIA IN TRANSIT

Modelling alternative transport transition pathways and investment needs in India in the Transport Transition Pathway Explorer

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SUMMARY

India, currently the most populous country globally and the fourth-largest economy, is at a crucial juncture in achieving decarbonisation. At the core is its transport sector, which is responsible for about 14% of the country's direct energy-related emissions (Climate Action Tracker, 2020; IEA, 2023). Despite commendable progress in reducing emissions intensity, India faces challenges in aligning its transport sector with a net-zero trajectory by 2070 or, ideally, 2050. The current transport landscape in India is characterized by challenges in accessibility, affordability, and sustainability, particularly impacting rural areas and low-income households. Road-based transport dominates, contributing significantly to air pollution and hindering progress in achieving sustainable development goals. The demand for private vehicles is growing, which cannot be reconciled with the objective of enabling transport access for all in a sustainable, convenient, efficient, and affordable manner. All of this highlights the need for a reconceptualization of India's transport transition.

In this vein, this paper employs the Transport Transition Pathway Explorer (TTPE) to show options for a just transport transition in India, reconciling the twin goals of achieving climate goals and meeting sustainable development targets. Developed by NewClimate Institute, the TTPE is an open-source tool to model and compare normative pathways for a country's transport sector transition. Covering various modes like road, non-motorized, railway, water, and air transport, the TTPE provides insights into mode distribution evolution and infrastructure needs, as well as emissions pathways and cost vectors, until 2050. Using the TTPE tool, we derived 5 scenarios exploring baseline development, least-cost options, and transition (decarbonisation) pathways for India's transport sector transition in a bottom-up stock-turnover framework.

The analysis conducted using the TTPE tool reveals that India's current transport trajectory is not in line with a Paris-aligned just transition. A baseline pathway, which models the expected development of India's transport sector based on existing national baselines, projects substantial emissions growth and higher costs. While least-cost pathways, which aim to minimise either total system costs or public expenditure, reduce costs, they fall short of decarbonising the sector within timeframes compatible with the Paris Agreement. Transition pathways

that assume decarbonisation of the power sector by either 2050 or 2070 show promise, indicating lower costs and emissions by shifting transport demand to public modes, particularly electrified rail.

For India to steer towards transition pathways, however, financial support is crucial. To put the sector on track towards achieving net-zero targets between 2050 and 2070, India needs significant public investments, estimated at around USD 164 billion per year (2020 USD) between 2023 and 2030. Public transport infrastructure and stock, especially for electrified rail and buses, require substantial upfront public expenditures. The role of climate finance is important in bridging the finance gap and supporting India's transition towards decarbonisation in the transport sector.

The transport transition in India would serve as a catalyst for sustainable development, offering substantial economic returns. A transport transition that leaves no one behind and facilitates affordable, convenient, and safe access to transport services in both rural and urban settings can reinforce progress towards a wide range of sustainable development goals, including poverty eradication. Large-scale infrastructure projects, as well as the ongoing development of the domestic automobile industry towards a global leadership position in electric vehicle production, are projected to also generate positive economic impacts by creating jobs and fostering economic growth. A push to transition transportation in India, focusing on reducing dependence on fossil fuels through modal shifts and electrification, can also greatly aid in decreasing the nation's heavy reliance on fossil fuel imports, particularly crude oil.

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/Λ 01 INTRODUCTION

India is growing fast. In 2023, India became the most populous country in the world, surpassing China. It ranks as the world's fourth largest economy and despite recent global economic crises and pressures, is expected to maintain a 7% growth rate over the coming years, primarily driven by strong domestic demand (Deloitte, 2024). Its emissions have also been growing rapidly, trailing only behind China and the United States in total annual emissions.

Despite India's progress on mitigation, emissions are set to increase over the coming decades. India has already made significant progress, including a 33% reduction in the emissions intensity of its economy compared to 2005 levels (The Econonomic Times, 2023). The government's push for renewable energy has been a key component of its success. However, actual emissions are still set to increase over the coming decades, contradicting the economy-wide emissions reductions needed to meet the government's 2070 net-zero target. The trend also heightens various risks associated with an unsustainable development model, with air and environmental pollution being prominent concerns.

A transition in transport towards a sustainable, net-zero development pathway is a priority for both climate action and development. As the third-largest source of emissions and the fastest growing sectoral source of emissions in India (Kamboj et al., 2022), decarbonising transport is imperative for the transition to net-zero and for meeting other sustainable development goals. Transport connects people to each other, to job markets, education opportunities, and essential services such as healthcare. Transport also connects goods to markets, both domestically and internationally. Transport is the lynchpin around which many Sustainable Development Gogal (SDG) targets and indicators revolve **(see → Fig. 1)**.

In this report, we share findings from the Transport Transition Pathway Explorer (TTPE), a new tool that enables us to explore possible transport transition pathways towards a just transition. Beyond examining total costs and emissions, we delve into different modal choices, capital and operating/usage costs for stock and infrastructure, and the resulting finance needs across multiple pathways for India's transport sector. Our analysis suggests that decarbonisation of the transport sector between 2050 and 2070 in India will cost less than following the current pathway, but India will need support to undertake the transition.

Fig. 1

Key sustainable development goals which are directly or indirectly linked to sustainable transport systems

- 1 NO POVERTY → Resilience, access to basic services
- 3 GOOD HEALTH AND WELL-BEING → Road safety and pollution
- 7 AFFORDABLE AND CLEAN ENERGY → Electrification of public transport, improving energy efficiency
- 9 INDUSTRY, INNOVATION AND INFRASTRUCTURE → Sustainable and inclusive infrastructures
- 10 REDUCED INEQUALITIES → Reduce income inequality, ensure equal opportunities
- 11 SUSTAINABLE CITIES AND COMMUNITIES → Affordable and sustainable transport systems, inclusive and sustainable urbanisation
- 13 CLIMATE ACTION → Integrate climate measures into policy and planning
- 17 PARTNERSHIPS FOR THE GOALS → Mobilizing finance, investment, promoting sustainable technologies, enhance global partnership for sustainable development

Source: Produced by authors.

/Λ 02

THE TRANSPORT TRANSITION PATHWAY EXPLORER

The Transport Transition Pathway Explorer (TTPE) is a new open-source tool NewClimate Institute developed to derive and compare transition pathways for the transport sector. The TTPE is a bottom-up stock-turnover model that covers road transport, non-motorized transport, railway transport, as well as water and airway transport (see Annex I for more details). The TTPE takes national transport demand estimates and breaks them down into transport modes, vehicle types, and fuel shares. The estimates include both total passenger and freight transport demand, demonstrating its evolution over time. We assume that all transport demand is met through available modes, but we limit the saturation level in the distribution of modes, vehicle types, and fuel types to ensure the realism of the pathways.

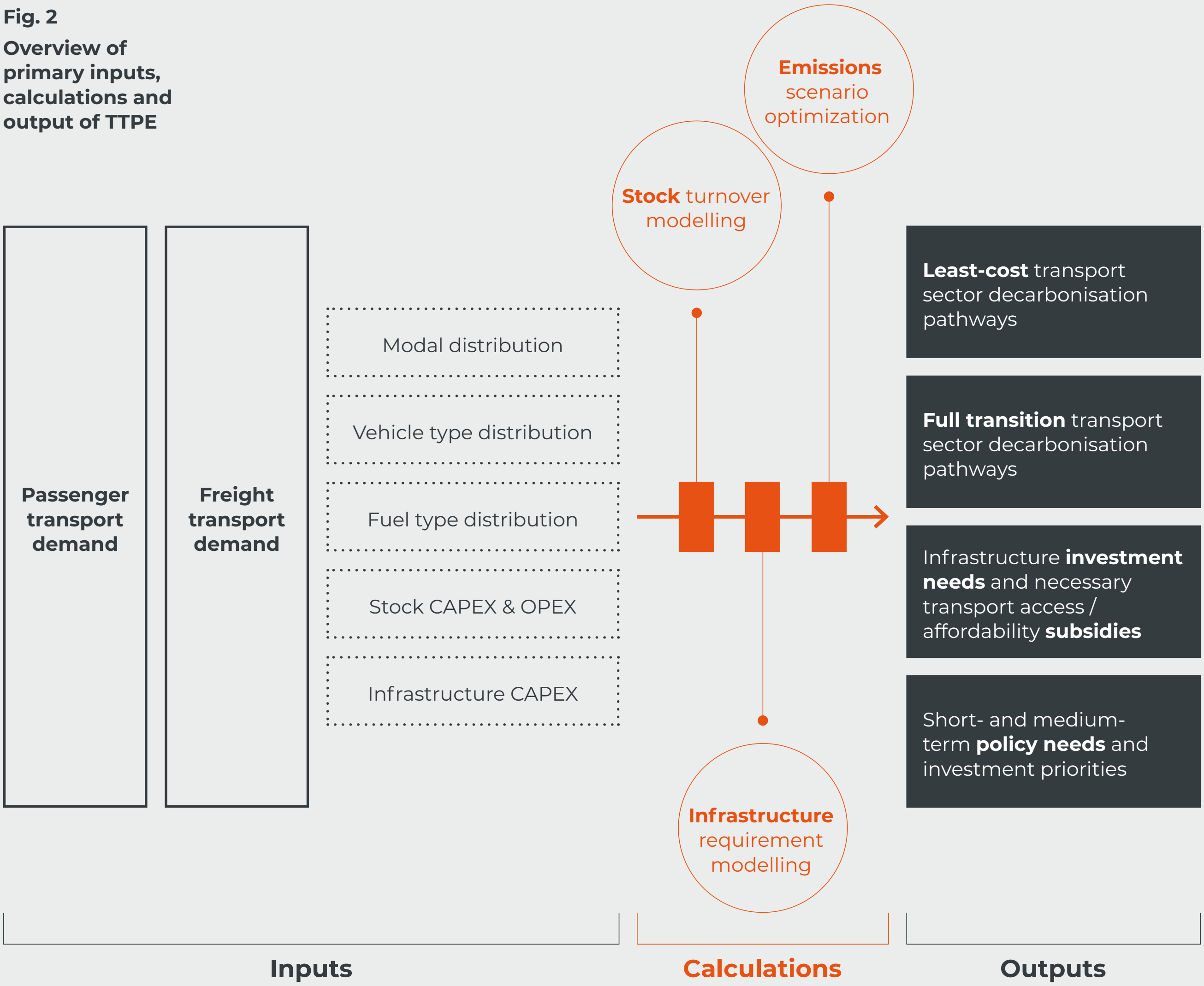
The TTPE models stock turnover, emissions, total cost of ownership (TCO) for both public and private vehicles, as well as infrastructure requirements and investment needs up to 2050. We use the TTPE to derive various pathways, including a baseline pathway, two least-cost pathways (least public expenditure and least total system cost), as well as two transition pathways (assuming power sector decarbonisation by 2050 or 2070).

The baseline pathway (Pathway 1) attempts to capture the expected development of the country's transport sector, based on national baselines developed by Niti Aayog (2023). For the least-cost pathways, the TTPE uses an optimization algorithm to minimize public expenditure (Pathway 2) or total system costs (Pathway 3), which may result from infrastructure development or public transport provision, while still meeting transport demand. Pathway 2 (i.e. the minimization of public expenditure) does not represent either realistic or ideal transport sector development; it is provided solely for illustrative purposes. For most of our analysis concerning least-cost options, we focus on Pathway 3 (i.e. the minimization of total system costs).

For the transition pathways, the TTPE uses an optimization algorithm to minimize emissions by 2050, assuming successful decarbonisation of the power sector by either 2050 (Pathway 4) or 2070 (Pathway 5). The main difference between the two pathways is the speed at which emissions decrease in the transport sector, with mode, vehicle, and fuel type distributions remaining largely similar. For most of our analysis, we focus on Pathway 4, which assumes decarbonisation of the power sector within a Paris-compatible timeframe.

Passenger and freight transport serve as key indicators for transport activity, entering the model. They are then broken down into modal, vehicle, and fuel type distributions. Capital expenditure (CAPEX) and operational expenditure (OPEX) estimates for vehicle stock and infrastructure are used to estimate cost vectors. The model employs the stock turnover modelling, the infrastructure requirement modelling, and the emissions scenario optimization to generate descriptive least-cost and transition pathways, along with respective investment needs.

Fig. 2
Overview of primary inputs, calculations and output of TTPE



Source: Produced by authors.

/Λ 03

THE INDIAN TRANSPORT SECTOR

"We continue to project car ownership as a mark of economic success and social status. And the state encourages and supports private car ownership, even providing incentives for car manufacturers. Citizens have a right to mobility, not to vehicle ownership. The sooner we use financial measures to discourage private car ownership and invest heavily in an efficient public transportation, the more sustainable our economic development will be."

Shyam Saran
India Foreign Secretary, 2017

India's transport sector consumes a lot of energy and is highly emissions-intensive, primarily relying on liquid and gaseous fossil fuels. Only the US, China, and Russia have a larger share of energy consumed by transport than India (Kamboj et al., 2022). It is not surprising that transport is one of India's main sources of greenhouse gas emissions, accounting for about 14% of the country's direct energy-related emissions (Climate Action Tracker, 2020; IEA, 2023). Petrol and diesel remain the primary fuels for various vehicles, including four-wheelers, three-wheelers, two-wheelers, buses, and trucks. However, there has been a significant growth in the regulated use of compressed natural gas (CNG), specifically in the public transport sector (Bandyopadhyay and Thurkral, 2010).

Road-based transport remains the predominant transport mode in India. We estimate that around 70% of passenger and freight transport demand in 2023 in India was met through road-based transport modes such as car, rickshaws, busses, or trucks. The insufficient capacity of alternative mass transit systems, such as metros and trains, and the lack of infrastructure for non-motorized transport mean that road transport is often without alternatives, both in urban and rural areas (Banerjee, 2022). Together with raising income levels, this has also led to, and is likely to further increase, the already high number of vehicles on the road (Kamboj et al., 2022), which in turn leads to more congestion and higher emissions and pollution levels. For example, the transport sector's contribution to air pollution is similar in magnitude to the power sector (Singh et al., 2021), with air pollution being responsible for at least 1.67 million deaths in 2019 (17.8% of total deaths) and contributing to economics losses of at least 1.36% of GDP (India State-Level Disease Burden Initiative Air Pollution Collaborators, 2020).

Freight transport demand is largely being fulfilled by road-based transport. Rail and other modes suitable for bulk cargo offer increased efficiencies and reduced costs through economies of scale, but the flexibility and responsiveness of road-based modes make them more attractive in a fast-growing economy. Overreliance on road transport implies greater inefficiencies and costs, as well as negative externalities such as environmental and air pollution, greenhouse gas emissions, road safety concerns and accidents, and land-use issues. The unit costs of moving goods by road in India are almost double that of rail (Sahu, Pani and Santos, 2022). Nearly one-third of India's logistics costs are attributed to inefficiencies in infrastructure (Kamboj et al., 2022). This presents a critical challenge for the government, which aims to reduce logistics costs from 13-14% of GDP in 2022 to 7.5% in 2028.

Passenger transport demand is already mainly met through public transport, but service levels can be low and barriers remain. Buses are the backbone of urban mobility, making up approximately 90% of public transport in cities (EMBARQ Network, 2017). Public rail services are among the most affordable public transport modes for long distance travel (Kamboj et al., 2022) and have increased significantly over the last two decades (IEA, 2019). However, the development of high-speed rail has been progressing slowly (Jones, 2022). Despite its rapid growth, high fares pose a barrier, especially for lower-income groups (The Economic Times, 2018).

As purchasing power and affordability of private road vehicles increases, the demand for public transport is projected to decrease. The modal share of public transport use is projected to decline as private ownership of four-wheelers and two-wheelers grows (Kamboj et al., 2022). Insufficient availability and service levels of public transport are major drivers of the shift away from public transport (Dash, 2018). However, it is important note that many cannot afford private vehicles, contributing to mobility inequality and exclusion.

Falling costs of technology are driving the faster adoption of electric vehicles, specifically in the two-wheeler, three-wheeler, and four-wheeler segments. The share of electric vehicles is the highest in the two-wheeler and three-wheeler categories, where cost parity has already been achieved or is imminent, and to a lesser extent in the four-wheeler segment (GIZ et al., 2021). In 2022, more than half of the three-wheel models sold in India were electric (Financial Times, 2023). However, the shift to battery electric buses and trucks has been marginal in India due to high upfront costs impacting small and medium-sized businesses, along with concerns regarding range anxiety (Singh, 2022). Railway electrification has advanced significantly but at the time of writing, India had not yet reached its aim to fully electrify its railway system (Indian Ministry of Railways, 2021).

Non-motorized transport is often not a deliberate choice but rather a necessity imposed by economic constraints. This is particularly the case for those with limited financial means, specifically in rural areas. In essence, the utilization of non-motorized transport falls short of its true potential (Kamboj et al., 2022). The availability and affordability of motorized transport and the social status associated with it (Waldman, 2005), the lack of appropriate infrastructure (Tiwari, Jain and Rao, 2016), exposure to environmental and climate risks, as well as road safety concerns, are all major factors in keeping the share of non-motorized transport below desirable levels.

Inequity in access to safe, affordable transport poses a barrier to India's sustainable development. The demand for transportation in India is rapidly rising, driven by the country's rapidly expanding population and economy. However, access to transport is not equitable, particularly in rural areas and among poor households, where sustainable, safe, affordable, and convenient transport options are lacking. This inequity poses a barrier to sustainable development. Limited access to affordable, reliable, safe, and sustainable forms of transportation can hamper socio-economic development by directly impairing access to employment (Thakuriah, 2010), education (Susheela, 2023), or health facilities (Syed, Gerber and Sharp, 2013). The socioeconomic benefits of a just transport transition are significant and go far beyond objectives of decarbonisation. The TTPE serves as a useful tool for exploring pathways that align the decarbonisation of the transport sector with progress on socioeconomic development goals.

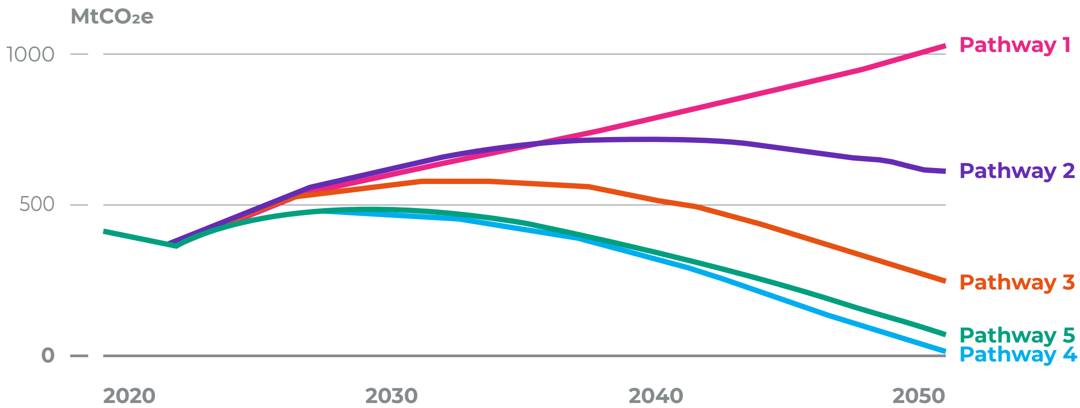
/ Λ 04

TTPE: INDIA'S TRANSPORT TRANSITION PATHWAYS

Efforts to promote a just transition in India's transport sector should start with a clear vision for change that informs the conceptualization of feasible transition pathways towards its objectives. Transition pathways for the transport sector are extremely complex given the multi-modal nature of transport systems and the complex interplay of demand and supply-side drivers and barriers influencing transport preferences. The TTPE offers a flexible framework that can guide decision makers towards a better understanding of what feasible and optimal transition pathways may look like for a country like India. The tool also provides estimates for investment needs, which can further inform policy making.

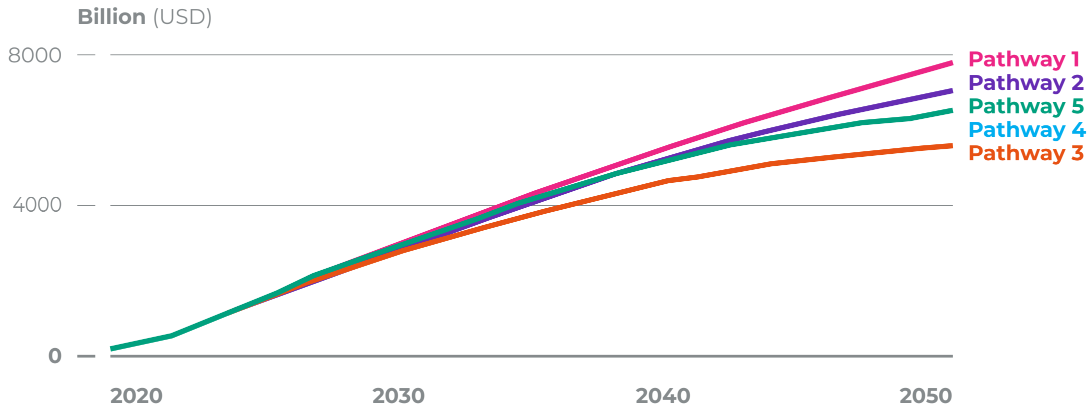
India's current pathway in the transport sector development is neither affordable nor sustainable. Decarbonising the transport sector is possible at lower costs. The baseline pathway (Pathway 1) leads to more than a two-fold increase in emissions between 2023 and 2050 and has the highest system cost **(see → Fig. 3 and Fig. 4)**. Although least-cost pathways (Pathways 2 and 3) drastically reduce public and private investment needs to sustain the transport system, they are far from reaching net zero in 2050 and may miss the net zero by 2070 target. Only the transition pathways (Pathways 4 and 5) allow for a (near) total decarbonisation of India's transport system in line with the Paris temperature targets, and, importantly, at lower total system costs than in the baseline pathway **(see → Fig. 4)**.

Fig. 3
Emissions of the five pathways



Source: Produced by authors.

Fig. 4
Cumulative costs of the five pathways



Note: Pathway 4 overlaps with Pathway 5.
Source: Produced by authors.

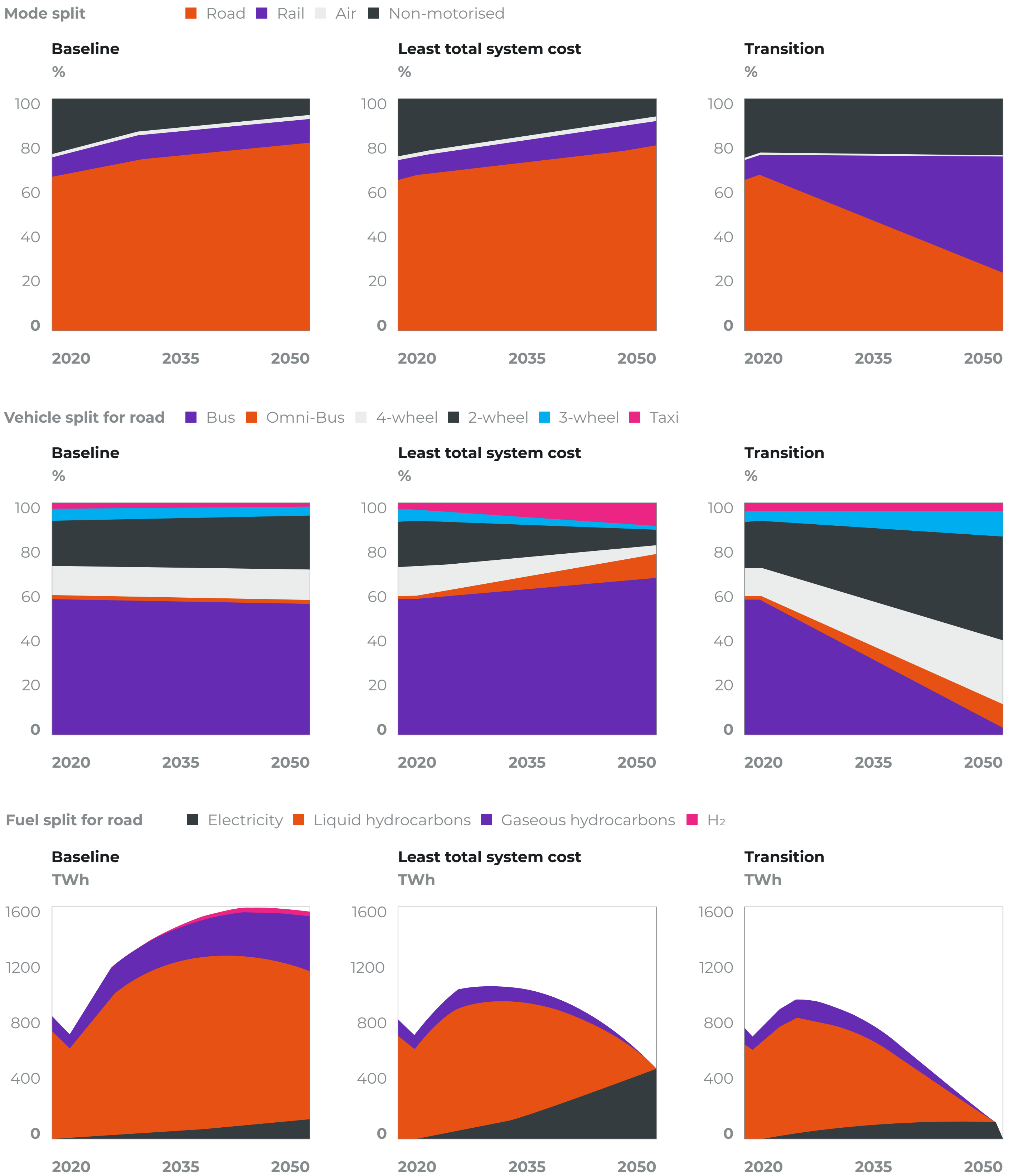
For passenger transport, costs and emissions can both be cut by moving away from personal vehicles. In the baseline pathway (Pathway 1), the share of total passenger transport demand met through road-based transport modes is projected to experience the most significant growth until 2050 **(see → Fig. 5)**. The vehicle split is assumed to stay mostly constant, with a slight decline in the role of public transport vehicles in favour of private road-based transport vehicles. In the baseline pathway, demand for gaseous hydrocarbons in road transport grows significantly, while electricity demand increases only slowly, and liquid hydrocarbons remain the main energy carrier.

In Pathway 3 (minimizing total system costs), the evolution of the passenger transport mode split looks similar, with road-based transport remaining the largest and fastest-growing transport mode until 2050 **(see → Fig. 5)**. In this least-cost pathway, minimizing total system costs, high infrastructure investment needs for rail and non-motorized transport act as barriers to stronger expansion. We do see, however, that road-based public transport modes such as buses and omni-buses play a significantly more important role in this least-cost pathway compared to private road-based transport vehicles. Additionally, in this least-coast pathway, electricity entirely replaces gaseous and liquid hydrocarbons until 2050.

In Pathway 4 (transition pathway assuming 2050 power sector decarbonisation), there is a notable shift in passenger transport modes towards railway and non-motorized transport, while the role of road-based transport modes for meeting passenger transport demand sees a significant decline until 2050 **(see → Fig. 5)**. At the same time, the transition pathway foresees a strong proliferation of highly energy-efficient electric two-wheelers, three-wheelers and four-wheelers, with a decline in the share of buses. In the transition pathway, electricity completely replaces liquid and gaseous hydrocarbons, and the overall energy demand of the road-based transport segment is significantly lower as well.

The energy efficiency of electric buses in terms of kWh/person-km is lower than that of other electric vehicles, given their weight, according to (NITI Aayog, 2023). This leads to a strong decline in the share of busses. It may be socially optimal to retain a larger share of busses versus two-wheelers and three-wheelers, for example, due to safety concerns. However, such dimensions were not directly modelled for this report.

Fig. 5
Passenger transport mode split, vehicle split, and fuel split



Source: Produced by authors.

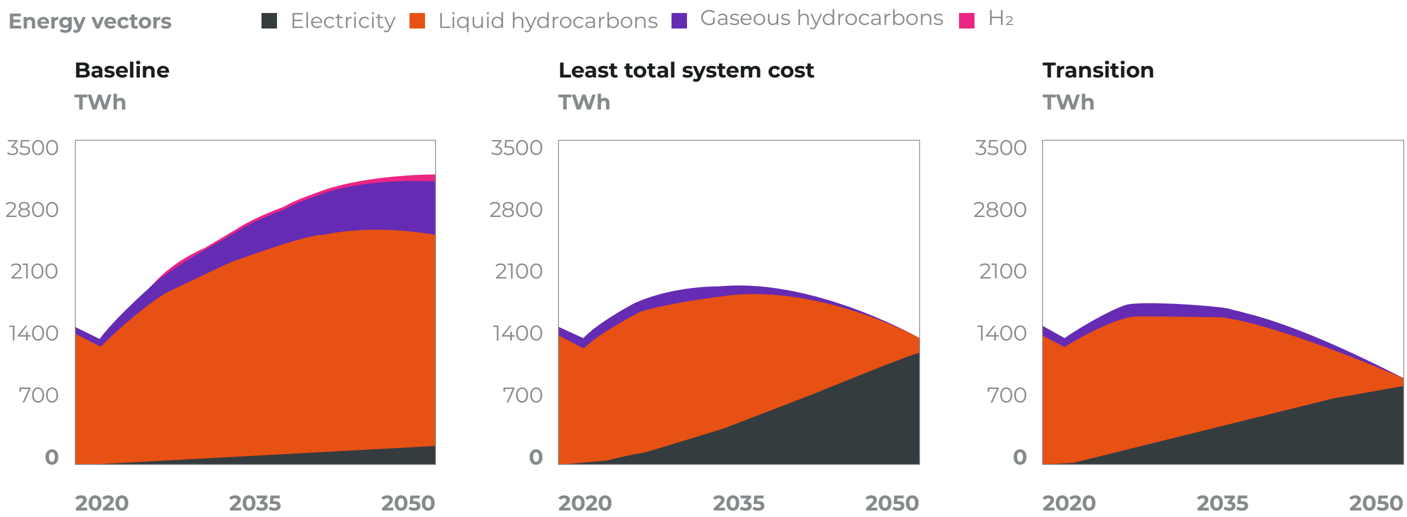
For freight demand, all three pathways foresee a shift towards increased railway usage. The shift is more pronounced in the least-cost (Pathway 3) and transition pathway (Pathway 4) **(see → Fig. 6)**. Road-based transport, however, remains the predominant mode, as it is not feasible to shift all freight to railway. Nonetheless, while the baseline pathway (Pathway 1) anticipates only slow electrification of heavy and light duty vehicles, the least-cost (Pathway 3) and transition pathway (Pathway 4) foresee complete electrification of the road-based freight fleet by 2050.

Fig. 6
Freight transport mode split and fuel split

Source: Produced by authors.

The emissions intensity of the total transport sector is driven by two key factors: the overall energy demand and the emissions intensity of the individual energy carriers, specifically also from the power sector. Among the pathways, the baseline pathway (Pathway 1) sees the highest energy demand, while this demand is significantly lower in the least cost (Pathway 3) and transition (Pathway 4) pathways, primarily due to a much higher reliance on public transport **(see → Fig. 7)**.

Fig. 7
Overall energy carrier split



Source: Produced by authors.

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FINANCE NEEDS FOR A JUST TRANSPORT TRANSITION IN INDIA AND THEIR PAYOFFS

For India to meet its net-zero target between 2050 and 2070, it will need to invest more in public transport infrastructure, particularly electrified rail. The upfront investment may be higher for developing public transport infrastructure, including rail and buses, compared to pathways relying on private road-based mobility. However, these investments can yield significant long-term benefits. Investing in public transport infrastructure can help reduce total transition costs, mitigate externalities associated with private vehicles, ensure universal access to transportation, and facilitate a transition to net-zero transport.

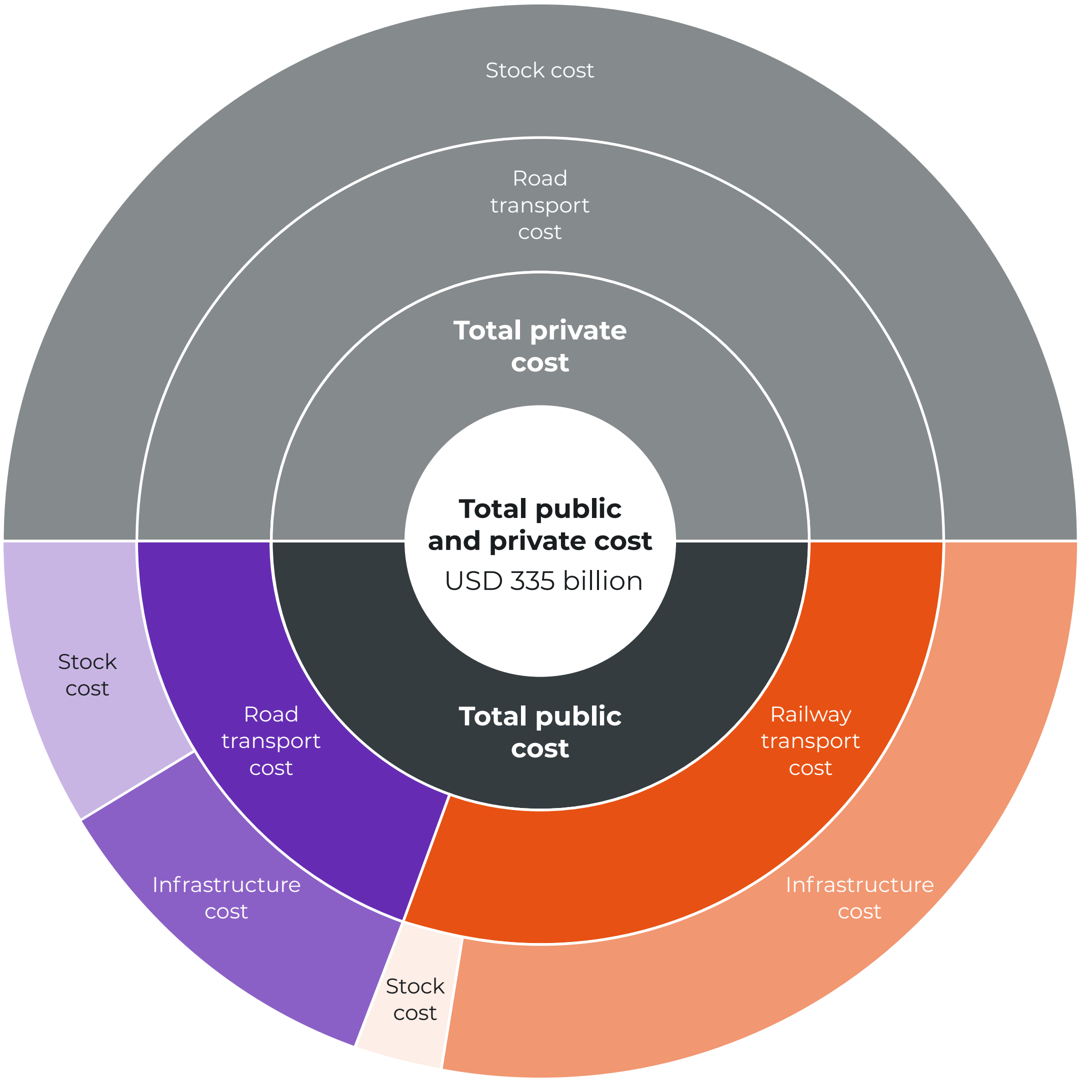
The total (public and private) investment needs associated with India's transition pathway (Pathway 4) amount to around USD 335 billion per year between 2023 and 2030 (in 2020 USD). These investment needs encompass the total cost of operation (TCO) of public and private vehicle stock, as well as public infrastructure investments. Around half of the total yearly investment needs fall on private actors (TCO of private vehicle stock), while the remaining investment needs and costs represent public spending needs **(see → Fig. 8)**. It is important to note, however, that our modelling does currently not cover potential other public expenditures for affordability subsidies (e.g. subsidies for public transport fares) or required incentive schemes (e.g. an EV subsidy).

While substantial, a significant portion of the public investment requirements can likely be met through reallocations within existing national budgets earmarked for the transport sector. Drawing from a possibly incomplete list of India's budget allocations for the fiscal year 2023-2024, we estimate a total allocation of at least USD 100 billion designated for the development, operation, maintenance, and subsidy programs within the transport sector (Cyrill and Bhardwaj, 2022; Mukherjee, 2023; PRS, 2023c, 2023a, 2023b; Sharma, 2023; The Economic Times, 2023). These funds can directly contribute to India's transportation transition if channelled towards the advancement and adoption of public transportation modes.

India's transport transition can contribute to the sustainable development of the entire country, provided that risks and benefits are appropriately distributed. Investments and expenditures on advancing the transport transition are likely to generate fiscal multipliers, resulting in direct and indirect positive economic impacts that can create positive ripple effects throughout the economy. Specifically, investments in large infrastructure projects or in existing domestic industries such as India's vehicle industry are likely to generate significant economic returns over time.

Economic impacts resulting from the transport transition in India are not necessarily evenly distributed, and there are likely to be both winners and losers. Utilizing the TTPE's input-output analysis module, we demonstrate that the transition pathway (Pathway 4), despite entailing lower total expenditure, ultimately yields greater added value compared to the baseline pathway (Pathway 1). Overall,

Fig. 8
Total cost split, public and private



Source: Produced by authors.

we estimate the transition pathway to create on average 7% more jobs per year between 2023-2030. While the emphasis on public transportation, particularly rail, may impose certain constraints on the growth prospects of the domestic vehicle industry, the potential for job creation and added value stemming from necessary infrastructure investments is expected to outweigh. A critical prerequisite for realizing positive economic impacts and maximizing job creation potential in the transition pathway, however, is to ensure that the workforce possesses adequate skills.

A transportation transition in India aimed at reducing reliance on fossil fuels through modal shifts and electrification can significantly help the country in decreasing its strong dependence on imports, especially crude oil. India's energy import dependence has escalated across all energy sources, particularly notable for crude oil (88.6%) and natural gas (54.3%) in 2020 (Singh and Jana, 2024). Crude oil accounts for approximately 20% of India's import bill (Bardhan, 2023), exposing the nation to risks associated with price volatility and exerting pressure on its balance of payments. In the modelled transition pathways, India could markedly diminish this import reliance, provided that the country advances the decarbonisation of its power sector through the deployment of renewable energy sources.

/Λ 06 CONCLUSION

A just transition of India's transport sector in India is achievable. Providing universal access to transport while decarbonising the transport sector are not conflicting objectives; rather, they can complement each other. However, reconciling universal access to transport and deep decarbonisation of the sector in India will require smart development cooperation. This involves providing support for a targeted and effective policy landscape that is capable of steering both public and private investments in a socially optimal way.

A just transition of India's transport sector requires significant shifts towards public transport modes. If India follows its current and cost-inefficient pathway, which heavily relies on private road-based transport, emissions will continue to climb, cities will become more congested, and transport demand will remain suppressed. The demand for private road-based private transport continues to rise, but it remains the least efficient mode in terms of emissions and cost.

To transition towards a decarbonisation pathway, India will need to increase investments in public rail and non-motorized transport infrastructure. This necessitates a realignment of current public expenditure, private investment, and development support. While redirecting existing resources towards the expansion of socially beneficial transport modes can significantly propel India towards a just transition pathway, we acknowledge that overcoming structural and cultural barriers can pose significant challenges and opposition even towards changes that entail clear cost-savings. Therefore, there is a distinct role and opportunity for climate and development finance to facilitate these shifts and mitigate inevitable frictions inherent in far-reaching transitions, as is the case in the transport sector.

A just transition of India's transport sector has the potential to generate significant economic benefits through economic multiplier effects and by reducing reliance on fossil fuel imports. Large sustainable infrastructure investments, along with support for the country's domestic electric vehicle industry, can serve as key drivers of economic growth and development. The transport transition can also help reducing dependence on fossil fuels through modal shifts and electrification, which would greatly aid in decreasing the nation's heavy reliance on imports, particularly crude oil. Although significant upfront investments are necessary to set off this transition, they can be justified by the expected economic payoffs.

Climate partnerships can help bridge climate support with climate ambition in India. Just Energy Transition Partnerships (JETPs) represent one of the innovative approaches that have been implemented in various contexts, including South Africa, Indonesia, Vietnam, and Senegal. While these partnerships have mainly focused on the power sector and the phase-out of coal, replicating such successful models in the transport sector context is important. India could lead the way in this regard by communicating a more concrete vision and support needs for a transport transition aligned with the objective of a Paris-compatible decarbonisation pathway. The TTPE tool could serve as a valuable resource to be used and developed further through stakeholder-driven dialogue and deeper collaboration with Indian experts to support such efforts.

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ANNEX

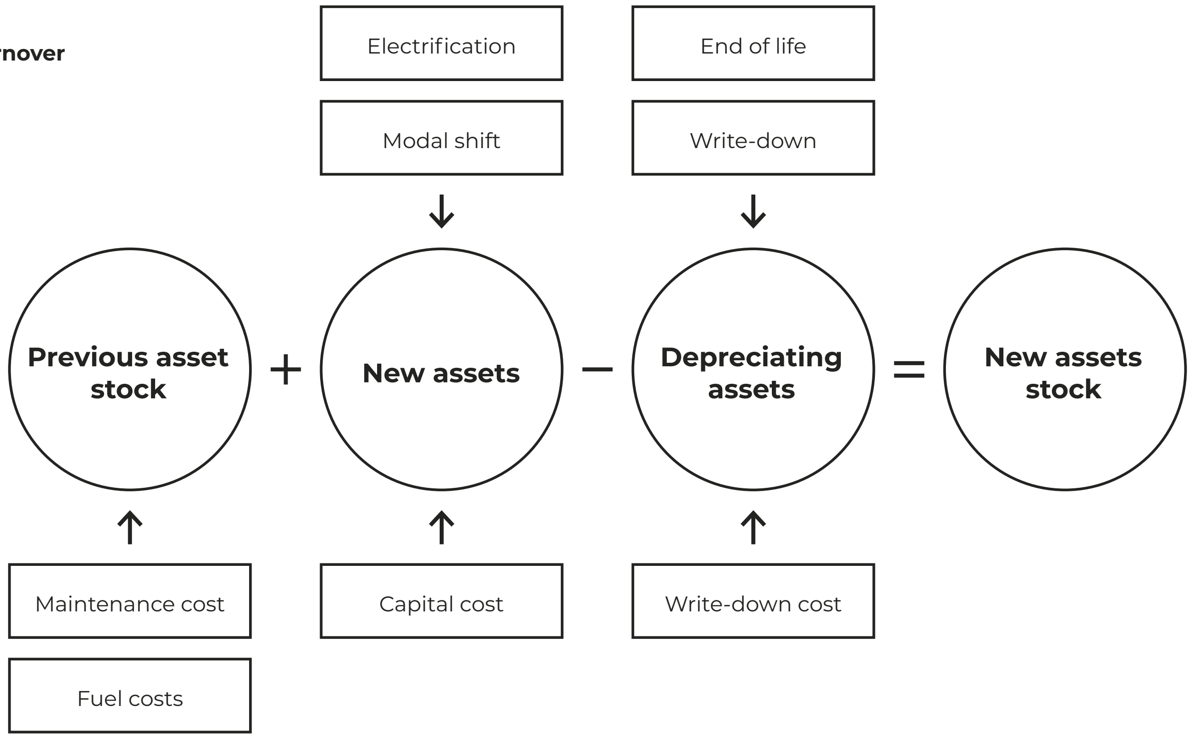
ANNEX I: TRANSPORT TRANSITION PATHWAY EXPLORER (TTPE)

The core module of the TTPE is its stock-turnover model. It explicitly estimates previous stock, new assets as the result of electrification or modal shift, as well as depreciating assets as a result of the end of the economic lifetime or premature write-downs. The explicit evaluation of stock turnover allows for tracking the evolution of total cost of operation of stock over time **(see → Fig. 9)**.

The evolution of stock triggers additional infrastructure needs, specific to each transport mode **(see → Fig. 10)**. We model infrastructure investment requirements based on assumptions on infrastructure usage shares, infrastructure utilization and load factors, as well as infrastructure CAPEX per km.

For all pathways developed in the TTPE, the optimization problem is bounded by exogenously set feasibility constraints (derived from literature and expert judgement). These bounds are minimum or maximum values that variables can take to avoid unrealistic outcomes, e.g. the share of non-motorized transport is limited to the range of 7%-24%. A full list of target year values for optimized policy leavers, as well as maximum and minimum bounds for the least-cost and the transition pathway are provided in Annex II. A discussion of data sources is provided in Annex III.

Fig. 9
Stock turnover model



Source: Produced by authors.

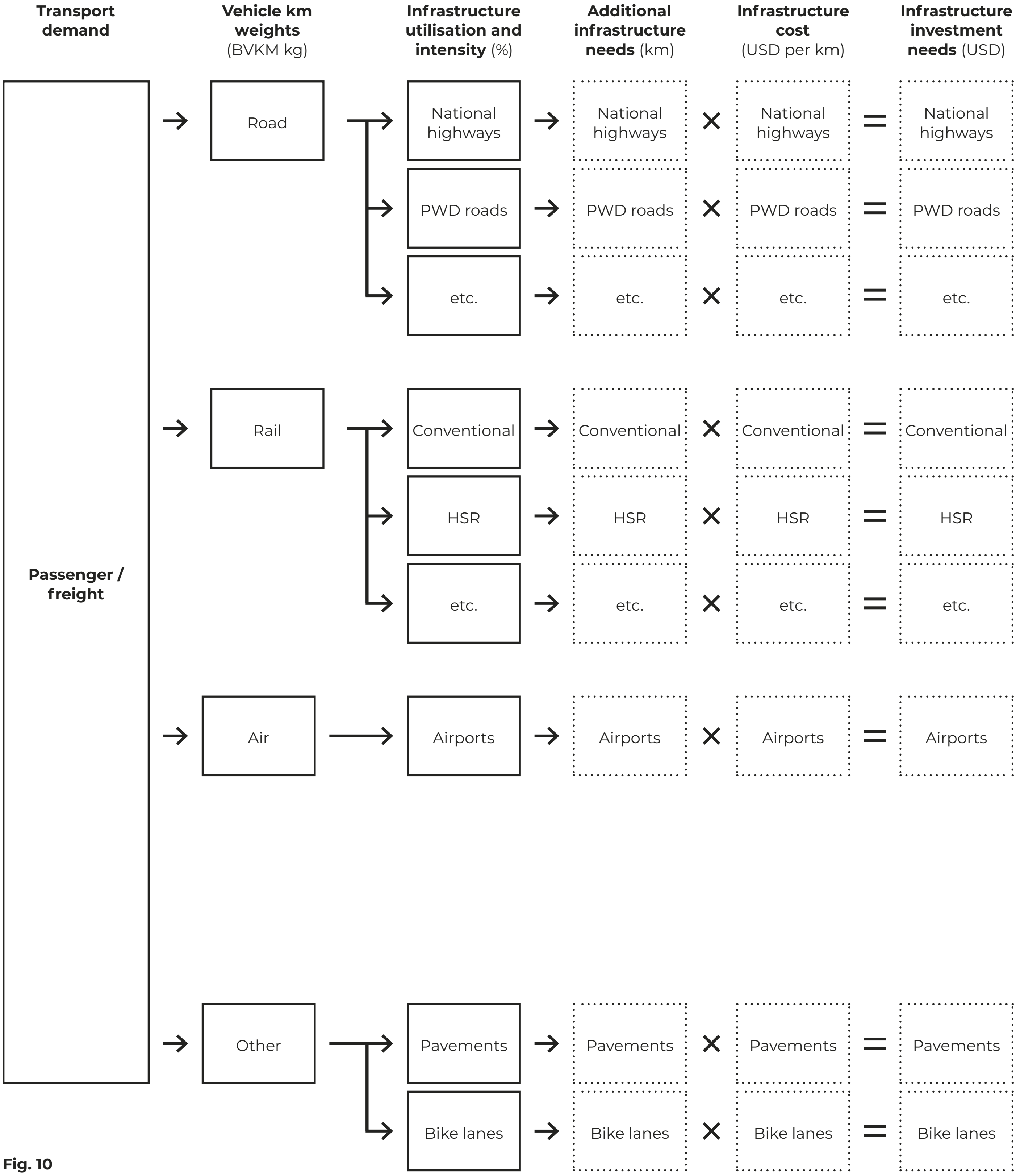


Fig. 10

Infrastructure investment model

Source: Produced by authors.

ANNEX II: TARGET VALUES AND BOUNDS

Lever	Total system costs				Transition pathway			
	Target value 2050 (%)	Min (%)	Max (%)	Functional form	Target value 2050 (%)	Min (%)	Max (%)	Functional form
Urban passenger trains	11	11	50	Quadratic	50	11	50	Quadratic
Urban NMT	24	7	24	Linear	24	7	24	Linear
Urban freight trains	50	35	50	Linear	50	35	50	Linear
Rural passenger trains	11	11	50	Quadratic	50	11	50	Quadratic
Rural NMT	24	7	24	Linear	24	7	24	Linear
Rural freight trains	35	35	50	Linear	50	35	50	Linear
Urban bus	68	3	68	Quadratic	3	3	68	Quadratic
Urban omnibus	10	1	10	Quadratic	1	1	10	Quadratic
Urban taxi	3	3	10	Quadratic	3	3	10	Quadratic
Rural bus	68	3	68	Quadratic	3	3	68	Quadratic
Rural omnibus	10	1	10	Quadratic	1	1	10	Quadratic
Rural taxi	3	3	10	Quadratic	3	3	10	Quadratic
Urban electric bus	100	0	100	Quadratic	100	1	100	Quadratic
Urban electric omnibus	100	0	100	Quadratic	100	1	100	Quadratic
Urban electric 4W	100	4	100	S-Curve	100	4	100	S-Curve
Urban electric 2W	100	8	100	S-Curve	100	8	100	S-Curve
Urban electric 3W	100	6	100	S-Curve	100	6	100	S-Curve
Urban electric taxi	100	6	100	S-Curve	100	6	100	S-Curve
Urban electric trains	52	52	100	Quadratic	100	52	100	Quadratic
Urban electric HCV	100	0	100	S-Curve	100	0	100	S-Curve
Urban electric LCV	100	0	100	S-Curve	100	0	100	S-Curve
Urban electric freight trains	100	68	100	Quadratic	100	68	100	Quadratic
Rural electric bus	1	1	100	Quadratic	100	1	100	Quadratic
Rural electric omnibus	100	1	100	Quadratic	100	1	100	Quadratic
Rural electric 4W	100	4	100	S-Curve	100	4	100	S-Curve
Rural electric 2W	100	8	100	S-Curve	100	8	100	S-Curve
Rural electric 3W	100	6	100	S-Curve	100	6	100	S-Curve
Rural electric taxi	100	6	100	S-Curve	100	6	100	S-Curve
Rural electric trains	52	52	100	Quadratic	100	52	100	Quadratic
Rural electric HCV	100	0	100	S-Curve	100	0	100	S-Curve
Rural electric LCV	100	0	100	S-Curve	100	0	100	S-Curve
Rural electric freight trains	100	68	100	Quadratic	100	68	100	Quadratic

Tab. 1

Target values and bounds

ANNEX III: DATA SOURCES

The transport model runs on publicly available data. Primary data sources used in the transport model comprise Niti Aayog's IESS 2047 (NITI Aayog, 2023), CEEW's India Transport Energy Outlook (Kamboj et al., 2022), TERI's Transitioning to a low carbon technology for the road transport (Kaushik et al., 2022), the ICCT's Decarbonizing India's road transport: Meta-analysis (Kumar et al., 2022), GIZ's Status quo analysis of various segments of electric mobility in India (GIZ et al., 2021), as well as the Climate Action Tracker's Decarbonizing the Indian transport sector pathways and policies (CAT, 2020). Power sector decarbonization enters the TTPE exogenously and is based on IEA WEO 2022 data (IEA, 2021).

Transport demand is the primary independent variable on which the TTPE bases its estimation. Projections of transport demand differ widely, also with respect to what they cover. Few estimates of transport demand, for example, robustly cover non-motorized transport. For passenger and freight transport demand, we use IESS 2047 transport demand estimates (NITI Aayog, 2023), but adjust using data from CEEW (2022) it to include non-motorized transport where applicable.

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