Compact Cities Electrified:
The Benefits of Small Vehicles

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COVER IMAGE
Jakarta highway traffic along Jendral Sudirman road on weekday.
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COMPACT CITIES ELECTRIFIED:
THE BENEFITS OF SMALL VEHICLES

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EXECUTIVE SUMMARY

The Institute for Transportation and Development Policy (ITDP), alongside the University of California, Davis (UC Davis), undertook the first known country-level analysis of the impact of growing vehicle sizes in urban passenger transport on road safety, energy use, battery consumption, and greenhouse gas (GHG) emissions, among other factors. Across the six countries we studied, we found notable benefits from limiting the growth in passenger car vehicle size in all areas where we had strong data. We noted particularly strong benefits for private sector direct costs, where we saw 19% to 22% reductions in consumer spending requirements, including lower costs for vehicle purchase, maintenance, and fuel. We also saw significant reductions from the use of smaller vehicles in liquid fuel requirements (11%–14% reduction), electricity consumption (8%–12% reduction), battery requirements (12%–14% reduction), traffic deaths (8%–9%), and GHG emissions (4%–10% reduction). The positive results held true regardless of whether policy scenarios limiting the growth of vehicle size were combined with scenarios representing current policy trajectories or with scenarios of ambitious electrification and/or mode shift.

Policies to limit the growth of vehicle size will likely yield significant and positive impacts, regardless of which other policy scenarios they accompany. By reducing overall costs, as well as battery and electricity requirements, a scenario with smaller vehicles would help to implement a *High EV* scenario by reducing the amount of money, infrastructure, and materials needed for rapid electrification. Current trends, however, show a worrying growth in vehicle size, particularly in sport-utility vehicles (SUVs), which grew from around 20% of global vehicle sales in 2008 to more than half of all vehicle sales in 2022 (see Figure 3.3.a). The spread of this North American model of increasing vehicle sizes will have substantial negative impacts for countries around the world if they continue along this path.

When strong *Electrification* and *Modal Shift* policies are combined with policies to limit vehicle size, we see even greater benefits. In addition to generating the largest benefits, these three strategies complement and support one another. For example, with *Mode Shift* policies leading to fewer vehicles to electrify and smaller vehicle policies leading to lower energy needs per vehicle, it is easier and faster to electrify more of the transport system. Together, the three policies lead to a world with massive reductions in local air pollution, traffic deaths, energy consumption, transport costs, and GHG emissions.

METHODS

To assess these impacts, the research team developed a global scenario–based outlook on the future of urban passenger transport, exploring the effects of modal shift, vehicle electrification, and vehicle sizes on overall cost, safety, and GHG and air pollutant mitigation. The analysis builds on more than a decade of collaborative modeling, evaluating the implications of various futures in six countries: Brazil, China, India, Indonesia, Mexico, and the United States. In each of these countries, selected for their large populations and influence, we imagine five plausible scenarios for urban passenger transport in 2050:

- ***Business as Usual (BAU):*** Current trends; increased car travel in most countries, slow electrification, rapid growth of vehicle sizes.
- ***Mode Shift (Only):*** Increased walking, cycling, and public transport.
- ***High EV (Only):*** Rapid vehicle electrification.
- ***Small Vehicles (Only):*** Smaller physical size of new vehicles relative to *BAU*, maintaining vehicle sizes at 2020 levels.
- ***Shift+EV+Small:*** Combined *Mode Shift*, *Electrification*, and *Small Vehicles*.

We describe each of these scenarios in quantitative specifics (Section 3)—including estimates of vehicle fleet characteristics and travel behavior—and then assess the implications of each scenario for several categories of impact (Sections 4 and 5). While we use the term *Small Vehicles*, we are referring to a scenario that avoids the increase in vehicle size and weight that has occurred in some countries. In countries where vehicles are still mostly small, the *Small Vehicle* scenario maintains existing vehicle size and weight. This is the first time an ITDP–UC Davis study has included an evaluation of the country-level impacts of growing vehicle sizes or the public health impacts of various scenarios.

KEY FINDINGS

- **Scenarios limiting the growth in vehicle size have significantly fewer negative impacts** than scenarios where vehicle sizes continue to grow, including reduced private sector direct costs (19%–22% reductions), liquid fuel requirements (11%–14%), electricity consumption (8%–12%), battery requirements (12%–14%), traffic deaths (8%–9%), and GHG emissions (4%–10%).
- ***Mode Shift* measures could save a total of 1,500,000 lives and reduce road traffic deaths by 40% annually by 2050.** The total of 1.5 million lives saved stems from the physical activity that comes with increased walking and cycling, countering cardiovascular and respiratory disease and death. With reduced travel, road traffic deaths, the world's leading cause of death for people under 30, would also decline.

- ***Small Vehicles* and *Mode Shift* can mitigate increasing demand for energy and batteries.** In the *High EV* scenario, energy consumption and battery requirements will rise dramatically, straining physical infrastructure. The *Small Vehicles* and *Mode Shift* scenarios reduce overall energy consumption by 70% and liquid fuel consumption by 85% across all countries, while delivering *High EV* outcomes that require only 4% more battery capacity than a *BAU* scenario.

- **GHG emissions can be strongly reduced by both *Mode Shift* and *High EV* strategies,** with a minor contribution from *Small Vehicles*. The synergistic effects of combining all three strategies can reduce annual GHG emissions across all six countries by more than two thirds (1.2 gigatonnes) by 2050, keeping emissions close to the sectoral threshold required for consistency with the Paris Agreement.

- **Direct public and private costs are projected to increase by an order of magnitude in countries such as India and China** in our *BAU*. In all six countries, *Mode Shift* (by reducing government infrastructure and consumer vehicle costs) and *Small Vehicles* (by reducing consumer vehicle costs) will cut costs by 50%.

- ***High EV* and *Mode Shift* can dramatically reduce local air pollution.** Local air pollutants cause many respiratory diseases. *High EV* measures abate the emission of tailpipe pollutants, particularly by reducing the NO_x emitted by diesel buses. At the same time, *Mode Shift* measures can reduce up to 50% of non-tailpipe emissions (from brake, tire, and road wear), which are a growing portion of local pollution that cannot be addressed by electrification. This combination could reduce 2050 primary emissions of fine particulate matter (PM2.5) from urban passenger transportation by around 67% across all countries.

	Mexico	Brazil	China	India	Indonesia	USA	Units
Annual electricity consumption savings in 2050, EV (Only) vs EV+Shift+Small	200	200	1,000	500	200	600	Petajoules/year
Annual liquid fuel requirement savings in 2050	100	200	800	500	200	800	Millions of barrels of gasoline-equivalent
Annual GHG emissions savings in 2050	50,000	60,000	400,000	200,000	70,000	300,000	Thousands of tonnes of CO2-equivalent
Annual direct public & private cost savings in 2050	200	200	2,000	700	100	900	Billions of USD
Annual battery requirement savings in 2050, EV (Only) vs EV+Shift+Small	100	100	800	400	50	400	Gigawatt-hours of battery capacity
Annual road safety fatalities avoided in 2050	2,000	10,000	40,000	90,000	10,000	8,000	Fatalities
Annual particulate matter (PM2.5) emissions avoided, 2050	9	8	60	30	50	40	Thousands of tonnes of urban PM2.5
Annual premature deaths avoided through physical health benefits of active mobility in 2050	50,000	80,000	700,000	300,000	100,000	300,000	Premature deaths

We reach three conclusions:

1. Policies to limit the growth of vehicle size, though not a panacea, can partially mitigate a wide variety of suffering—particularly reducing transport costs.

2. The greatest societal benefit is from combining all three strategies. Often the strategies complement each other. For example, while battery demand increases in the *High EV* scenario, it is reduced by the other two scenarios. Similarly, the *Mode Shift* strategies reduce non-tailpipe emissions while the *High EV* strategies reduce tailpipe emissions.

3. These strategies bring many benefits that we could not quantify. For example, *Mode Shift* strategies reduce the destruction of natural areas and farmland, and *High EV* strategies reduce urban noise and improve vehicle performance. Smaller vehicles can help free up road space for other uses.

All five scenarios are equally possible. Without a change in the policies that guide urban development, transportation investments, and vehicle fleets, it is likely that the Business as Usual scenario will come to pass, bringing high costs, pollution, and loss of life to cities around the world. The EV+Shift+Small scenario brings the greatest economic, social, environmental, and humanitarian benefits, but it will require strong city- and country-level policies to achieve.

The implications are clear, and the choice of urban future rests with each city and each country's government. How will they choose?

BACKGROUND

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This study is the continuation of more than a decade of collaboration between ITDP and UC Davis in modeling the impacts of potential futures for the urban passenger transport sector.[1] Previous High Shift and Compact Electrified publications have established a basic model then refined that model with closer attention to bicycling, autonomous vehicles, and vehicle electrification, and most recently, to analysis at the level of individual countries. With this report, we take two new steps: First, we include analysis of trends in the physical size of vehicles, particularly cars and SUVs; and second, we include new dimensions of impact, most notably air quality, physical activity, and road safety.

As with our previous work, this is a scenario-based “outlook” study rather than a “forecasting” analysis. We do not begin with particular policies, investments, or decisions that may be made in the present and then attempt to predict their impacts; rather, we begin with scenarios. “What if the world continues on its current trend?” “What if cities switch as much travel as possible to walking, cycling, and public transport?” “What if countries reduce car sizes by the maximum feasible amount?” As described in Section 3, below, we define what these scenarios might look like through data collection and regional expert review. Then, in Sections 4 and 5, we answer questions about their implications: What infrastructure would be needed to achieve them, how much it would cost, and what might these scenarios mean for emissions and public health among other impact variables?

This is not a detailed analysis of specific policies that are on the table for different governments. Neither is it an unrealistic fantasy. The scenarios are based on actual trends, actual policy goals, and international experience in urban planning reform; they have been reviewed by experts from around the globe. This study is an attempt to envision various possible futures, grounded in rigorous analysis and ambitious but feasible scenarios. *The Compact Cities Electrified* approach gives us an opportunity to imagine the future world as different, and better, than where it is currently headed.

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[1] ITDP & UC Davis. (2021). The Compact City Scenario—Electrified; ITDP & UC Davis. (2017). Three revolutions in urban transportation; ITDP & UC Davis. (2015). A global high shift cycling scenario; ITDP & UC Davis. (2014). A Global High Shift Scenario: Impacts and Potential for More Public Transport, Walking, and Cycling with Lower Car Use.

3

SCENARIO DESIGN

3.1. SUMMARY OF SCENARIOS

In this study, we consider three major factors in the development of a country's urban passenger transportation sector: modal split, vehicle electrification, and vehicle size. We call these our "scenario variables." We ask what these factors could entail for seven categories of impact: GHG emissions, direct public and private costs, air pollution, public health, road safety, energy consumption, and battery material requirements.

To understand the relationship between these three factors and those seven impacts, we examine various scenarios for the future of urban passenger transportation in each country. We start with a *Business as Usual* (*BAU*) scenario representing current trends. Then, for each of the three factors, we devise a scenario representing substantial reform. We study several permutations of these scenarios:

Figure 3.1.a. Five scenarios studied

	SCENARIO NAME	MODAL SPLIT	VEHICLE ELECTRIFICATION	VEHICLE SIZE
1	***Business as Usual (BAU)***	Car-oriented	Slow electrification	Large vehicles
2	***Small Vehicles (Only)***	Car-oriented	Slow electrification	Small vehicles
3	***High EV (Only)***	Car-oriented	Fast electrification	Large vehicles
4	***Mode Shift (Only)***	Transit + walk + bicycle oriented	Slow electrification	Large vehicles
5	***Shift+EV+Small***	Transit + walk + bicycle oriented	Fast electrification	Small Vehicles

Note that this does not include certain permutations that use only two of the three scenario variables (for example, a scenario including *High EV* and *Small Vehicles* but not *Modal Shift*). We did calculate these results, but we do not report them in this publication to maintain clarity in the presentation of findings. (Full findings for all scenarios are available by request at data@itdp.org.)

This study builds on past work in country-level modeling from ITDP and UC Davis, particularly the Compact Cities Electrified series of country-level reports from 2023 and 2024. That series of reports included only two of the three factors we consider here: It included modal split and vehicle electrification but did not include vehicle size. Therefore, we have adapted our scenarios for modal split and vehicle electrification from those past studies (Section 3.2), but we had to develop scenarios for vehicle size anew for the current effort (Section 3.3).

3.2. MODAL SHIFT AND ELECTRIFICATION

The 2023–2024 series of Compact Cities Electrified country-level reports included definitions of *BAU*, *Mode Shift*, *High EV*, and *Shift+EV* scenarios for each of the six countries examined in the present study. We use those exact, previously published scenario definitions for modal splits and electrification rates here. Our only change since 2023–2024 is the addition of vehicle size as a scenario variable, described in Section 3.3, below.

The methods for defining those scenarios are described in detail in the previous series of country-level reports. In summary: Our process began with industry-standard data for current transportation statistics and trends through 2050 from the International Energy Agency's Mobility Model.[2] We modified its Business as Usual scenario based on country-specific data in each geography. We constructed *Mode Shift* scenarios based on analysis of urban form and the potential for change in the transportation system. These *Mode Shift* scenarios have very different 2050 travel shares than the *BAU* (see Figure 3.2.a and b). We constructed *High EV* scenarios based on analysis of vehicle electrification policy goals (see Figure 3.2.c), aligned with the Glasgow Agreement at COP27. We refined both the *Mode Shift* and the *High EV* scenarios through extensive, iterative review with country-level and international experts representing academia, the public sector, and civil society and nongovernmental organizations in each country or region. The names and affiliations of reviewers are listed in each of the 2023–2024 country-level reports.

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[2] *The Mobility Model* is proprietary and cannot be shared directly. Relevant country-level data excerpts are availability in the methodological documentation of the relevant *Compact Cities Electrified* country-level report, available at itdp.org. For background information about the *Mobility Model*, see: Cuenot, Francois, Lew Fulton, and John Staub. (2012). "The Prospect for *Modal Shift*s in Passenger Transport "Worldwide and Impacts on Energy Use and CO_2." *Energy Policy* 41:98–106. DOI: 10.1016/j.enpol.2010.07.017.

Figure 3.2.a. Urban passenger travel by mode, country, scenario, and year

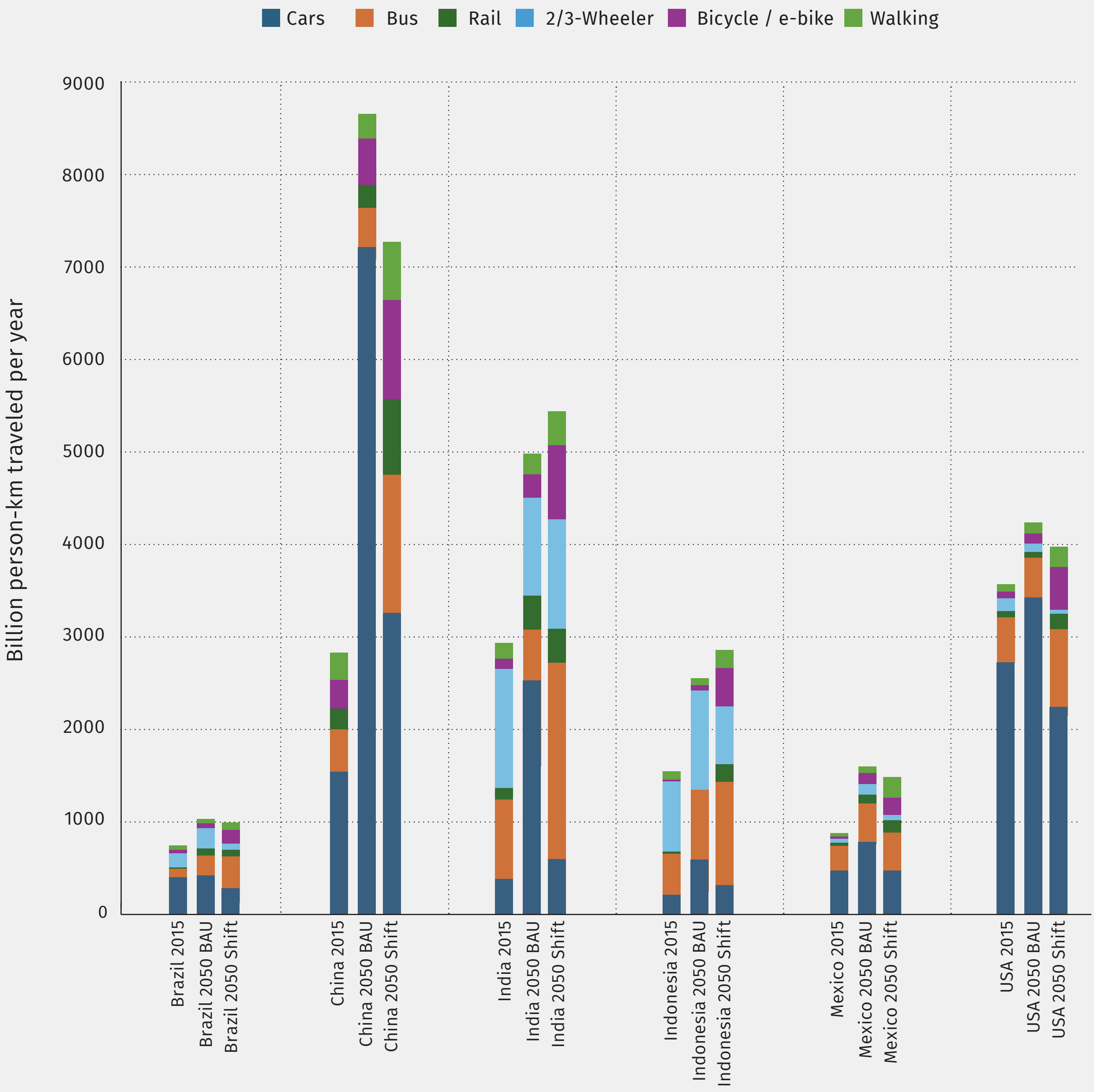


Figure 3.2.b. Urban passenger travel by mode, country, scenario, and year—normalized

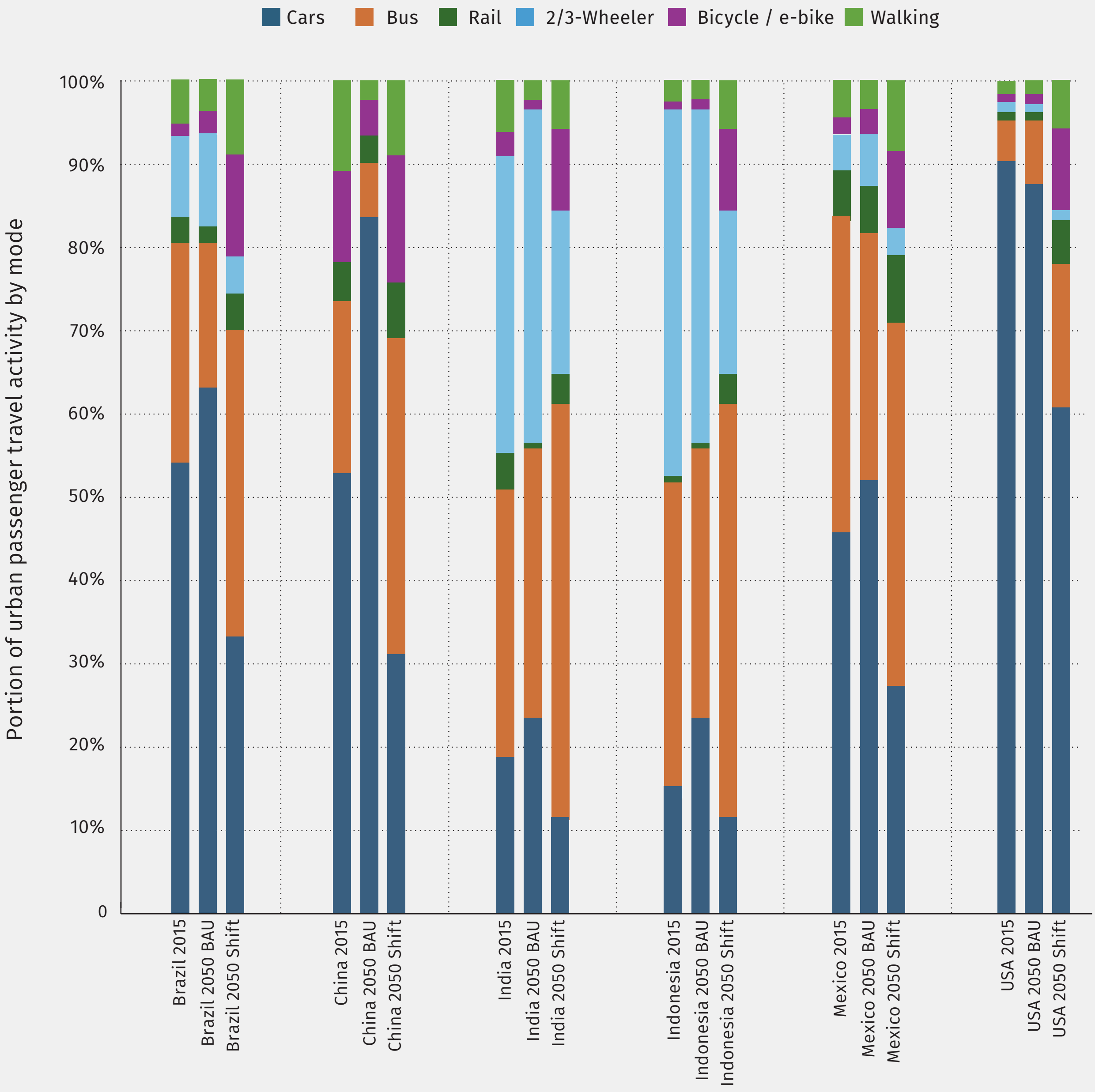
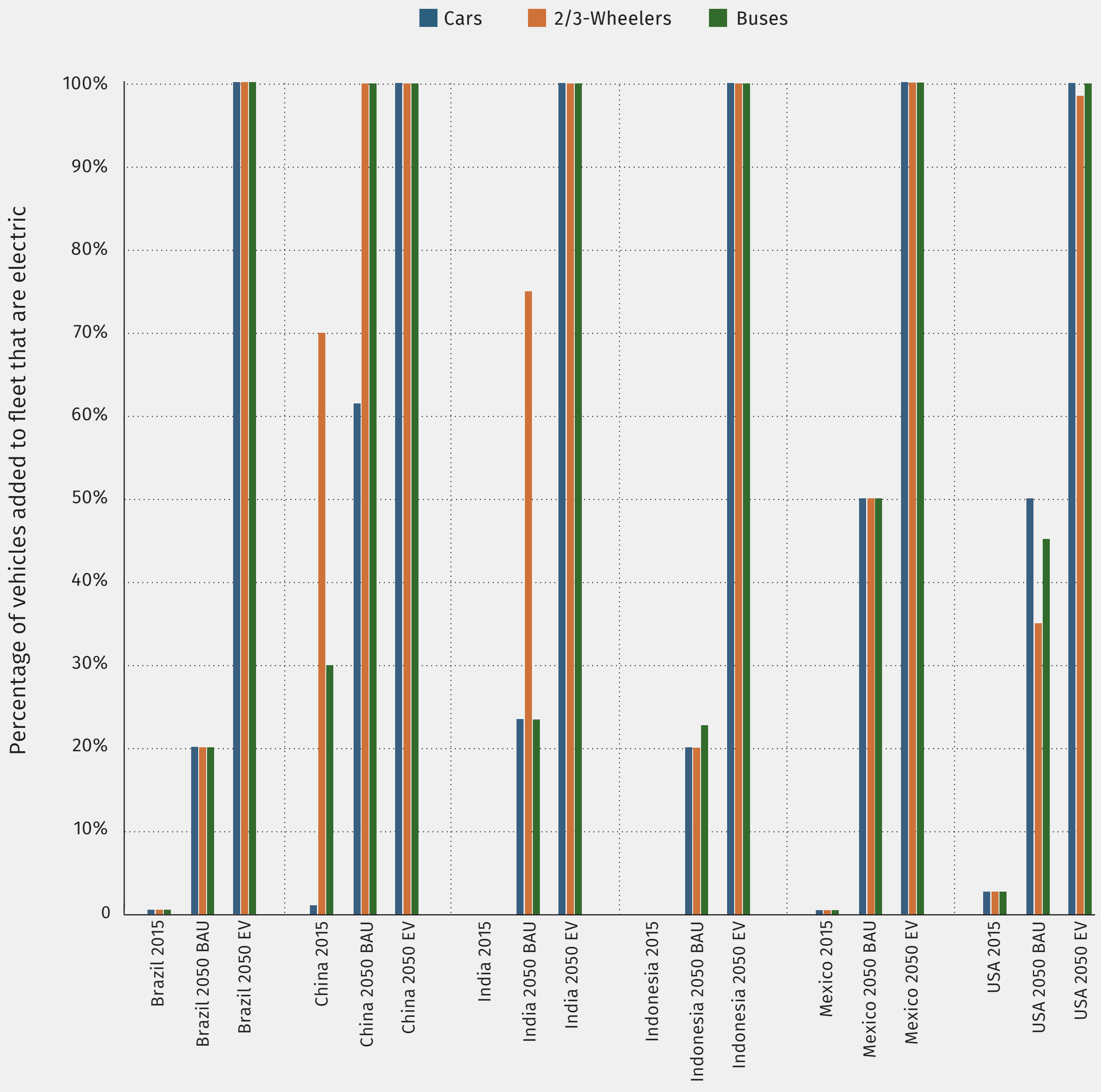


Fig 3.2.c: Electrification Rates (Sales Shares) by Country, Scenario, and Year

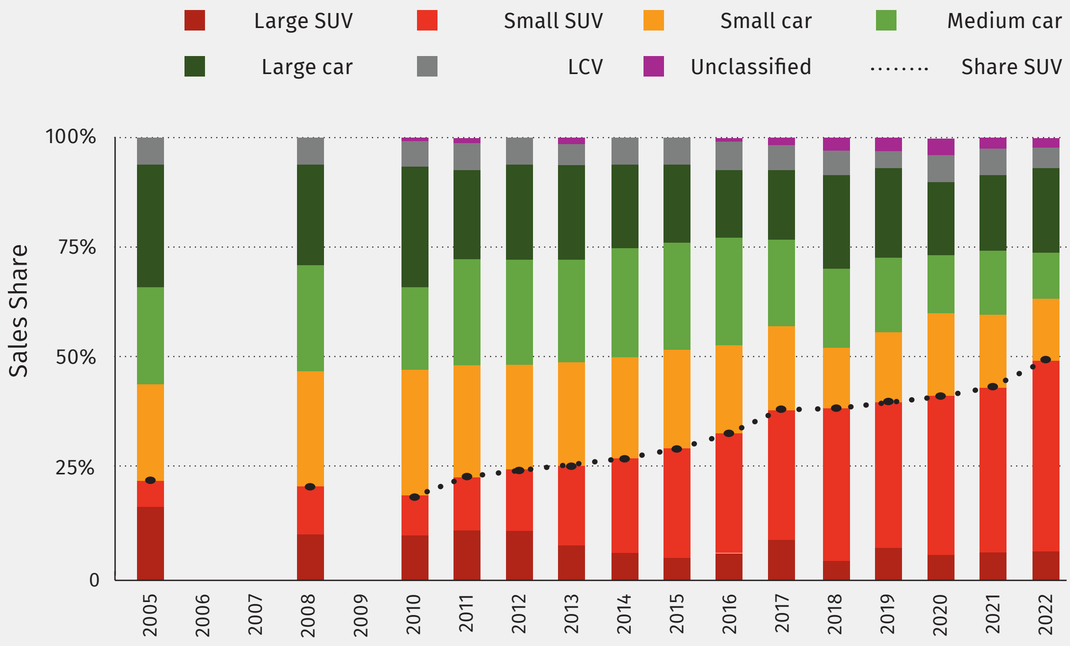


3.3. VEHICLE SIZE

This study builds on the 2023–2024 country-level reports by considering a new variable: the physical sizes of light-duty passenger vehicles (LDVs). Thus, just as we have scenario definitions for *BAU* (slow electrification) vs. *High EV* (rapid electrification) and *BAU* (continued rise in car use) vs. *Mode Shift* (dramatic shift toward walk/cycle/public transport), we also create scenario definitions for *BAU* (continued growth in vehicle sizes) and *Small Vehicles* (in which the sizes of new vehicles return to 2020 levels by 2030 and remain at that level). These scenario definitions are combined in all permutations to produce the eight scenarios shown in Figure 3.1.a, above.

To create the *BAU* (continued growth in vehicle size) and *Small Vehicles* scenario definitions, we begin with recent work done by UC Davis and its related European Center (ETERC). UC Davis/ETERC published a foundational report for the Global Fuel Economy Initiative (GFEI) in 2023[3] that used detailed vehicle registration data for a range of countries and "rest of world" to track national and global trends in light-duty vehicle sizes and size-class market shares. Since 2005, and especially since about 2010, vehicle sizes have been rising rapidly globally, with small SUVs displacing cars as their market share has grown. As of 2022, SUVs accounted for fully half of new LDV sales around the world, up from about 20% in 2010, including increased SUV sales in all countries included in this study. Nearly all the increase over the past decade has been in smaller SUVs, but average sizes have been rising. In the future, the share of large SUVs could grow rapidly in many countries, as it is in the US already. The global historical trend, adapted from GFEI (2023), is shown in Figure 3.3.a, below.

Figure 3.3.a. GFEI results describing global LDV sales by size class and year



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[3] Cazzola, Pierpaolo, Leonardo Paoli, and Jacob Teter. (2023). "Trends in the Global Vehicle Fleet 2023." Retrieved March 10, 2025 https://www.globalfueleconomy.org/data-and-research/publications/trends-in-the-global-vehicle-fleet-2023.

Following GFEI, we understand the changing size of vehicles in terms of changes in the sales of vehicles of five different size classes: small cars, medium cars, large cars, small SUVs, and large SUVs. We do not include unclassified vehicles or light commercial vehicles (LCVs) in our study because they account for a relatively small proportion of passenger travel and it is difficult to project scenarios for future trends in these categories.

Our vehicle class categories are broad, and some countries may have smaller or larger vehicles on average in each class than other countries. We use detailed model-level data to estimate the actual characteristics of vehicles in each class and in each country. Thus, the actual vehicle composition for each country, with its average weight and efficiency, can vary significantly. We also use the specific vehicle prices for models available in each country, and the class average can vary considerably on that basis as well. In general, even within the same vehicle class, models in countries such as India or Indonesia tend to be smaller and more affordable than in the US. That said, this varies by specific country and segment.

The GFEI report provides estimates for the 2023 market shares of different vehicle size classes for each of the six countries examined in this study, and we adopt those directly as a base year. (Although the study as a whole uses 2015 as an overall base year, our modeling of vehicle size uses projections that include known values through 2023).

To define Business as Usual scenarios for vehicle size, we project current trends into the future. In Figure 3.3.a, above, we observe that the growth in SUV sales has been roughly linear for the past decade. Although the particular rate of growth in sales of different vehicle classes varies by country, we generally project *BAU* as a linear increase in the sales of larger vehicles, following trends of the past decade.

To define *Small Vehicles* scenarios in each country, we assume that the market share of each vehicle size class will gradually revert to its 2020 proportion by 2035. From 2035 through 2050, we hold these proportions nearly constant. In each country, from 2035 through 2050 in the *Small Vehicles* scenarios, small cars, medium cars, and SUVs would make up roughly the same share of the fleet as they did in 2020, even if the total number of vehicles grows. This is meant to represent a “maximum feasible” reform of vehicle size regulations, reflecting regulatory action to internalize the negative externalities of increased vehicle size or otherwise disincentivize large vehicles, while still permitting consumers the choice to purchase a larger vehicle if they so desire. The *BAU* and *Small Vehicles* scenarios for vehicle size classes are shown in Figure 3.3.b, below. Because of the relatively long time frame for the study, vehicle fleet stocks follow sales closely, as shown in Figure 3.3.c.

Figure 3.3.b. Vehicle sales by size class, country, scenario, and year

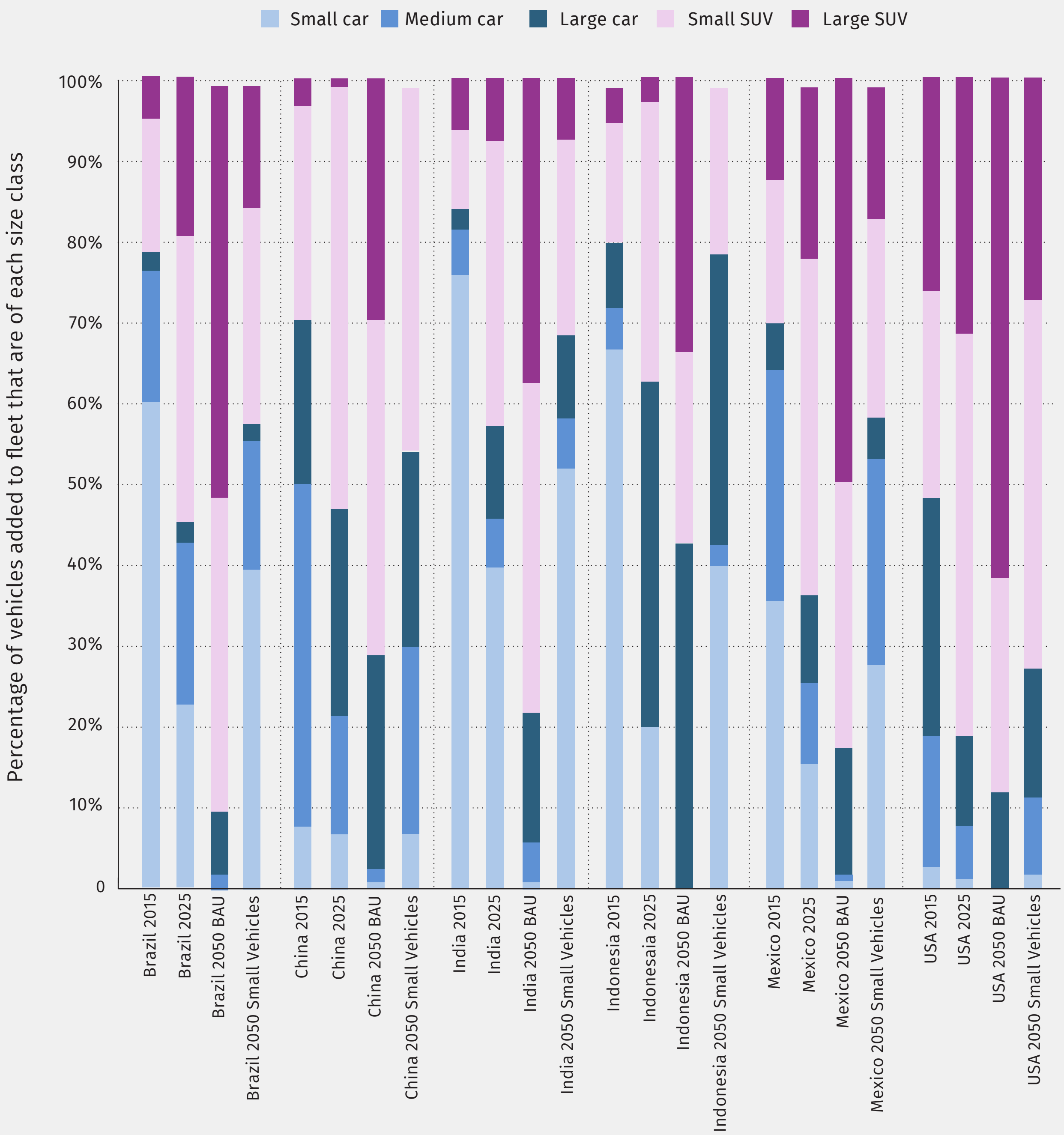
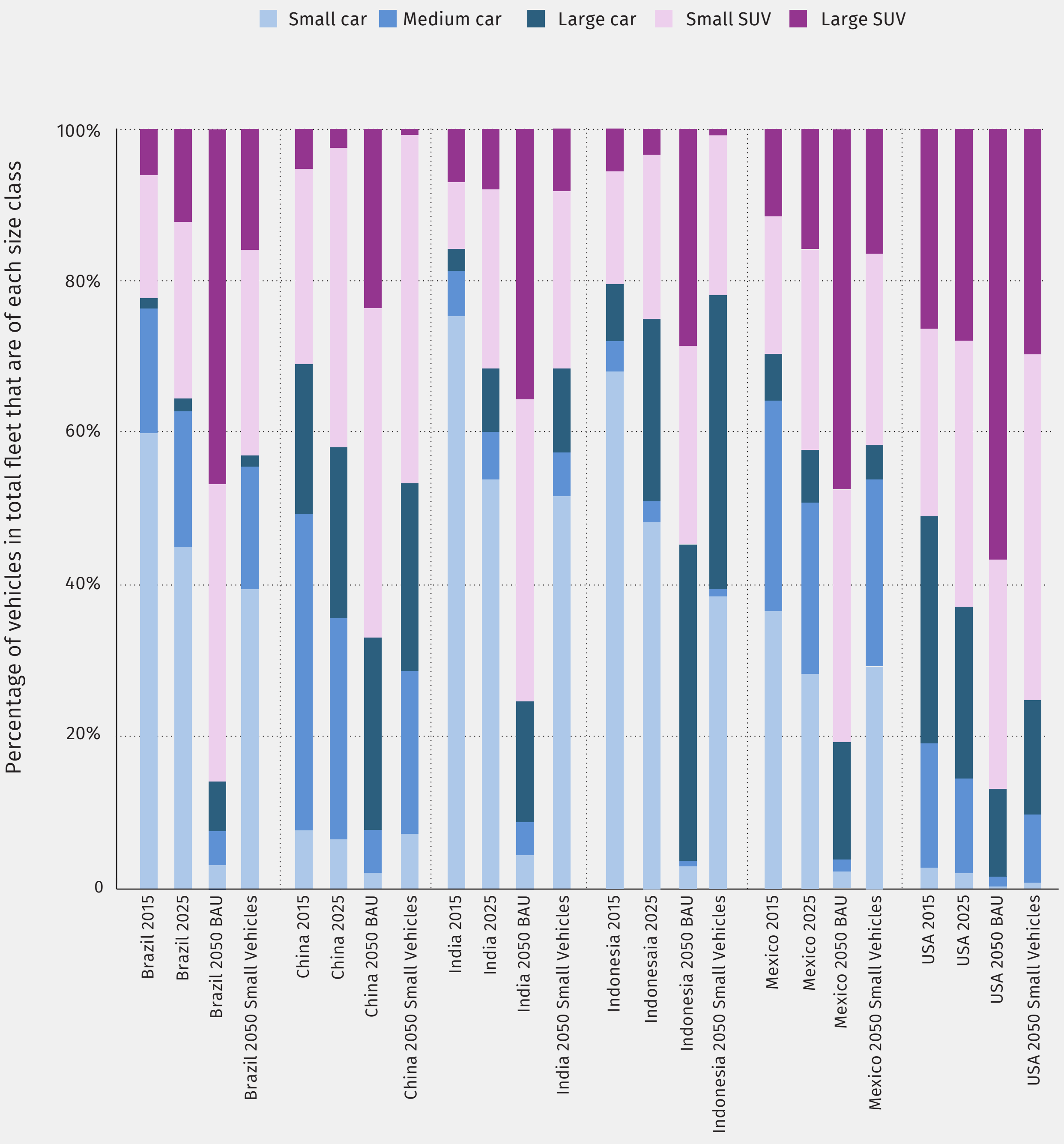


Figure 3.3.c. Vehicle stocks by size class, country, scenario, and year



3.4. ASSUMPTIONS AND LIMITATIONS

Modeling the next decades of urban passenger transport for six of the planet's largest countries is an ambitious task. To complete this effort, we have had to make some simplifying assumptions. In general, we have consistently tried to be conservative in these assumptions—that is, to make the assumptions that would underestimate rather than overestimate the difference between scenarios. We have also tried to document assumptions clearly.

In all scenarios, we report a base year of 2015, but we typically report 2025 as well.[4] When we began the Compact Cities Electrified research program in 2021 with a global study, cities around the world were still under the COVID-19 lockdowns, and it was not feasible to use any analytical base year that was affected by those lockdowns. The 2023–2024 country-level analyses did update the Business as Usual scenarios to reflect emerging post-COVID trends, but a full update to a new base year will have to wait until more census-based country-level data becomes available. The year 2025 will be the appropriate time when all the data is available and collated. Until then, we believe that using the 2015 base year is best. However, we also provide estimates for 2025 for many variables. We've also been able to obtain data on vehicle size through early 2025, making these estimates quite current. **We do not account for the potential role of autonomous vehicles**. The potential impacts of autonomous vehicles are discussed in our previous study, *Three Revolutions in Urban Transportation*.[5] Since that report was published, industry expectations for the proliferation of autonomous vehicles have become more conservative. To avoid the uncertainty in predicting progress in and uptake of autonomous vehicle technology, we have omitted automation from our study, focusing instead more cleanly on electrification, vehicle size, and modal shift.

Further limitations related to the calculation of particular impacts are documented in the subsections of Section 4, below.

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[4] ITDP & UC Davis. (2021). The Compact City Scenario—Electrified.

[5] Lew Fulton, Jacob Mason, and Dominique Meroux. (2017). Three Revolutions in Urban Transportation. ITDP and UC Davis.

4

METHODS

4.1. SELECTION OF IMPACT VARIABLES

Urban passenger transportation has some connection, direct or indirect, to almost every facet of modern life. The way people move plays a role in economics, health, politics, even culture, and all of these, in turn, affect the way people move. We defined various scenarios in Section 3, and now we estimate the impacts that each of these scenarios would have for several categories. Some of these categories of impact were included in the previous Compact Cities Electrified reports (2021 and 2023–24), while others are new to this publication.

Perhaps the most direct impacts of our scenarios for urban passenger transportation are the impacts on energy consumption. Energy is required for all forms of transportation, and the energy efficiency of various forms of transport is one of the most important factors in determining other impacts, such as cost. Our examination of energy consumption in Section 4.2 (with results shown in Section 5.2) includes electricity as well as liquid fuels, and also an estimate of the total quantity of liquid fuels that can be saved in each alternative scenario.

We examine GHG emissions in Sections 4.3 and 5.3. Transportation is the second-largest source of GHG globally, after the combined category of electricity and heat.[6] In a rapidly urbanizing and rapidly warming world, it is crucial for our planet's future that we dramatically reduce GHG emissions, including from urban passenger transport.

Around the world,[7] transportation isn't only costly to individuals but also to governments, which spend tens or hundreds of billions of dollars on urban transportation infrastructure, maintenance, and operations every year. The design of our urban transportation systems and vehicles determines the extent of these costs and how they are distributed between public and private payers. Over the next 25 years, cities and countries will have many opportunities to change this design and reduce—or increase—the costs of transportation. In Sections 4.4 and 5.4, we look at the direct public and private costs of urban passenger transportation. This includes costs associated with both vehicles and infrastructure, as well as systems costs for public transport and shared mobility systems.

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[6] Hannah Ritchie, Pablo Rosado, and Max Roser. (2020). "Breakdown of carbon dioxide, methane, and nitrous oxide emissions by sector." Published online at OurWorldinData.org. Retrieved from https://ourworldindata.org/emissions-by-sector.

[7] This varies by country and by income level within a country; see https://itdp.org/2024/01/24/high-cost-transportation-united-states.

Sections 4.5 and 5.5 examine the battery requirements of our different scenarios. With rising electrification not only in the transport sector but throughout the global economy, batteries will be increasingly in demand worldwide. There is rising awareness of the often-harmful impacts associated with the extraction of minerals used in batteries,[8] and although research points to ways of mitigating these impacts,[9] it is clear that our planet will benefit from reducing battery requirements as much as possible while also minimizing the use of fossil fuels.

Road safety is another key impact of urban passenger transport, examined in Sections 4.6 and 5.6. Well over a million people are killed each year by avoidable traffic violence. While human error is inevitable, it is possible to greatly reduce the risk of fatalities by adopting safer urban transport systems, including smaller vehicles, roads designed for lower speeds, and a less car-dependent mobility system.[10]

Air pollution is among the world’s leading causes of death, and transportation is a major contributor. However, previous ITDP–UC Davis collaborations, as well as other sector-wide outlook analyses, have not quantified country-level prospective changes in how transportation contributes to air pollution. We take up this subject in Sections 4.7 and 5.7.

Finally, in Sections 4.8 and 5.8, we look at the implications of our scenarios for physical activity and public health. Around the world, the next 25 years could see a substantial growth or shrinkage in the number of people who travel by walking and cycling. It is widely recognized that walking and cycling have beneficial effects for public health, and research has provided extensive evidence that traveling via physical activity has a variety of health benefits, including a decrease in cardiovascular strain and positive changes in cholesterol levels. Remarkably, the health benefits of physical activity outweigh the negative impacts from exposure to air pollution even in highly polluted cities.[11] [12] However, there is little work that investigates the potential benefits of increased walking or cycling at the country-level or at global scale.

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[8] Hoffs, Charlie. (2022). Challenges and Opportunities in Mining Materials for Energy Storage Lithium-Ion Batteries. Union of Concerned Scientists. Blog post. https://blog.ucs.org/charlie-hoffs/challenges-and-opportunities-in-mining-materials-for-energy-storage-lithium-ion-batteries.

[9] Lovins, Amory. (2022). Six Solutions to Battery Mineral Challenges. Rocky Mountain Institute. https://rmi.org/insight/six-solutions-to-battery-mineral-challenges/.

[10] https://toolkit.irap.org/management/safe-system-approach/

[11] Tainio, Marko, Audrey J. de Nazelle, Thomas Götschi, Sonja Kahlmeier, David Rojas-Rueda, Mark J. Nieuwenhuijsen, Thiago H. de Sá, Paul Kelly, and James Woodcock. (2016). “Can air pollution negate the health benefits of cycling and walking?” *Preventive Medicine*, 87:233–236. DOI: 10.1016/j.ypmed.2016.02.002.

[12] US Department of Energy. Alternative Fuels Data Center: Electric Vehicle Benefits and Considerations. (n.d.). Retrieved July 25, 2025 https://afdc.energy.gov/fuels/electricity-benefits.

4.2. ENERGY CONSUMPTION

As in all previous modeling studies conducted by ITDP and UC Davis, and along with most other sectoral models published in the field, we use the industry-standard Activity, Structure, Intensity, Fuel (ASIF) framework for relating different aspects of travel and estimating GHG emissions from vehicles:

- **Activity:** Travel per capita.
- **Structure:** The share of modes used (in turn, a function of vehicle sales and stocks by mode and technology type).
- **Intensity:** The efficiency of modes, measured as fuel use per kilometer.
- **Fuel:** The carbon intensity of the fuels and energy carriers used by different types of vehicles, measured in carbon emissions per unit of fuel.

The foundational ASIF approach captures fuel/energy consumption. The ASIF variables are largely adopted from the International Energy Agency's (IEA) Mobility Model, with modifications for our scenario variables and expert review, as described in Section 3. The *High EV* scenario examines a dramatic reduction in carbon intensities (Fuel) and a moderate change in energy-efficiency (Intensity). The *Mode Shift* scenario examines a dramatic change in modal split (Structure) and a reduction in total Activity.

In this report, we examine a new scenario variable: *Small Vehicles*. For the purposes of calculating energy consumption, this variable only affects Intensity. Given the five vehicle-size classes that we are using to adjust future sales growth, we also use country-specific estimated fuel economy for each size class, which then is used to create a weighted average fuel economy for all LDVs based on the sales shares in a particular year. We have obtained fuel economy values for the top-selling vehicles in each size class in a recent model year (typically 2023 or 2024), based on model-level sales data available through sales and vehicle registration databases. We also estimate the fuel economy (kWh/km) for the electric vehicles by size class using a combination of data sources and in some cases making adjustments or assumptions if few models are available in that size class. We were able to obtain vehicle sales and characteristics data for most countries and vehicle size classes, but where data gaps exist, as a rule of thumb, we assume that BEVs of a certain size class use 40% as much energy per km as internal combustion engine (ICE) vehicles of that size class. This is based on the typical efficiency advantage of battery electric vehicles (BEVs) over ICE vehicles in a "matched pairs" type of analysis.

In projecting fuel economy, we have used a relatively simple assumption—that fuel economy (measured as energy/km) within size classes improves about 1% per year into the future. This means that if the size mix of sales were constant, fuel economy overall would improve at that rate; however, if more large vehicles are sold, the overall rate of improvement is less, and there could even be an increase in average energy use per km if there is enough shifting to larger, less efficient vehicles.

4.3. GREENHOUSE GAS EMISSIONS

Estimating GHG emissions requires only a small addition to the ASIF approach described in Section 4.2. We include emissions factors that capture the emissions intensity of liquid fuels (CO_2-equivalent GHG grams per Litre), as well as country-specific estimates of grid carbon intensity (CO2-equivalent GHG grams per KWh).

Our calculations include “tank-to-wheel” tailpipe emissions as well as “well-to-tank” emissions caused by gasoline extraction, refinement, and shipping. In the case of electric vehicles, we include the emissions associated with electricity generation and typical losses during transmission, distribution, and charging. In all scenarios, we make fairly optimistic estimates of the decarbonization of the electricity grid, in line with the IEA’s Sustainable Development Scenario and the Paris Agreement to limit climate change to 1.5 degrees Celsius.

In addition to fuel/electricity emissions, we also include the indirect “life cycle” emissions associated with infrastructure construction and maintenance and also vehicle manufacture, maintenance, and disposal. We estimate infrastructure emissions by calculating the extent of infrastructure that will be required to support the amount of urban travel by each mode in each scenario. We then estimate the emissions needed for its construction—asphalt, steel, and other materials—using data from the University of California Pavement Research Center, some of which is reported in Filani et al, 2024.[13] For vehicle production emissions, we use data from the International Transportation Forum,[14] that differentiates between ICE and EV production emissions (EVs being higher because of battery production). These coefficients are then multiplied by the total vehicles of each type sold in each scenario.

4.4. DIRECT PUBLIC AND PRIVATE COSTS

Our model estimates the direct public and private costs of urban passenger transport in each of the eight scenarios described in Section 3. We include in this calculation the costs of building and maintaining infrastructure such as roads, bicycle lanes, and rail tracks; operating transportation systems such as public transport services and taxi/ride-hailing networks; and purchasing, fueling, insuring, maintaining, and disposing of vehicles.

We use the same factors to estimate these costs that we have used in previous ITDP–UC Davis collaborations. These are largely drawn from IEA Mobility Model sources, and in many cases we use a broad average cost factor for specific aspects (e.g., bus price) for Organisation for Economic Co-operation and Development (OECD) and non-OECD countries. These data have been modified over time based on regional specifics and reviewed by experts as part of the review process of those earlier publications. For this project, we have added a tracking of the price of new LDVs by size class. The

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[13] Filani, I., A. A. Butt, J. T. Harvey, & L. M. Fulton. (2024). Framework to Quantify the Life Cycle Greenhouse Gas Emissions from the Build-Out and Maintenance of Global Roadway Networks. https://doi.org/10.7922/G27P8WQK.

[14] International Transport Forum. (2024, November 12). *GHG Emissions Accounting and Reporting for Transport*. ITF. https://www.itf-oecd.org/ghg-emissions-accounting-reporting.

resulting average cost is similar to what we have used in previous studies, though in our projections with a significant shift to larger vehicles, this average cost rises, since larger vehicles are more expensive. We have used various national and commercial vehicle registration databases to estimate the average sales price and characteristics of both ICE and electric vehicles by size class in each country.

As we enumerate these costs, including the LDV purchase costs and all other costs we track for a wide range of modes, we divide them between the public and private sectors. This division is only approximate and does not account for details in the variation between countries. For example, we assume that the full cost of fuel for private cars is borne by the private owners of those cars; we do not include any fuel subsidies or taxes in our tabulations. Similarly, we assume that the full cost of public transport investments and operations is borne by the public sector (we do not account for public transport fare payments).

It is important to stress that this is an urban (or metro area) passenger transport study; as in our calculations of other impacts, we do not include intercity or rural transport, nor do we include the transport of goods. Furthermore, we do not include any of the many secondary or indirect costs of transportation in these cost calculations. Some of those indirect costs, such as air pollution and road safety, are included in our discussion of other benefit categories in Sections 4 and 5. There are other secondary costs that are not included in this study in any quantitative way, including:

- Pollution of waterways from particulate runoff of tire particles (made worse by heavier vehicles and more car-dependent transport systems).

- Depletion of productive farmland and reduction in natural lands by conversion to suburban developments, roads, and parking (made worse by greater car-dependence; this is greatly reduced in our Shift Mode scenario, with its more compact urban development).

- The ecological impacts of air pollutant emissions (made worse by greater car dependence but alleviated by electric vehicles).

- Economic costs associated with noise pollution in densely populated areas (made worse by greater car-dependence but alleviated by electric vehicles).

- Time lost in commuting (we design our scenarios to reflect equal levels of commuting convenience, but in reality, the convenience of travel is determined by the design of transport systems).

- The cost of supplying electricity, water, and sewer systems to houses in low-density suburbs subsidized by urban highways (made worse by car-dependence).

4.5. BATTERY REQUIREMENTS

For electric vehicles, we project battery requirements (in kWh) for each size category of vehicle, given expected future range requirements and efficiencies. We use commercially available data on the current average battery capacity for recent-year battery electric and plug-in hybrid vehicles by size class and country, and we track the trends in these averages over the past five to 10 years. This data shows strong differences in average battery capacity by vehicle size class but also a typically steady increase in battery capacity in vehicles of a given size class over time, related to ongoing increases in vehicle driving range.

In markets with a substantial portion of plug-in hybrid vehicles (PHEVs), we take a weighted average of BEV and PHEV kWh of batteries based on their relative sales in each size class. We then project future battery capacity per vehicle based on an ongoing trend in these averages per vehicle type and size class, with an assumption that there will be a slowing in the rate of increase in battery capacity, given the fairly high average range of vehicles by 2024. We also assume that eventually BEVs reach a high share of total EV sales, with PHEV sales shares declining, such that by 2050 the BEV sales shares are typically 80% or higher for most size classes and 100% for small cars. Since BEVs have significantly more batteries per vehicle than PHEVs, this tends to drive the overall average higher over time. The estimated average kWh for the base year, *BAU* projection, and Small Vehicle projections for each country are shown in Figure 4.5.a. These figures are exogenous inputs to the model rather than endogenous model predictions.

We make the conservative assumption that a single battery pack lasts the entire vehicle lifespan without needing replacement. This results in a possible underestimation of the true amount of battery capacity that will be needed in each scenario.

Figure 4.5.a. Weighted average battery capacity (kWh) for BEVs by vehicle segment and country, 2025

Segment	US	China	India	Brazil	Indonesia	Mexico
Small car	32.8	23.6	22.7	35.7	28.3	35.7
Medium car	51.0	52.5	38.0	50.8	52.8	56.3
Large car	84.4	74.4	86.5	83.9	73.1	81.3
Small SUV	79.1	66.6	62.9	69	62.4	68.4
Large SUV	115.6	88.0	81.5	81.8	79.9	86.0

We also track and project battery requirements for buses and 2-wheelers, which also electrify toward 100% in our *High EV* scenario.

Within urban passenger transport, we capture the overall increase in battery capacity needed for the *High EV* scenarios, as well as the relative reduction in battery needs from *Mode Shift* and *Small Vehicles*. Given our projections of average battery capacity by size class, the total battery requirements for new LDVs each year are the product of the sales by class multiplied by the kWh per vehicle. As with all aspects of this study, our findings are limited to urban passenger transport: We exclude nonurban passenger vehicles as well as all trucks and many other vehicle types. We do track battery requirements for urban 2- and 3-wheelers (electric motorcycles, scooters, tuk-tuks, etc.) as well as e-bikes and electric buses; however, these vehicles represent only a small fraction of battery requirements even in the *Mode Shift* scenarios. Most battery demand, as shown in Section 5.5, below, comes from cars.

We report the battery capacity requirements of each scenario in gigawatt-hours. We have not made formal estimates of the vehicle weight effects or material requirements of these batteries, but they will be substantial. Yet, battery technology is changing rapidly and given improvements in energy density and shifts to new battery chemistries, the demand for specific materials could be lower than would be estimated from a straight projection. It is outside the scope of our expertise to predict the materials that will be required for a given level of battery capacity one or two decades from now. We are nonetheless confident in saying that there will most likely be some external social and economic costs in obtaining whatever materials are needed, and that reducing the total requirements of battery capacity will also reduce those social and economic costs.

4.6. ROAD SAFETY

To estimate the impacts of different scenarios for road safety, our analysis includes two factors: First, we include the effect of total travel activity, broken down by vehicle type. For example, we expect that if a country sees an increase in the overall amount of urban travel by car (measured in vehicle-kilometers traveled), it will see a related increase in road traffic fatalities involving cars. This operation is discussed in Section 4.6.2. Second, we include the effect of vehicle size distribution. This reflects the increased likelihood of a fatality in each incident when the vehicle(s) involved in the incident are larger and is discussed in Section 4.6.3. First, though, we must be clear about the factors we are not including in this analysis.

4.6.1. Methodological Limitations and Assumptions

Road safety is a complex topic, influenced by many factors that are far outside the scope of this country-level study. We have taken a simplified approach with the goal of producing estimates that are directionally correct and relationally accurate. It is not possible to precisely predict how many people will lose their lives on the world's roads in 2050, but it is possible to say that in a future of smaller vehicles and more public transportation, fewer people will be killed by traffic than in a future of larger vehicles and car-dependent cities. For this reason, we have chosen to report the results of our road safety analysis in Section 5.6 with only one significant digit.

To simplify the complexity of road safety to the level of including it in this study, we have made certain assumptions:

- For this road safety analysis, we do not differentiate between vehicle sizes within a vehicle class (that is, we do not differentiate between large and small SUVs, or between large, medium, and small cars, even though we do differentiate between these sizes in other methods, such as battery requirements (Section 4.5) and energy consumption (Section 4.2). This is because we could not identify reliable data for the various safety levels of different vehicle sizes within those classes.

- We only account for vehicle size and not for vehicle weight within a size group. Heavier vehicles traveling at a given speed have a higher momentum, which makes them more dangerous in a collision. In general, electric vehicles are heavier than combustion-powered vehicles because of battery weight. However, insufficient data was available in our six countries to model this effect in detail.

- In each country, we are able to use country-specific baseline data about the number and distribution of fatalities. However, the only available data on the proportional increase in danger with vehicle size comes from the US, and we have had to assume that these proportions also apply in other countries.

- We only account for the effect of vehicle size on the fatality of collisions, not the likeliness of collisions. Some research has found that not only are SUVs more dangerous in collisions but that they are also more likely to cause collisions because of larger blind spots.[15] SUVs make it especially difficult for drivers to see small children. Although research indicates the significance of this effect, however, we found insufficient literature to integrate it into our country-scale analysis.

- In comparing the *Mode Shift* scenarios with the Business as Usual scenarios, we only account for the effect of the reduction in vehicle travel. We do not account for the likelihood that increased support for walking, cycling, and public transport will also result in streets with wider sidewalks, slower vehicle speeds, and more clearly marked crossings. These, in turn, reduce both the likelihood and severity of crashes.

We believe that these assumptions are generally conservative. That is, whenever we were forced to make an assumption, we attempted to understate rather than overstate the impact of our scenario variables. The one exception is our use of vehicle-size-to-fatality-rate factors from the US, rather than country-specific rates, since only US data was available in the literature. Because SUVs in the US may be larger than SUVs in other countries, this may overstate the impacts of vehicle size.

To our knowledge, this is the first time that road safety has been included in a country-level transportation outlook study; we hope that other authors will improve on our methods. The Python script we used to make these calculations is available upon request at data@itdp.org.

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[15] Fenton, Stephen J., Eric R. Scaife, Rebecka L. Meyers, Kris W. Hansen, and Sean D. Firth. (2005). “The prevalence of driveway back-over injuries in the era of sports utility vehicles.” *Journal of Pediatric Surgery* 40 (12):1964–68. DOI: 10.1016/j.jpedsurg.2005.08.016.

4.6.2. The Effect of Total Travel Activity

First, we predict the effect of increased travel on road fatalities. This is calculated by taking the growth rate in each mode's vehicle-kilometers traveled (vkt) and applying that growth rate to fatalities in that mode. We apply a discounting exponent of 0.8 to account for conservatively for the nonlinear relationship between vkt and fatalities.[16]

$$\begin{array}{l}\textit{Growth in fatalities from} \\ \textit{increased travel for mode}\end{array} = \left(\frac{(\textit{New vkt})}{(\textit{Current vkt})}\right)^{\textit{Discounting factor}}$$

Figure 4.6.2.a. Categories of road traffic fatalities

Category of fatalities	**Determined by which category of travel activity?**
Single-vehicle motorcycle fatalities	2-wheeler vkt
Note: For simplicity, we also include crashes between motorcycles and other modes (i.e., other motorcycles, pedestrians, trucks, and buses) in the single-vehicle category, since they will not be affected by the changing share of light trucks as a proportion of the car fleet.	
Single-vehicle car fatalities	Car vkt
Motorcycle–car multi-vehicle fatalities	2-wheeler vkt
Bicycles/pedestrians–car fatalities	Car vkt
Car–car multi-vehicle fatalities	Car vkt
Others	Overall total vkt by all modes

We include the following categories of traffic fatalities, with accident rates taken from a study discussed below. For simplicity of analysis, we assume that each category is determined by a single category of travel activity.

Note that these figures do not include fatalities caused by freight vehicles. Motorcycle/pedestrian collisions, as well as those between motorcycles and other vehicles, are included as single-vehicle motorcycle fatalities because they are only affected by motorcycle fleet numbers and not by the trends in the size of cars.

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[16] See Kopitz and Cropper. (2003). Traffic Fatalities and Economic Growth. World Bank Policy Research Working Paper 3035. https://www.econ.umd.edu/sites/www.econ.umd.edu/files/pubs/wp3.pdf

As an illustrative example, our baseline data indicates that India suffered about 20,000 fatalities from single-vehicle motorcycle collisions in 2015, with about 450 billion urban vehicle-km traveled by motorcycle. As we predict that motorcycle travel will increase to about 750 billion urban vehicle-km by 2050 in the *BAU* scenario, we predict that fatalities from single vehicle collisions will increase to: $(1 + (((750-450)/450) \cdot 0.8)) \cdot 22{,}000 \approx 33{,}300$ fatalities/year.

We obtain baseline fatality rate data, broken down by type of collision, from the following sources:

- United States: Insurance Institute for Highway Safety[17]
- Mexico: International Transport Forum[18]
- Brazil: Confederação Nacional de Municípios[19]
- India: Ministry of Road Transport and Highways[20]
- China: National Bureau of Statistics of China[21]
- Indonesia: World Health Organization[22]

4.6.3. The Effect of Car-Size Shift

Next, we estimate the effect of a growth in vehicle size in the car fleet on road fatalities. In this case, we capture the effect resulting from a higher proportion of light trucks, which include SUVs and pickups. We do not capture the effect resulting from larger or heavier vehicles within a given class (cars or light trucks), meaning that we likely underestimate the overall effect of increased car sizes.

To do this, we'll find the effect of larger vehicles on the likelihood of fatality for each kind of incident listed in Figure 4.6.2.a, above. We begin with the assumption that changing the relative share of SUVs and pickups has no impact on single-vehicle motorcycle and "other" categories. For multiple-vehicle crashes, we use this form:

$$\begin{array}{l}\text{Growth in fatalities}\\ \text{from carsize shift}\end{array} = \frac{\left(\text{Fatality Rate}_{\text{Car}} * \text{Proportion}_{\text{Cars-Final}}\right) + \left(\text{Fatality Rate}_{\text{LT}} * \text{Proportion}_{\text{LT-Final}}\right)}{\left(\text{Fatality Rate}_{\text{Car}} * \text{Proportion}_{\text{Cars-Initial}}\right) + \left(\text{Fatality Rate}_{\text{Car}} * \text{Proportion}_{\text{Cars-Initial}}\right)}$$

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[17] IIHS. (2024.) "Fatality Facts 2022: Urban/rural comparison" https://www.iihs.org/topics/fatality-statistics/detail/urban-rural-comparison

[18] International Transport Forum: OECD. (2023). "Road Safety Country Profiles Mexico 2023." https://www.itf-oecd.org/sites/default/files/mexico-road-safety.pdf

[19] Confederação Nacional de Municípios. (2013). *Estudos Tecnicos*, Vol. 5 https://cnm.org.br/storage/biblioteca/ET%20Vol%205%20-%2002.%20As%20mortes%20e%20as%20interna%C3%A7%C3%B5es%20por%20acidentes%20de%20tr%C3%A2nsito%20no%20Brasil.pdf

[20] Ministry of Road Transport and Highways, Transport Research Wing. (2015). Road Accidents in India 2015. https://morth.nic.in/sites/default/files/Road_Accidents_in_India_2015.pdf

[21] National Bureau of Statistics of China. (2016). China Statistical Yearbook. https://www.stats.gov.cn/sj/ndsj/2016/indexeh.htm

[22] World Health Organization. (n.d.). Global Heath Observatory Data Repository. https://apps.who.int/gho/data/view.main.51310?lang=en. Unfortunately, data broken down by category of incident was not available in Indonesia, so we estimated the fatality distribution based on the average of the other countries, weighted by Indonesia's distribution.

Which may also be interpreted as:

$$\frac{(\textit{Weighted average of fatality rates under new conditions})}{(\textit{Weighted average of fatality rates under existing conditions})}$$

For all fatality rates, we use data from Anderson (2008), shown below in Figure 4.6.3.a. For crashes involving pedestrians, cyclists, and motorcyclists, as well as single-vehicle car crashes (i.e., where only one vehicle is facing a significant fatality risk), we can directly take the fatality rates from the Anderson study in the table below.

As mentioned above, it is a severe limitation of our analysis that the only usable dataset describing the effects of vehicle size class on incident fatality likelihood is from only one country (the US) and nearly two decades old. In the absence of more up-to-date, international data, we believe it is better to roughly approximate the impacts of vehicle size on fatality rates than to ignore them. The continuing global growth in vehicle size underscores the need for more detailed research to give us a more comprehensive picture of the safety implications of larger vehicles in various countries.

Figure 4.6.3.a. Predicted probabilities of fatality in struck vehicle, from Anderson (2008)

Predicted probabilities of fatality in struck vehicle

	Logit results	Fatality probability	Sample
Two-vehicle crashes w/cars			190,791
Striking vehicle is light truck	0.486	0.00178	
Striking vehicle is car	(0.135)	0.00110	
Two-vehicle crashes w/light trucks			117,549
Striking vehicle is light truck	0.684	0.00137	
Striking vehicle is car	(0.221)	0.00070	
Single-vehicle crashes			118,069
Striking vehicle is light truck	0.191	0.00891	
Striking vehicle is car	(0.073)	0.00741	
Crashes w/motorcycles			3,191
Striking vehicle is light truck	0.728	0.07245	
Striking vehicle is car	(0.189)	0.03773	
Crashes w/pedestrians or pedalcyclists			15,990
Striking vehicle is light truck	0.663	0.04342	
Striking vehicle is car	(0.105)	0.02451	

For categories of incident involving multiple vehicles, we use:

$\text{Fatality Rate}_{\text{Car}}$ = Fatality rate of cars in a car-car crash (**0.00110**)

$\text{Fatality Risk}_{\text{Light Truck}}$ = (Average (Fatality risk of a car in a light truck–car crash (**0.00178**), Fatality risk of a light truck in a light truck–car crash (**0.00070**)) = **0.00124**

These are plugged into the same formula above.

The approach described above provides us with a scaling factor for vehicle size shifts for Single Vehicle (Car), Car–Motorcycle, and Car–Pedestrian/ Bicycle.

4.6.4. Combining the Effects

For each crash type—Single Vehicle (Motorcycle), Single Vehicle (Car), Car–Car, Car–Motorcycle, Car–Pedestrian/Bicycle, and others—we multiply the factors from increased travel and car-size shift effects with the country's current fatality number to provide an estimate of fatalities for that crash type under the new condition. The obtained new fatality numbers are added up to create an estimated total new fatality count under the new vkt condition.

4.7. AIR POLLUTANTS

To model the impacts of urban passenger transportation on air pollution and therefore on public health, we conduct an analysis in two steps: First, we identify emissions factors that relate each kilometer of vehicle travel activity to the emission of a certain amount of particulate matter and then use these to calculate annual pollutant emissions from urban passenger transport in each country and scenario.

We focus on three primary pollutants: fine particulate matter with a diameter of less than 2.5 microns (PM2.5), nitrogen oxides (NO_x), and carbon moNO_xide (CO). We selected these pollutants because they are the most significant and best-studied air pollutants emitted by vehicles. Our omission of other pollutants (especially sulfur dioxide and all secondary pollutants) is one way in which we err on the side of a conservative estimate of impact. We also only include air pollutant emissions from vehicle operation and not fuel production and distribution.

There are two ways in which the operation of vehicles emits pollutants: tailpipe and non-tailpipe. Tailpipe emissions, including all three of our studied pollutants, are from the combustion of fuel. Recent decades have seen a dramatic improvement in emissions standards and a rapid decline in tailpipe emissions for some pollutants. At present, several primary tailpipe pollutants are declining quickly in wealthy countries. Electric vehicles are, of course, entirely free of tailpipe emissions. If the world's fleet fully electrifies, tailpipe emissions could disappear altogether. We use currentday statistics and future projections of tailpipe emissions factors at the country level for small particulate matter (PM2.5), nitrogen oxides (NO_x), and carbon monoxide (CO), sourced from the International Council on Clean Transportation (ICCT) Roadmap model, version 2.2.5.

Non-tailpipe emissions of particulate matter are a different story. They are primarily caused by three mechanisms: the creation and resuspension of road dust, the abrasion of tires, and the abrasion of brake pads. The use of regenerative braking in electric vehicles results in a substantial reduction in brake pad abrasion. This contrasts with electric vehicles' greater weight, which causes a minor increase in both tire abrasion and road dust resuspension.

Our study only includes urban passenger transport and therefore does not include freight. Trucks are a major source of several local air pollutants, including NO_x and particulate matter, through both tailpipe and non-tailpipe mechanisms. Because trucks will likely take longer to electrify than cars, freight pollution is a major area of concern for many cities, but that issue is outside the scope of this study.

We identified two studies that listed non-tailpipe PM2.5 emissions factors: a 2023 report by the European Environment Agency (EEA) and a 2020 study by the OECD. Both sources were in relatively close agreement in their estimates of non-tailpipe emissions factors for various vehicle types. Neither source provided any reason to expect that non-tailpipe emissions factors would decrease in the coming decades, finding that "non-exhaust PM emissions are largely unregulated," so we do not project any change in non-tailpipe emission factors over the time frame covered by this study.

Likewise, neither the EEA nor the OECD provided information on the variation in emissions factors across geographies. These two sources provide information on vehicles in higher-income countries, where the majority of urban roads are relatively clean and well-paved. In lower- and middle-income countries, a greater portion of roads are likely to be unpaved or in poor repair, meaning that more dust will be resuspended per vehicle-kilometer traveled. For the sake of conservatism in our estimates, we do not account for this variation.

Unfortunately, we were unable to identify reliable estimates for the variation in either tailpipe or non-tailpipe emissions with vehicle size or size class. Although we expect that smaller vehicles would have lower emissions of air pollutants through both tailpipe and non-tailpipe mechanisms, specific factors were not available from the ICCT or any other source, and therefore we do not include the *Small Vehicles/Large Vehicles* scenario distinction in our analysis of air pollutant emissions. Similarly, we believe that as vehicles age, their on-road emissions may rise, with large vehicle emissions rising more than small vehicle emissions, but we were unable to find systematic estimates to support this. Thus we only calculate the effects of the *High EV* and *Mode Shift* scenario parameters, alone and combined, in contrast to *Business as Usual*. More research on pollutant emissions from vehicles of different sizes, both new and aging, would be valuable for estimating the impacts of size class shifts on air quality.

We attempted to investigate the potential impacts of these varying levels of pollutant emissions for public health, but no model appropriate to this use case is available. Certain reduced-form models are available but do not permit necessary disaggregation between urban and rural emissions, while full-scale models would have been outside the scope of this analysis.

4.8. PHYSICAL ACTIVITY AND PUBLIC HEALTH

We employ a simplified version of the World Health Organization's Health Economic Assessment Tool for Walking and Cycling (HEAT)[23] to estimate the societal impacts of a country-level change in urban walking or cycling for each of the six countries in our analysis, following these steps:

1. We begin with the 2050 projections of total passenger-kilometers traveled per year by all urban residents of the country in both the *BAU* and the *Mode Shift* scenarios (see Figure 3.2.a, above). Note that the *Small Vehicles* and *High EV* scenarios have no implications for walking or cycling rates.

2. Comparing those numbers to projections of total urban population, we calculate the average number of kilometers traveled per person per week across the urban population of the country in 2050 in each scenario.

    - For example, in Indonesia, the average urban resident currently bicycles approximately 1.7km per week; in 2050 *BAU*, this will rise to 2.4km, but in 2050 *Mode Shift*, it will rise to 13km.

3. We use the WHO HEAT tool's documentation[24] and work by Kelly et al. (2014)[25] for the "relative risk of death" caused by a reference volume of increase in walking or cycling, and we compare that to the projected change in cycling rates in our scenarios to determine "relative risks" (mortality rate adjustments) for each scenario.

In Indonesia 2050 *BAU*, cycling will contribute a 1% reduction in mortality rates relative to a future in which there is no cycling in urban Indonesia, while in 2050 *Mode Shift* that number will be 5%.

Finally, we multiply that reduction in mortality rate by the total urban population to find the number of premature deaths avoided per year due to walking and cycling in each country and scenario.

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[23] See Kahlmeier, Sonja, Nick Cavill, Meelan Thondoo, Harry Rutter, Thiago Herick de Sa, Francesca Racioppi, and Thomas Gotschi. (2023). "The Health Economic Assessment Tool (HEAT) for Walking and Cycling: Experiences from 10 Years of Application of a Health Impact Assessment Tool in Policy and Practice." *Frontiers in Sports and Active Living 5*: 1146761. DOI: 10.3389/fspor.2023.1146761.

[24] Kahlmeier, Gotschi, Cavill, et al. (2017). Health economic Economic Aassessment tool Tool (HEAT) for walking and for cycling: Methods and user guide on physical activity, air pollution, injuries, and carbon impact assessments. World Health Organization Regional Office for Europe. https://iris.who.int/bitstream/handle/10665/344136/9789289052788-eng.pdf. See p. 22.

[25] Kelly, Paul, Sonja Kahlmeier, Thomas Götschi, Nicola Orsini, Justin Richards, Nia Roberts, Peter Scarborough, and Charlie Foster. (2014). "Systematic Review and Meta-Analysis of Reduction in All-Cause Mortality from Walking and Cycling and Shape of Dose Response Relationship." *International Journal of Behavioral Nutrition and Physical Activity* 11(1):132–132. DOI: 10.1186/s12966-014-0132-x

We have made a few simplifying assumptions to be able to conduct this analysis at the level of a country's entire urban population. First, we assumed that the increases in walking and cycling are taking place as averages over the whole urban population, which of course includes the very young and the very old as well as people who do not walk or cycle at all. This is congruent with our metric for measuring the volume of walking and cycling as a population's total kilometers traveled by foot and bicycle. However, the quantitative reductions in all-cause mortality due to walking and cycling that our estimates use are most accurately applied to ages 20 to 64 for cycling and 20 to 74 for walking. We did not adjust our urban population numbers to reflect these specific age limitations, instead assuming that the difference would balance out in the averages—a smaller number of people will walk more instead of a large number walking less, but the overall impact will be the same. In contrast, to limit the influence of death from old age, the mortality rates used do reflect these age-groups. We chose this assumption to reflect the understanding that generally it will be people within these age ranges who see the most substantial increases in active travel in the *Mode Shift* scenarios. These age-adjusted mortality rates were taken from WHO HEAT, which provided peer-reviewed, age-adjusted mortality rates for all the countries in this analysis.

Our estimates do not consider the differing air quality of each city and how that might affect health benefits of physical activity—this topic is covered in Section 4.5, but it was beyond the scope of our analysis to include the interplay between air quality and active mobility—and, in general, the benefits of physical activity are known to outweigh the harms of poor air quality in urban environments. Finally, we do not account for the psychological or social benefits of active travel, which include reduced depression, anxiety, and loneliness.[26]

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[26] Scrivano, Luana, Alessia Tessari, Samuele M. Marcora, and David N. Manners (2023). "Active Mobility and Mental Health: A Scoping Review Towards a Healthier World." Cambridge Prisms: *Global Mental Health 11*: e1. DOI: 10.1017/gmh.2023.74.

RESULTS

5

5.1. SUMMARY OF RESULTS

All six countries in our analysis stand to gain dramatically in a variety of impact categories by promoting modal shift, vehicle electrification, and smaller vehicles. Each of those three areas can bring substantial improvements alone, but the most dramatic benefits will only come when all three are combined. Figure 5.1.a shows the benefits of the *Shift+EV+Small* scenario in each impact category.

Figure 5.1.a. Summary of key impacts in 2050. Unless otherwise stated, "savings" refers to the difference between EV+Shift+Small and BAU scenarios

	Mexico	**Brazil**	**China**	**India**	**Indonesia**	**USA**	**Units**
Annual electricity consumption savings in 2050, EV (Only) vs EV+Shift+Small	200	200	1,000	500	200	600	Petajoules/ year
Annual liquid fuel requirement savings in 2050	100	200	800	500	200	800	Billions of barrels of gasoline-equivalent
Annual GHG emissions savings in 2050	50,000	70,000	400,000	200,000	70,000	300,000	Thousands of tonnes of CO2-equivalent
Annual direct public & private cost savings in 2050	200	200	2,000	700	100	900	Billions of USD
Annual battery requirement savings in 2050, EV (Only) vs EV+Shift+Small	100	100	800	400	50	400	Gigawatt-hours of battery capacity
Annual road safety fatalities avoided in 2050	2,000	10,000	40,000	90,000	10,000	8,000	Fatalities
Annual particulate matter (PM2.5) emissions avoided, 2050	9	8	60	30	50	40	Thousands of tonnes of urban PM2.5
Annual premature deaths avoided through physical health benefits of active mobility in 2050	50,000	80,000	700,000	300,000	100,000	300,000	Premature deaths

It is important to remember that we only include urban passenger transport in this analysis. A study that included rural and intercity travel—such as the electrification of cars and buses used for nonurban travel, or modal shift from aviation to rail and coach—would no doubt find greater impacts in most of these categories, as would a study that included electrification of freight vehicles, or modal shift of intercity freight from trucks to freight rail and shift of intracity goods from delivery cars to electric cargo bicycles. Yet since urban passenger travel represents an estimated 60% to 70% of total national passenger travel in most countries, this study does capture a major share of the impacts.

5.2. ENERGY CONSUMPTION

There are a wide variety of levels of energy consumption in different scenarios. In the *Business as Usual* scenario, energy consumption rapidly grows in most countries, with the greater part of that growth coming in the usage of liquid fuels. *High EV* reduces energy consumption considerably while also replacing much of the use of liquid fuels with electricity—but this replacement is not complete, because in the *High EV* scenario, 100% of vehicle sales will be electric by 2050, but the fleet will continue to have many legacy ICE vehicles.

Figures 5.2.a and 5.2.b show the breakdown of energy consumption, with ICE vehicles in shades of blue and electric vehicles in shades of brown, orange, and pink. Cars are represented by the darkest shades. *Small Vehicles* and *Mode Shift* both reduce the overall consumption of energy without substituting electricity for liquid fuels. By far the greatest overall reduction in liquid fuel consumption comes in the combined *EV+Shift+Small* scenario. This reduction is considerable. As we show in Figures 5.2.c and 5.2.d, each of the six countries stands to save massively on liquid fuel requirements. India alone could eliminate the need for more than 500 million barrels of oil annually by 2050 by adopting the *EV+Shift+Small* combination.

Figure 5.2.a. Energy consumption by country, scenario, and year

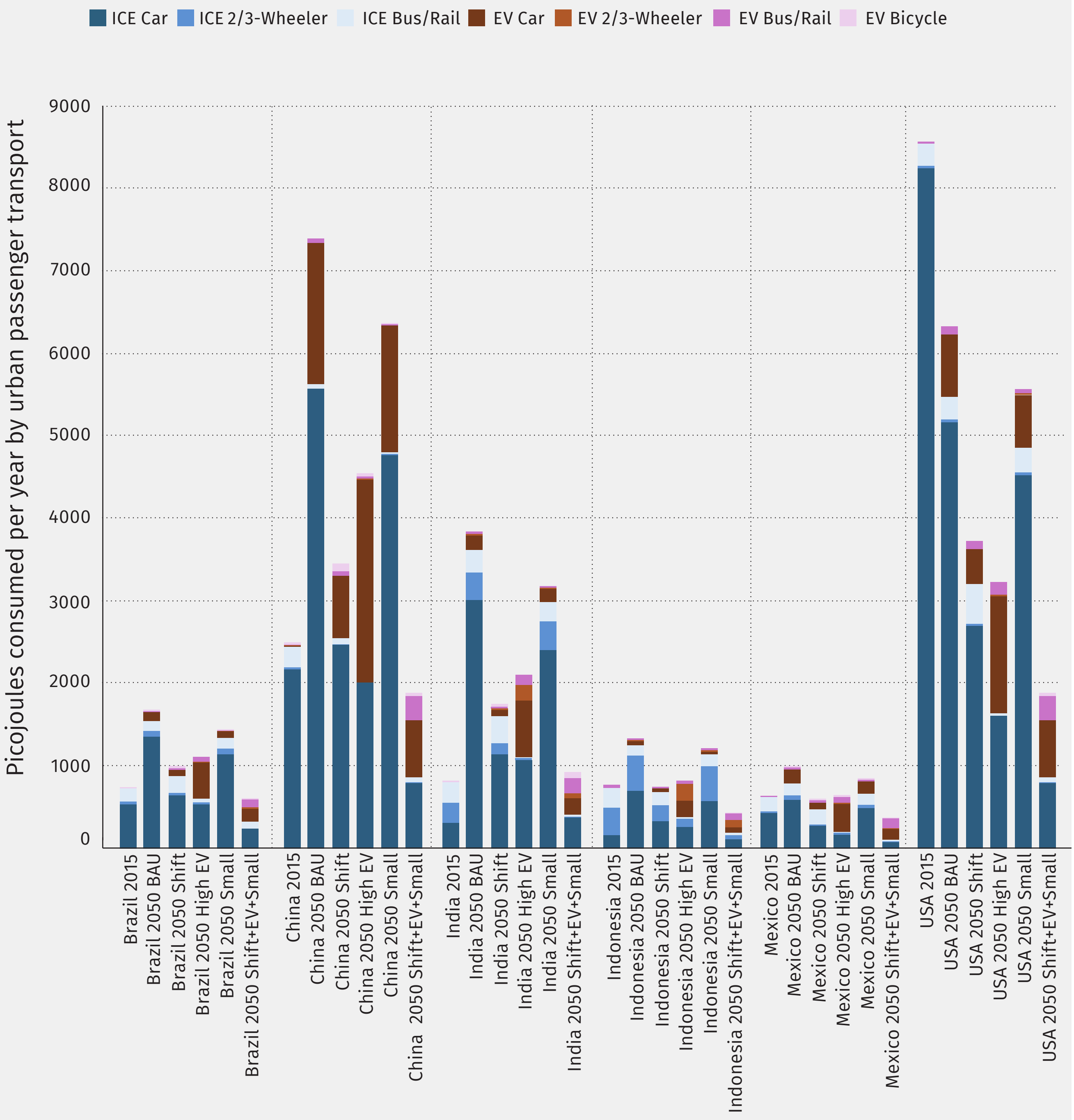


Figure 5.2.b. Energy consumption by country, scenario, and year—normalized to 100% for BAU in 2050

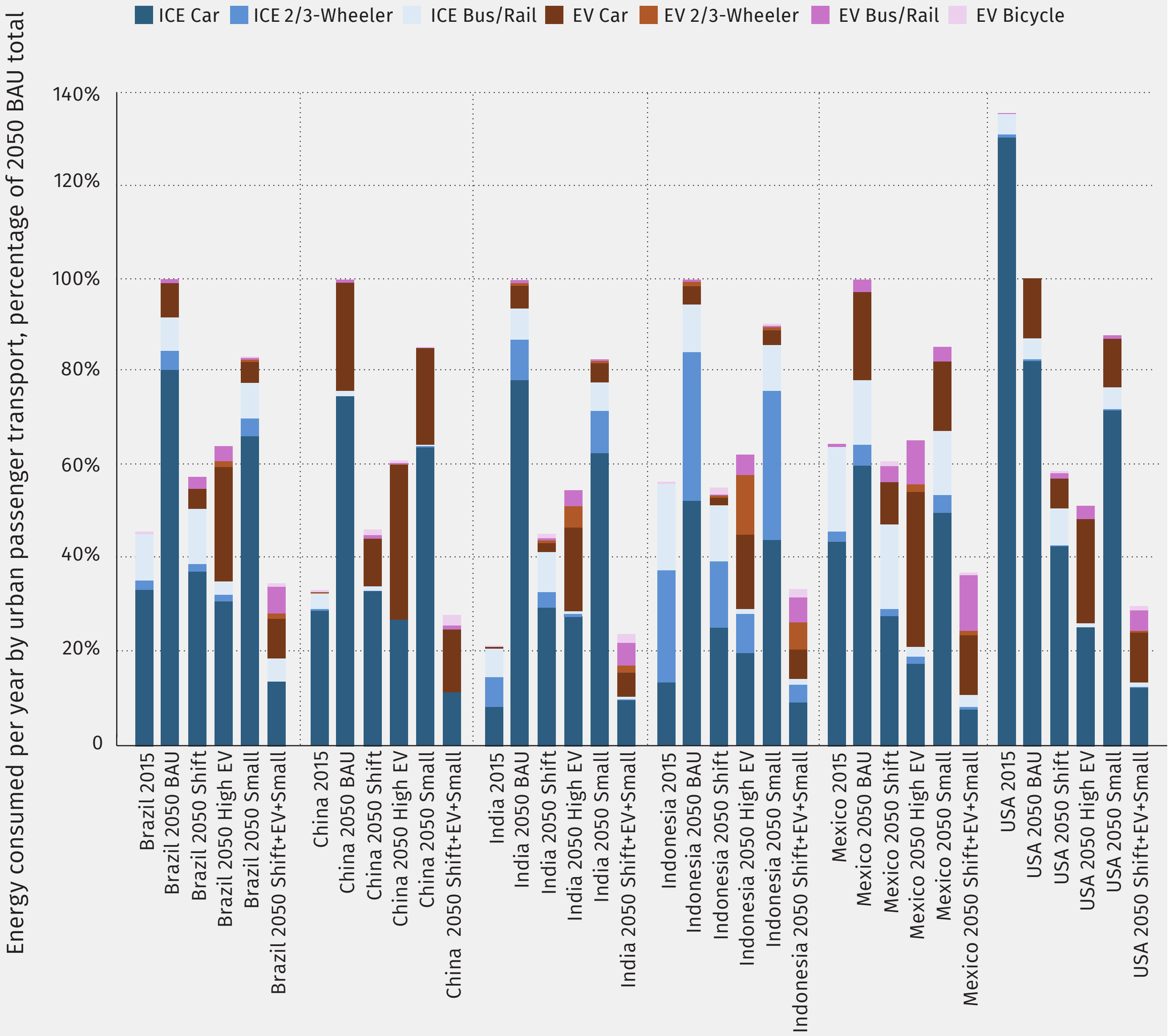


Figure 5.2.c. Liquid fuel consumption by country, scenario, and year

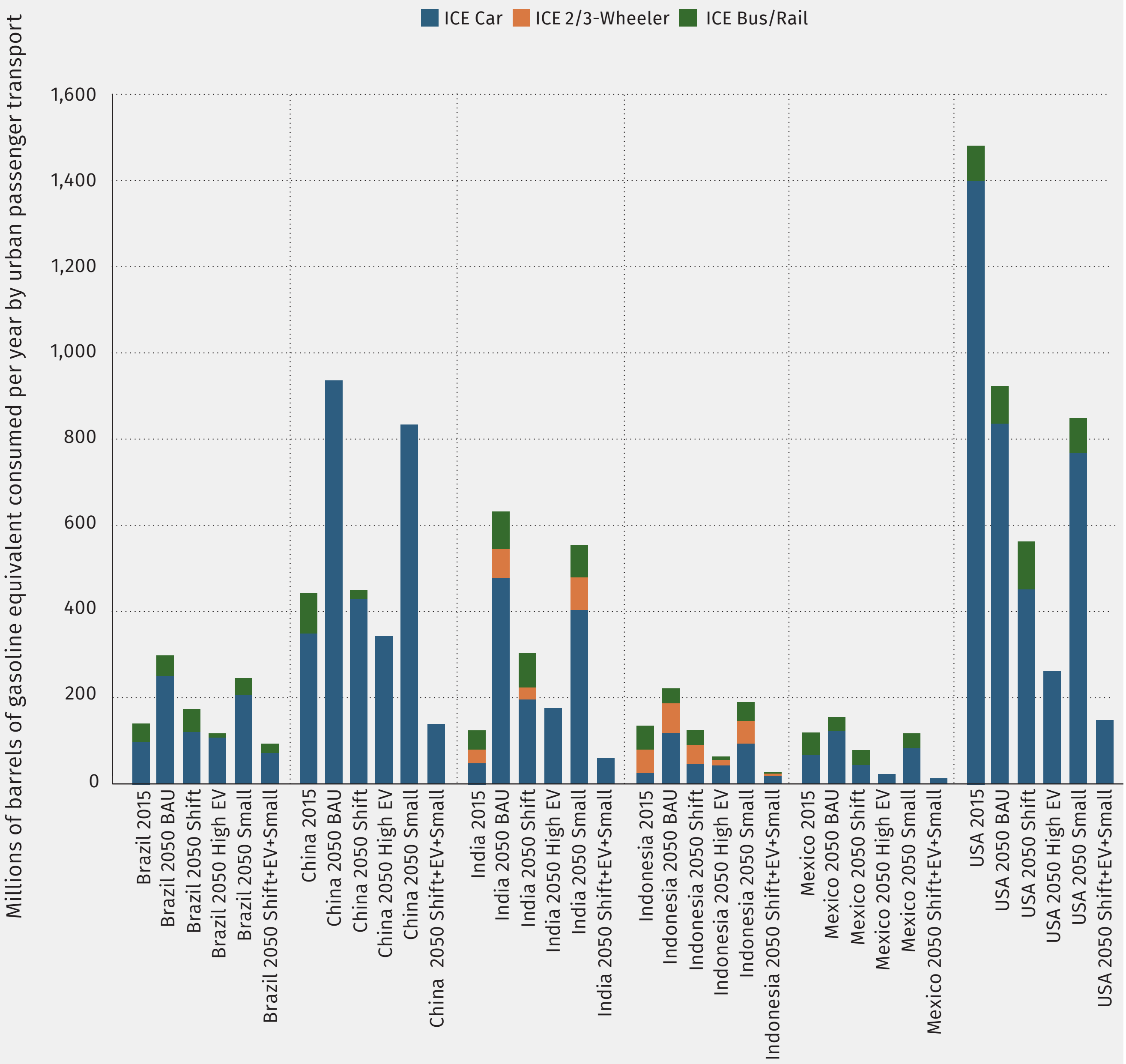
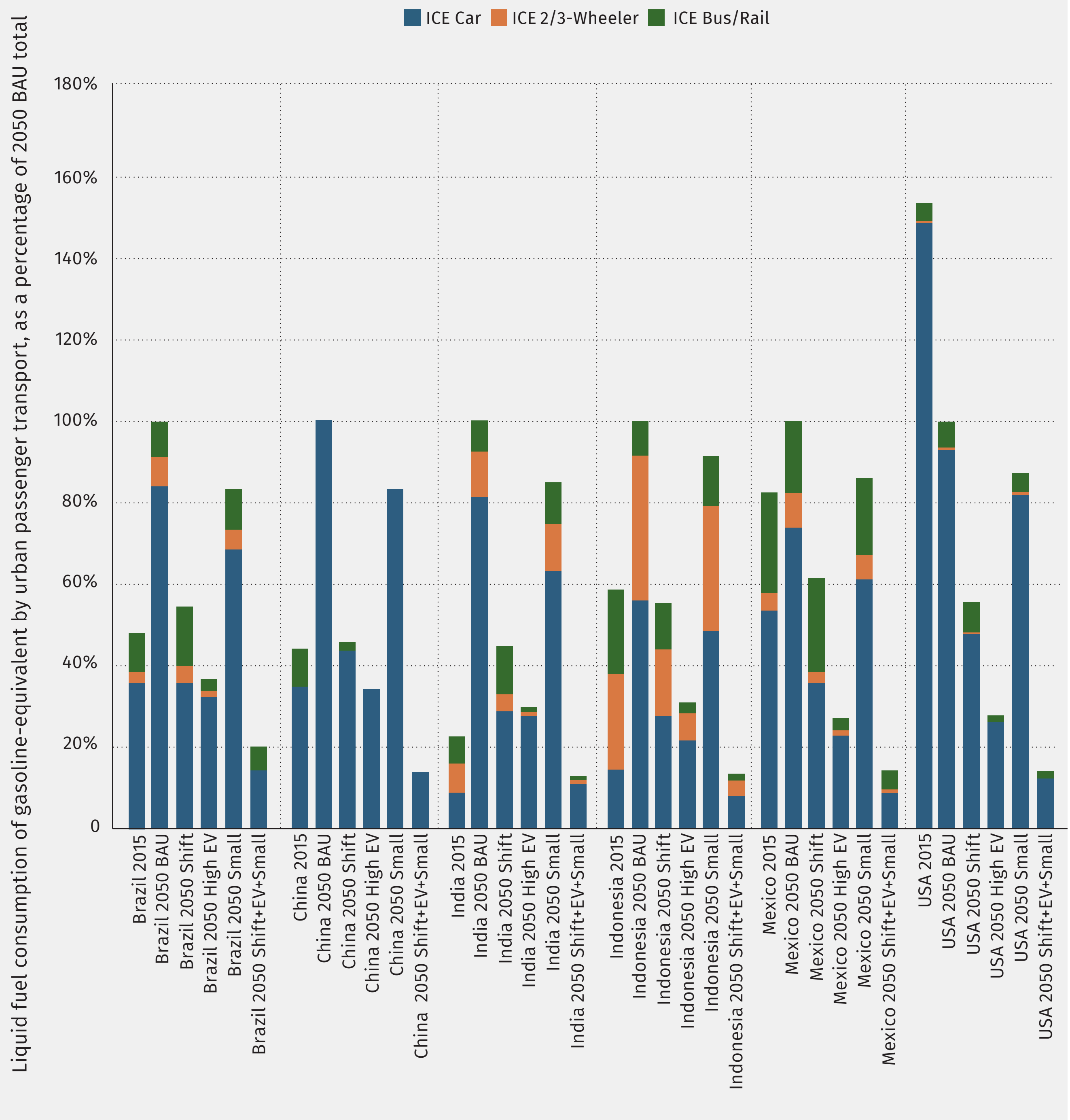


Figure 5.2.d. Liquid fuel consumption by country, scenario, and year—normalized



5.3. GREENHOUSE GAS EMISSIONS

The potential for dramatic reductions in the combustion of liquid fuels implies an equally meaningful opportunity to prevent the emission of GHG. Although none of the scenarios achieves net zero emissions from urban passenger transport by 2050 (as shown in Figures 5.3.a and 5.3.b), the *EV+Shift+Small* scenario comes by far the closest of the scenarios studied.

There are significant differences in the "ranking" of different scenarios by country. The US is an outlier because it starts from a far higher CO_2

per capita than any other country, has relatively flat LDV stocks, and experiences a fair bit of efficiency improvement and EV uptake, even in the *BAU*. In the *High EV* scenario, it reaches 100% by 2040, whereas some countries do not reach 100% even in 2050. In the other five countries, the biggest CO_2 reductions are from *Mode Shift*, followed by *High EV*, then *Small Vehicles*; for every country, combining these three leads to very low vehicle emissions and big reductions in emissions related to infrastructure construction. Emissions from vehicle production drop less in relative terms, because even in the *High Modal Shift* scenarios, the number of vehicles drops proportionately less; much of the CO_2 reduction comes from driving those vehicles less, with fewer road kms needed.

Figure 5.3.a. Annual GHG emissions by country, scenario, and year

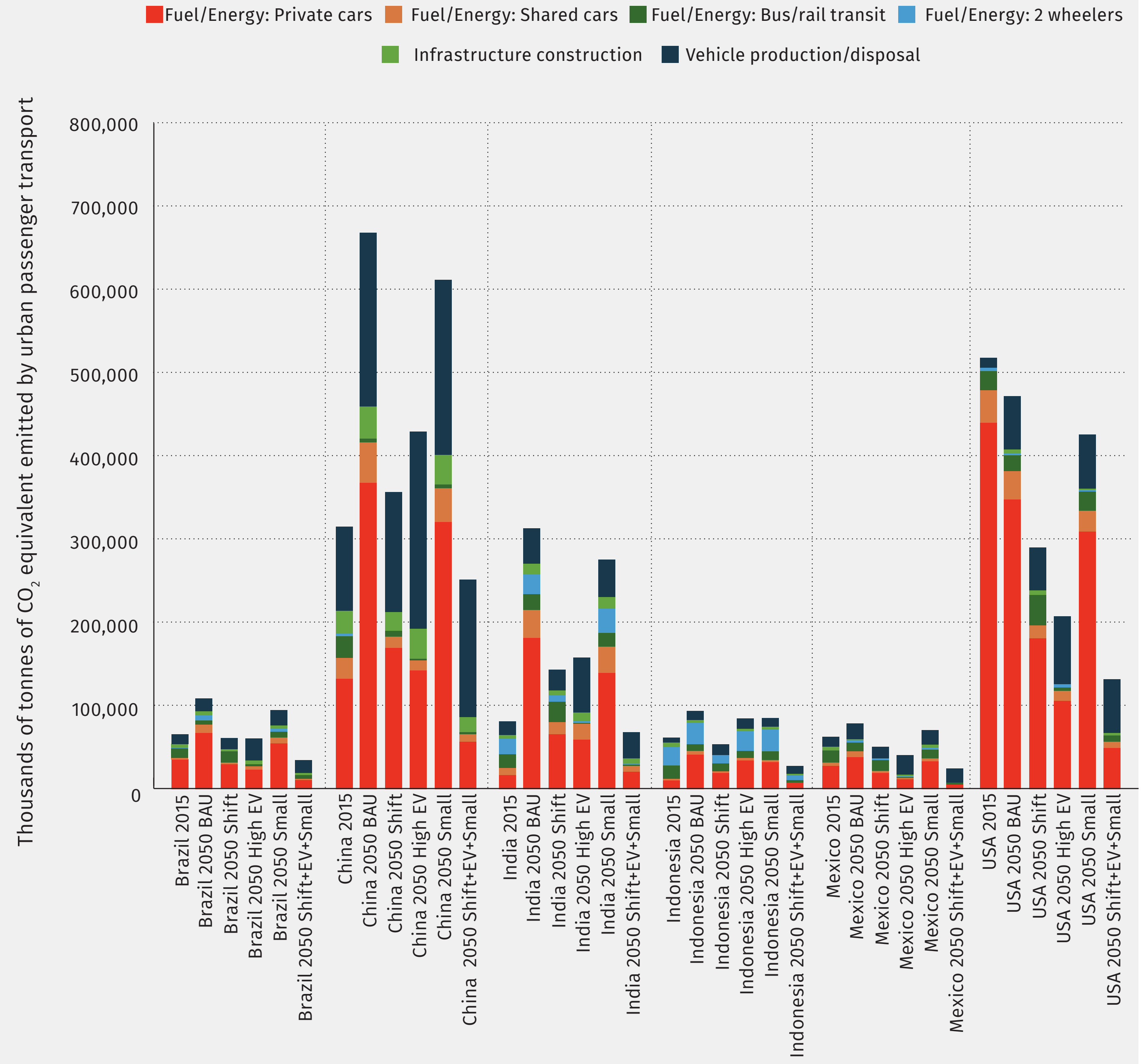
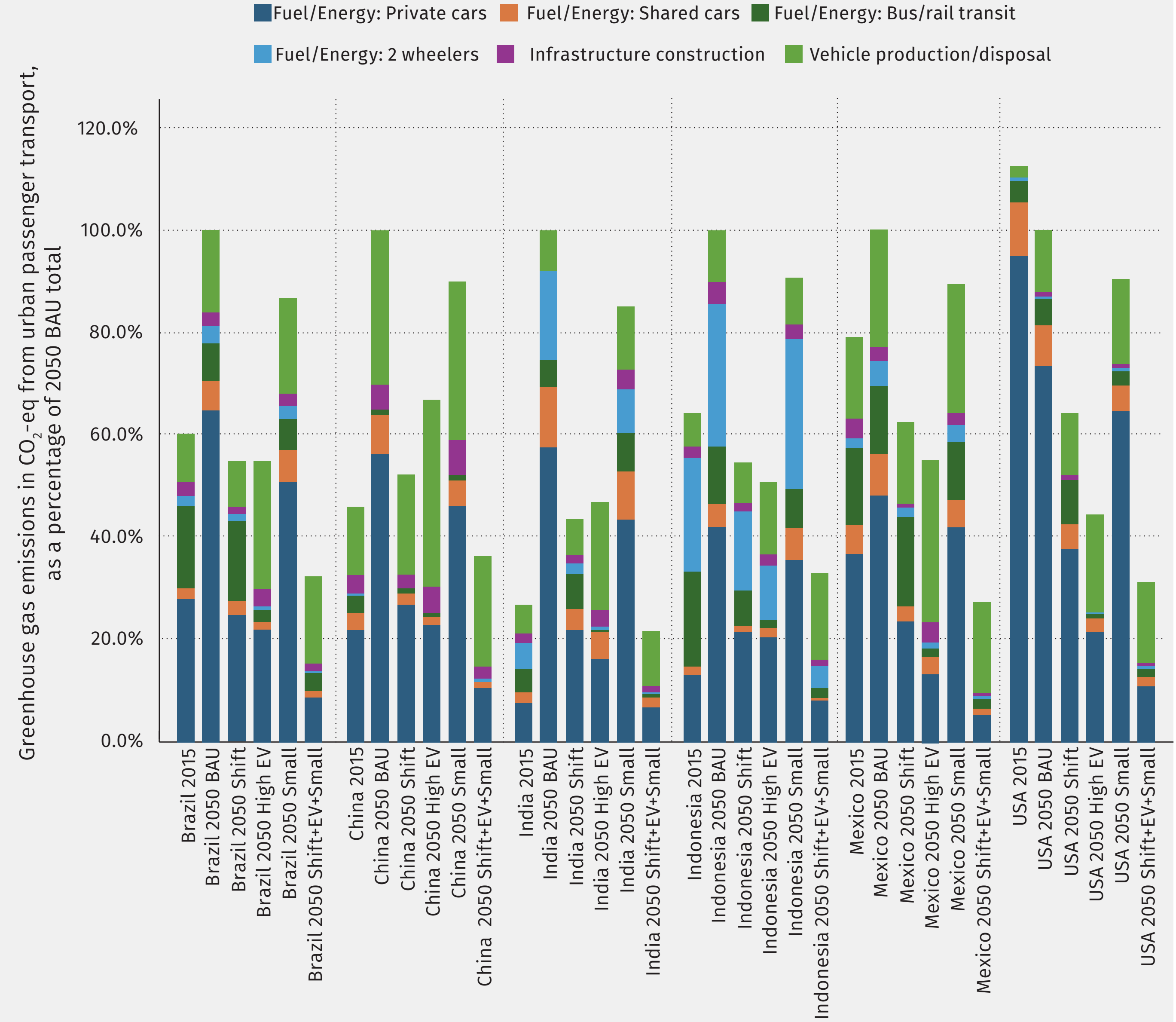
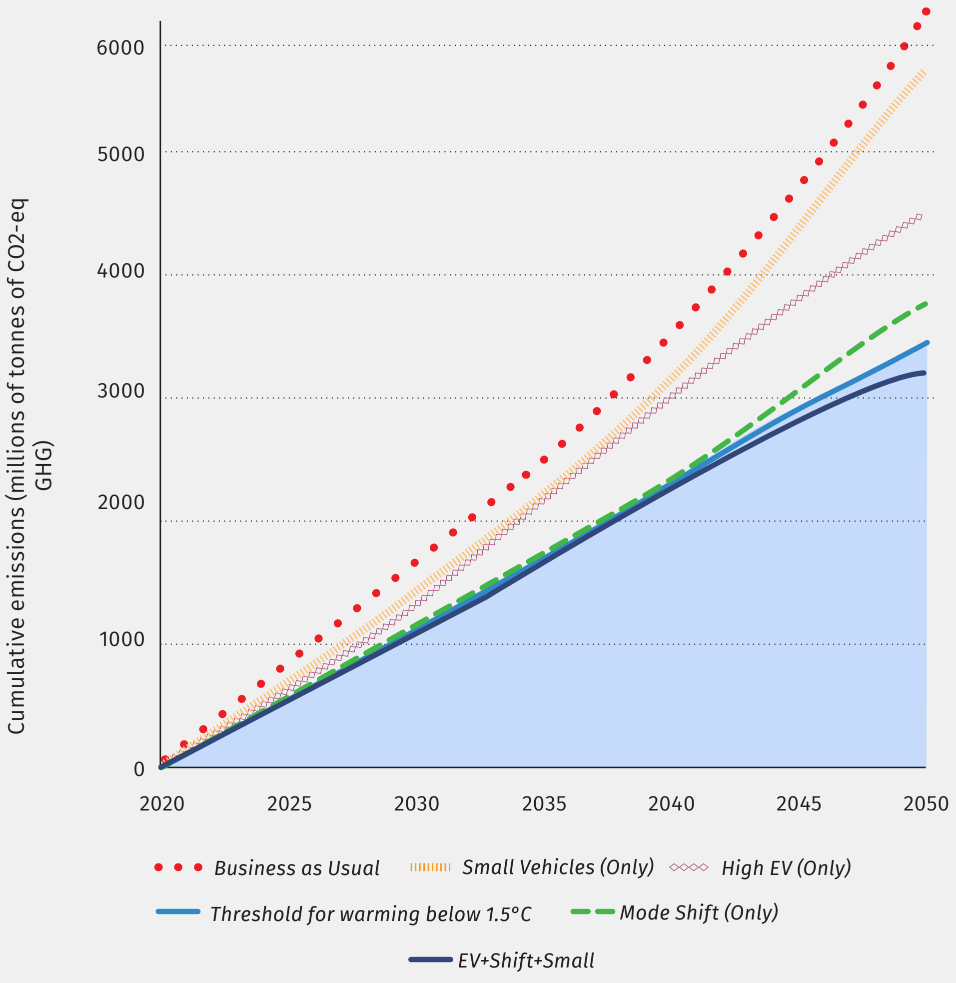


Figure 5.3.b. Annual GHG emissions by country, scenario, and year—normalized



Note that in both the *High EV* and the *EV+Shift+Small* scenarios, nearly half of GHG emissions from urban passenger transport are from the manufacture of vehicles rather than their operation.
available in the **Public Graphics file**.

Figure 5.3.c. Cumulative urban passenger transport emissions, by scenario: India



5.4. DIRECT PUBLIC AND PRIVATE COSTS

Urban passenger transportation can impose great costs on all parts of society—the governments that build, maintain, and operate transport systems; the individuals who spend money on vehicles, fuel, and transit fares; and the businesses who operate for-hire services or transport people as part of their operations. In many parts of the world, these costs are on track to balloon over the coming decades: For example, in India, under the *Business as Usual* scenario, annual costs of urban passenger transport could be over eight times higher in 2050 than they were in 2015.

In Figure 5.4.a and Figure 5.4.b, we show how different scenarios have very different implications for total (public and private) direct costs. Although *High EV* and *Small Vehicles* both offer incremental savings relative to *BAU*, only the *Mode Shift* scenario is capable of substantially reducing the cost burden of urban passenger transportation for society. As shown in more detail in previous studies, this cost savings is felt by all members of society but especially by private individuals and most particularly by lower-income people. This improvement could free up valuable resources for productive reinvestment in education, healthcare, and small businesses.

Figure 5.4.a: Annual Direct Public and Private Costs

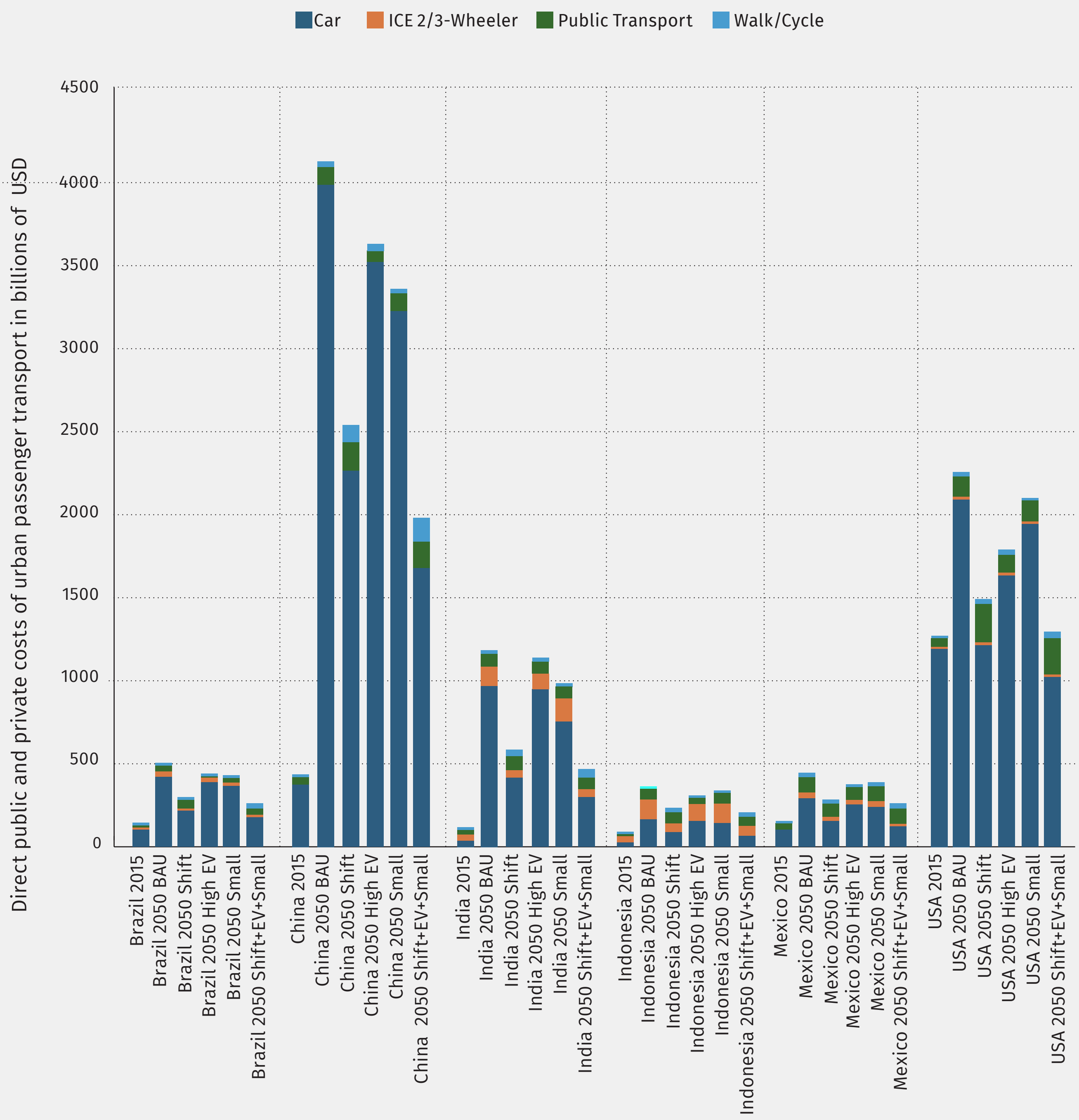
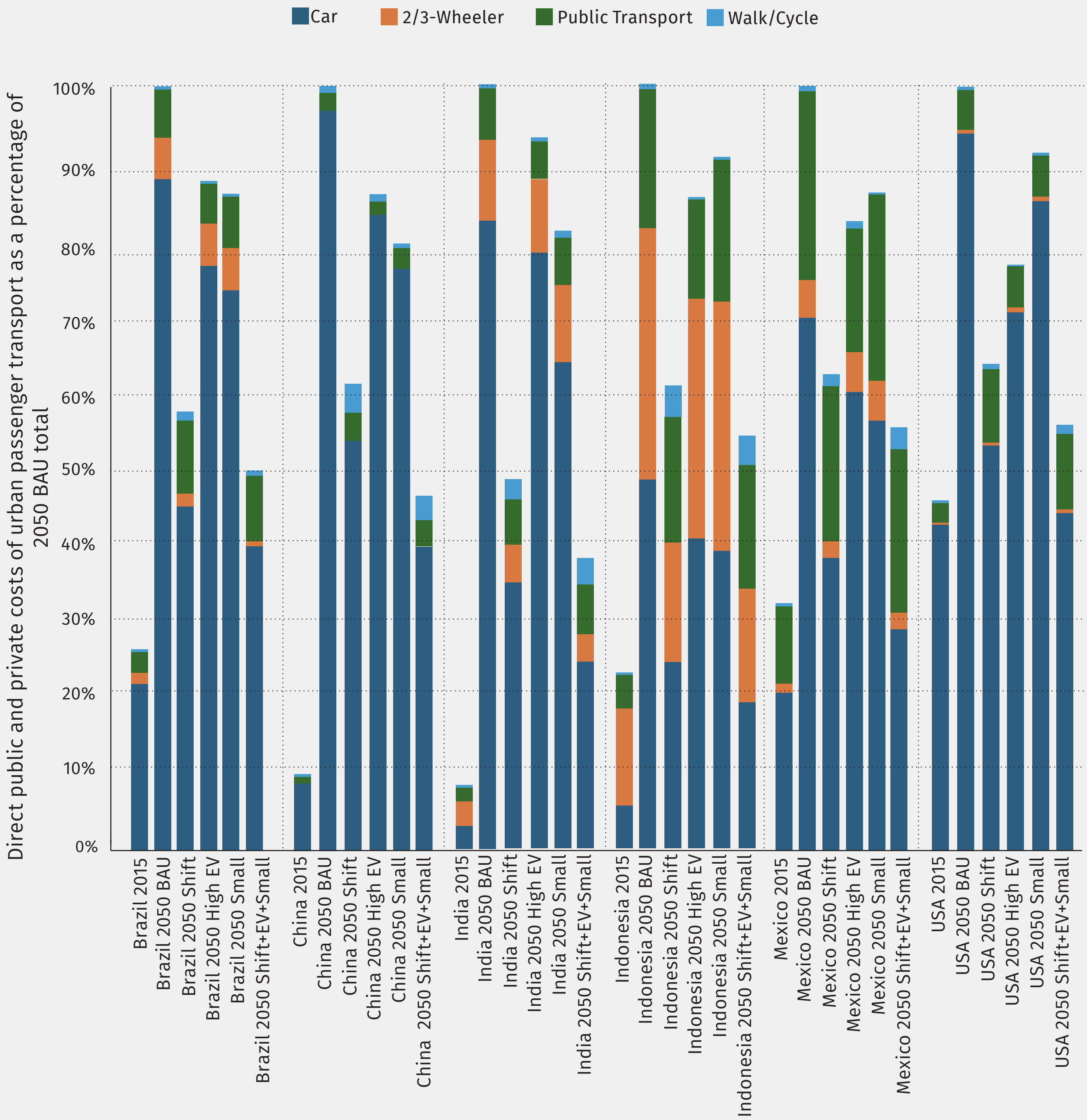


Figure 5.4.b. Annual direct public and private costs—normalized



The addition of vehicle size scenarios in this study does not have any major implications for public-sector costs of urban passenger transport, only for the private costs borne by purchasers, operators, and insurers of these more expensive vehicles. As such, we do not repeat our publication of detailed analysis of public-sector costs in this section. These are included in the 2023–2024 Compact Cities Electrified country-level reports, and the numbers would be unchanged. Readers interested in understanding how the *Mode Shift* and *High EV* scenarios would affect public costs should consult those publications directly.

5.5. BATTERY REQUIREMENTS

Vehicle electrification will greatly increase demand for batteries and battery materials in all scenarios. In the *BAU* scenario, countries will require thousands of gigawatt-hours of batteries for urban LDVs by 2050, a requirement that increases significantly in *High EV* scenarios. However, both *Mode Shift* and *Small Vehicles* scenarios are capable of reducing battery requirements relative to *BAU*, and combining these scenarios with *High EV* results in the lowest possible requirement for battery materials while achieving a high degree of electrification.

Note that this is the only impact category for which we report impacts in a scenario other than the usual five. We include estimates of battery capacity requirements in the *EV+Small* scenario to illustrate the potential benefits of reducing vehicle size in an electrification-heavy world in the absence of *Modal Shift*, and we show this as well as the usual scenarios in Figures 5.5.a and 5.5.b. We find that the benefits of smaller vehicles in this scenario range from a 10% reduction in battery requirements (US, China) to a 35% reduction (India).

It is interesting to compare this figure with Figure 3.2.a, above, and see how battery demand is dominated by cars even in scenarios where much or most urban travel is by other modes. Buses and 2- and 3-wheelers become electrified, and buses use large battery packs per vehicle, but the total number of these vehicles is very small compared to LDVs. The 2- and 3-wheelers, in contrast, appear in large numbers but require very small battery packs per vehicle.

Figure 5.5.a. Annual battery requirements by year, country, and scenario

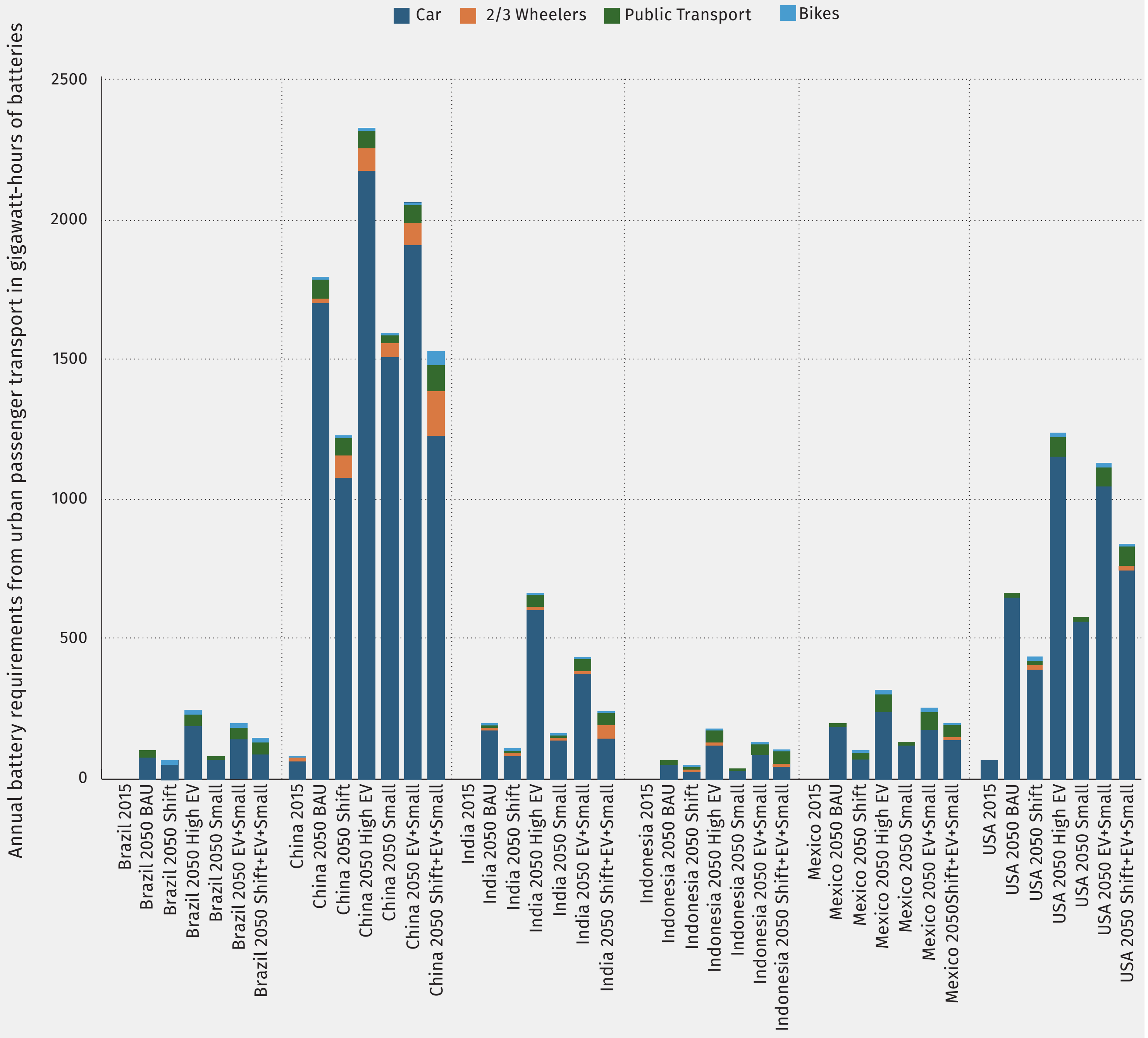


Figure 5.5.b. Annual battery requirements from urban passenger transport by year, country, and scenario—normalized

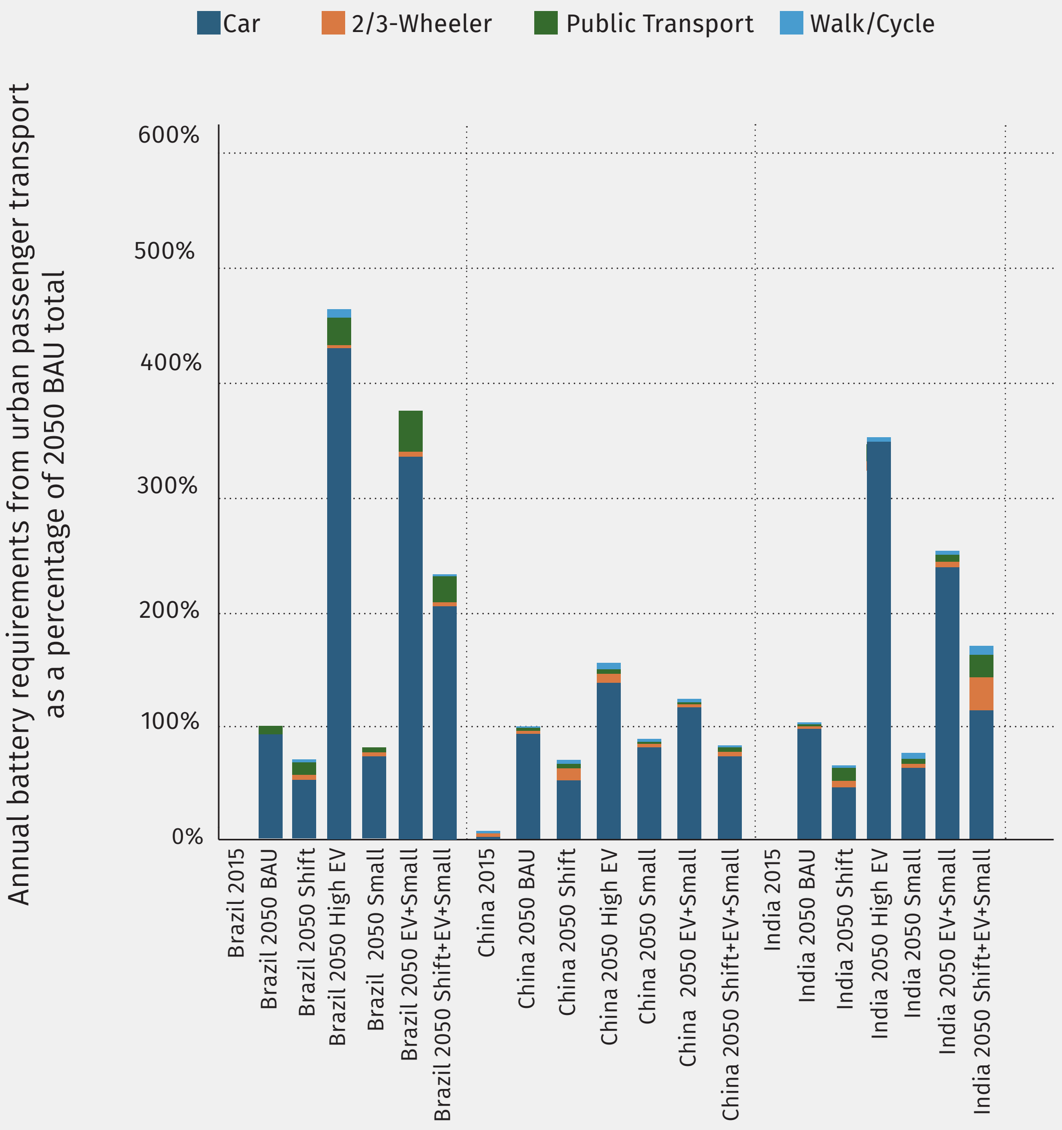


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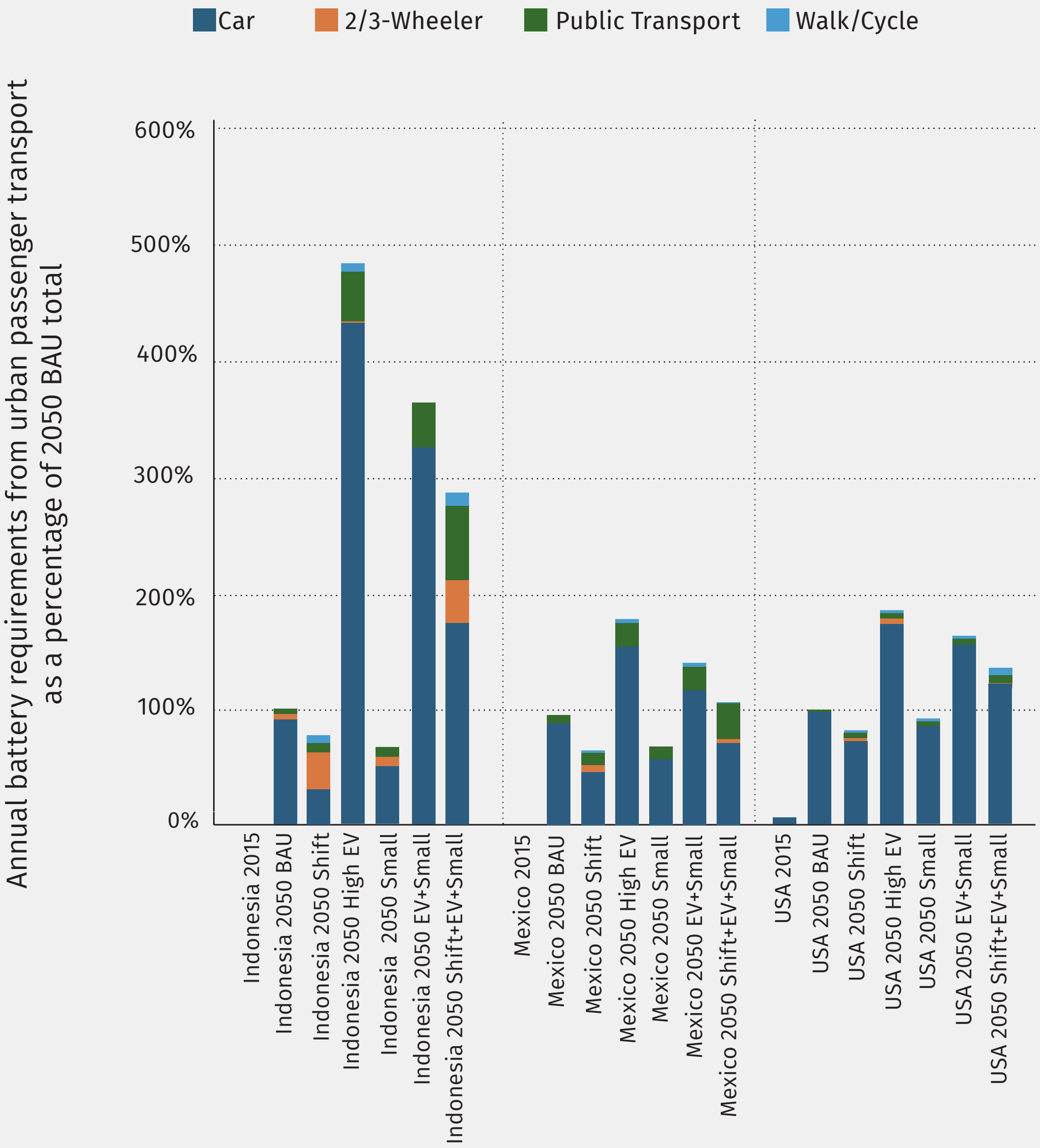
Figure 5.5.b. Annual battery requirements from urban passenger transport by year, country, and scenario—normalized



5.6. ROAD SAFETY

Two of our scenario variables have implications for road safety: *Mode Shift* and *Small Vehicles* modal shift and vehicle size. As shown in Figures 5.6.a and 5.6.b, both of these variables have the potential to meaningfully reduce road fatalities, although *Mode Shift (Only)* has a greater benefit than the *Small Vehicles (Only)* scenario. The greatest benefit universally comes from combining the two.

The dynamics of this difference vary slightly between countries. For example: India, the US, and Brazil could all reduce road fatalities by roughly 10% by adopting policies to favor smaller vehicles. This is because these countries have relatively high proportions of vehicle–pedestrian collisions—the category of collisions where vehicle size is most important in determining lethality. China, on the other hand, will see only a reduction of about 3% from smaller vehicles because fewer of China's (reported) fatalities come from vehicle/pedestrian collisions.

Figure 5.6.a. Road safety impacts by country and scenario

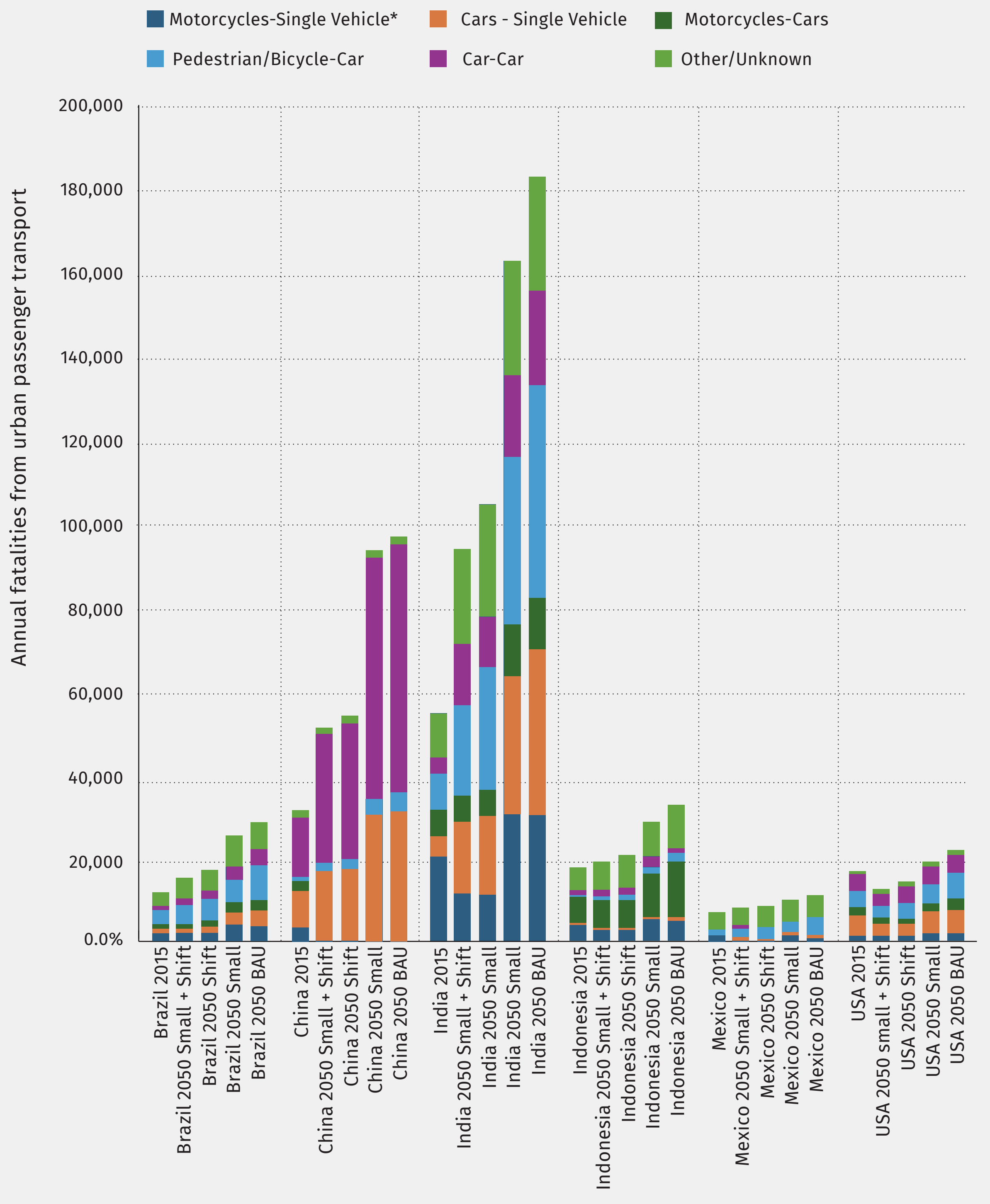
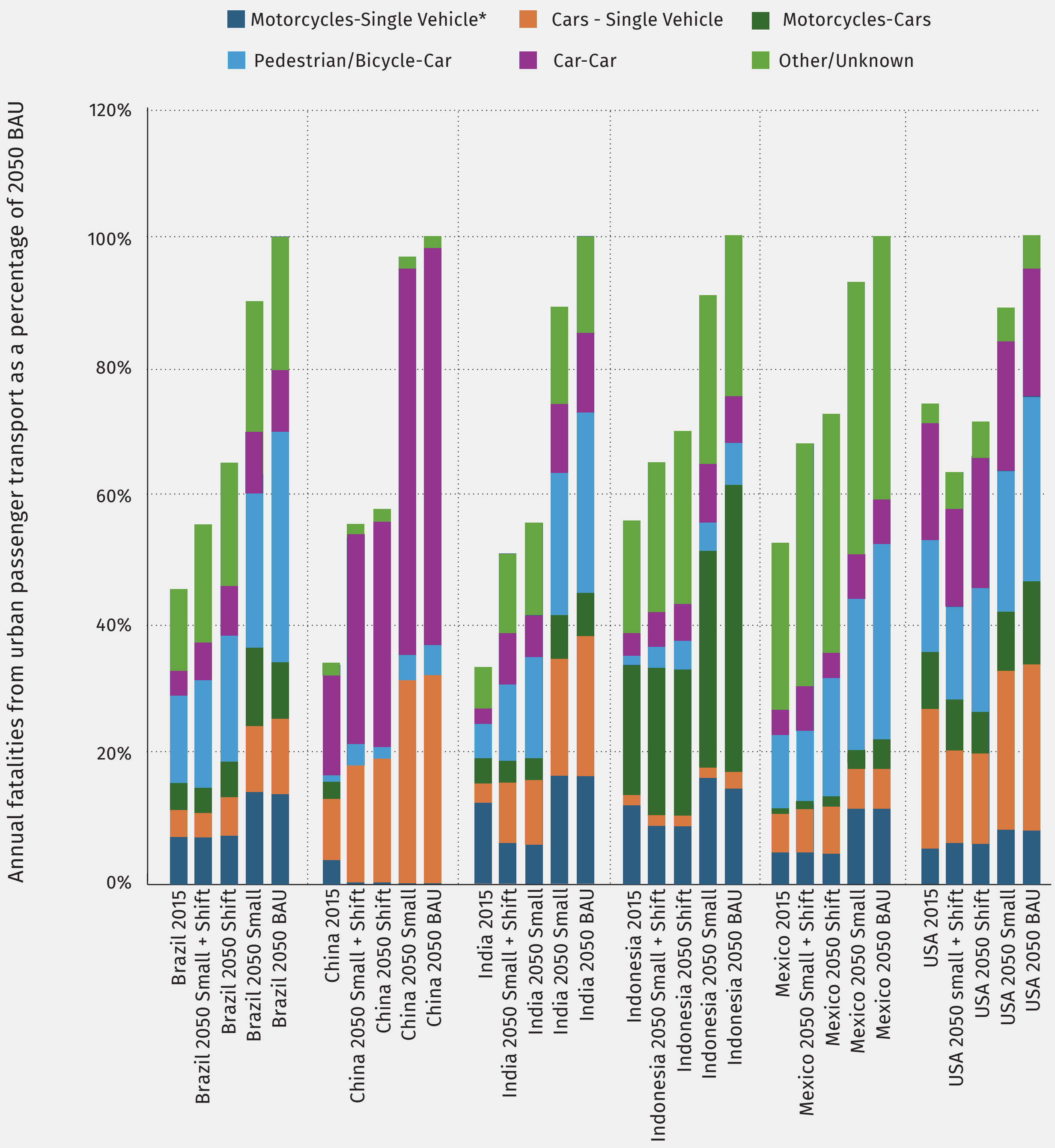


Figure 5.6.b. Road safety impacts by country and scenario—normalized



5.7. AIR POLLUTANTS

In most countries, particulate matter emissions from urban passenger transport are set to grow over the next quarter-century, even as tailpipe emissions of nitrogen oxides and carbon monoxide fall dramatically.

As Figures 5.7.a and 5.7.b show, emissions of fine particulate matter will increase in most of the world under *BAU*, and even in the policy reform scenarios, PM2.5 emissions will often be higher in 2050 than they were in 2015. The benefit of electrification by 2050 is noticeable, but electrification only addresses tailpipe emissions, while most PM2.5 emissions in 2050 will come from non-tailpipe sources (brakes, tires, and road dust). Indeed, by 2050, emissions standards will improve to the degree that even most ICE vehicles will produce more PM2.5 from non-tailpipe than from tailpipe sources. The *Mode Shift* scenarios show the largest reductions in PM2.5 emissions relative to *BAU*, since they address non-tailpipe emissions through a reduction in overall vehicle travel.

Figure 5.7.a. PM2.5 emissions by country, scenario, and year

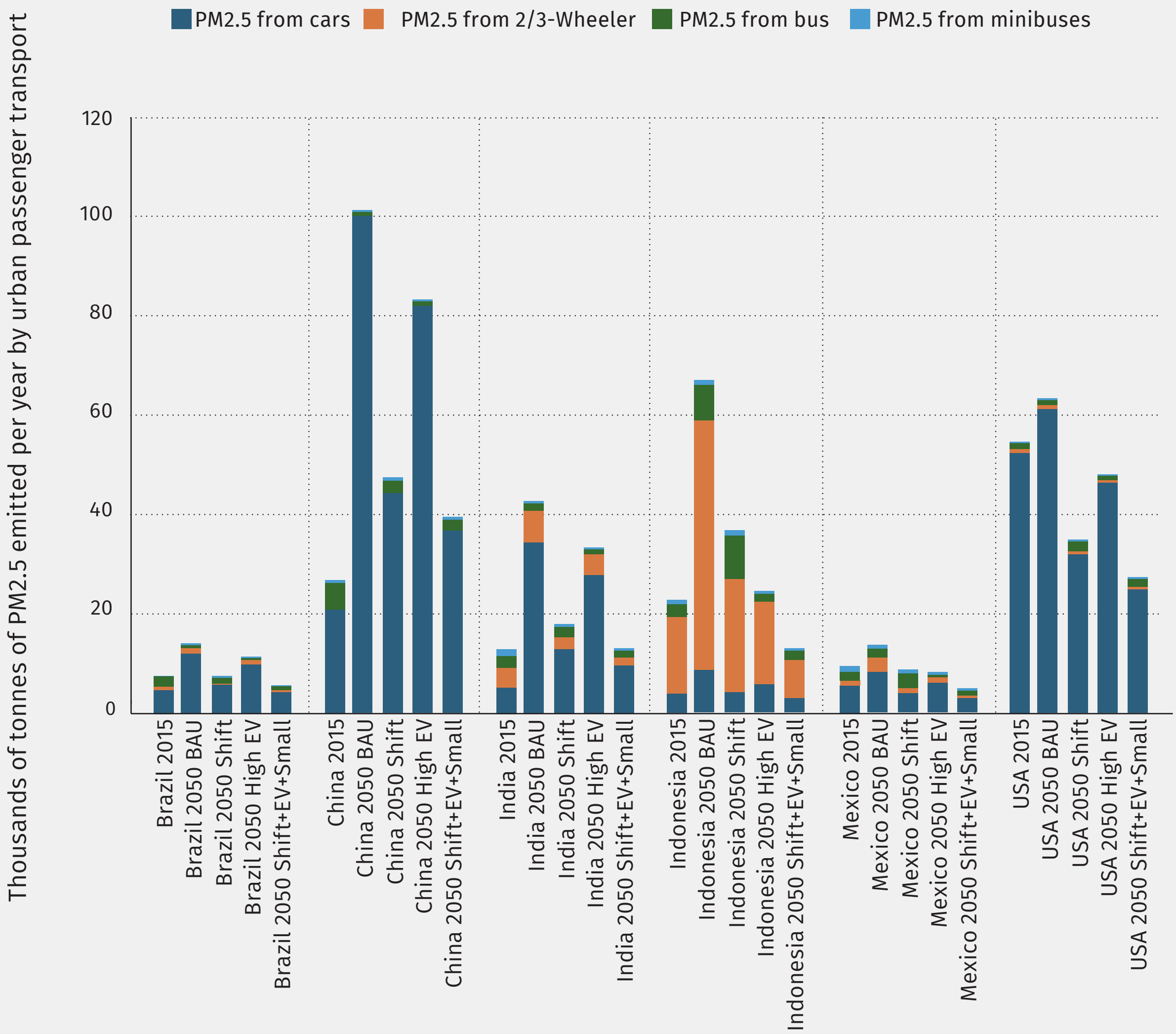
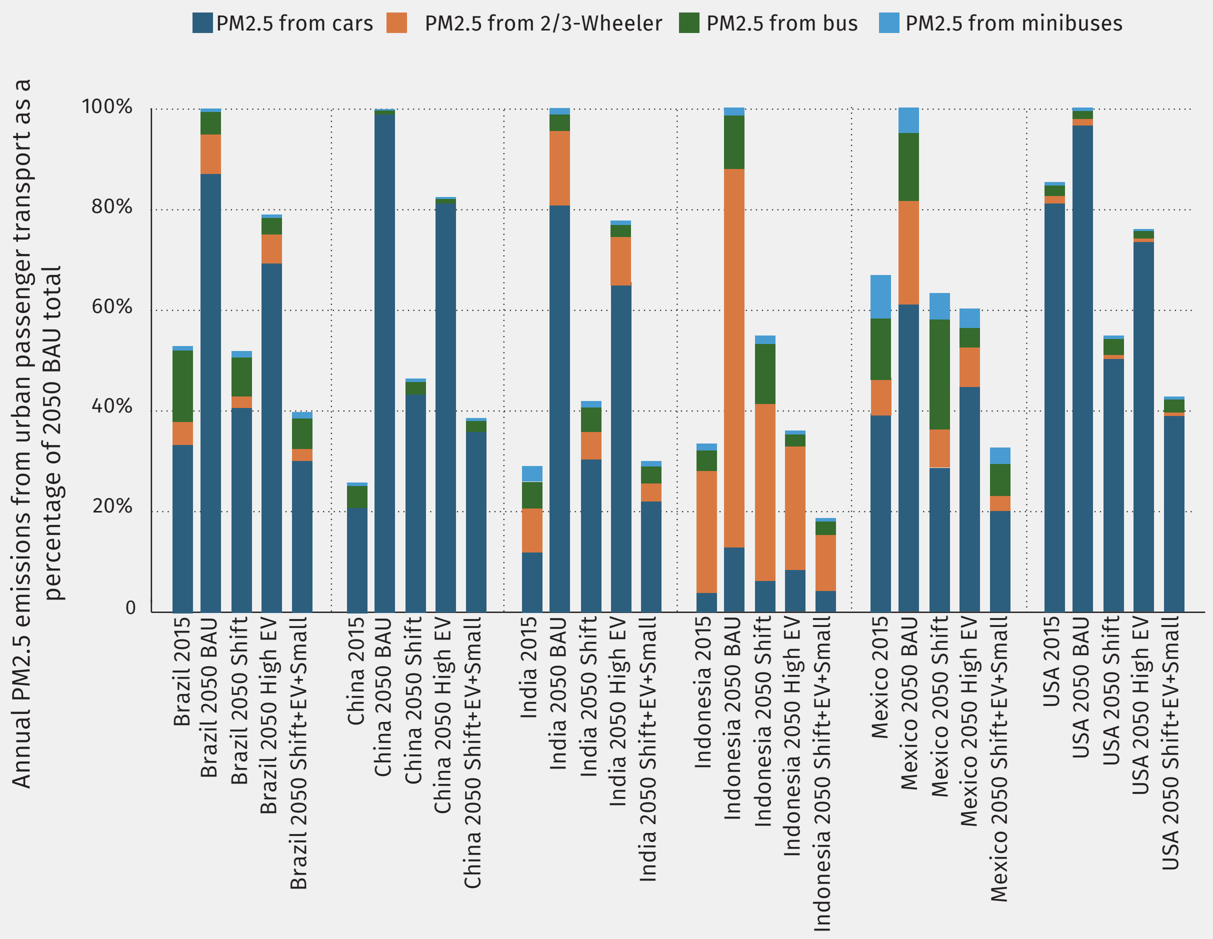


Figure 5.7.b. PM2.5 emissions by country, scenario, and year—normalized



An interesting exception is Indonesia, followed by Mexico to a lesser extent. Because of the unique dominance of highly polluting 2- and 3-wheeled vehicles in urban Indonesia, the *High EV* scenario has unusually dramatic potential to reduce PM2.5 emissions there. In Mexico, the prevalence of 2- and 3-wheelers is lower, and the benefit of electrification is correspondingly less pronounced.

The results of our analysis of emissions of NO_x and CO tell a different story. These pollutants are emitted only by tailpipes and are therefore subject to the emissions regulations that are effectively reducing tailpipe emissions globally. In all countries and scenarios, NO_x emissions per vehicle, and thus in total, are on track to fall rapidly by 2050 (see Figure 5.7.e). CO will also fall by 2050 in all scenarios in the US, China, Brazil, and Mexico, though not as dramatically as NO_x. India and Indonesia will see an increase in CO by 2050 under the *BAU* scenario (see Figure 5.7.c).

Figure 5.7.c. CO emissions by country, scenario, and year

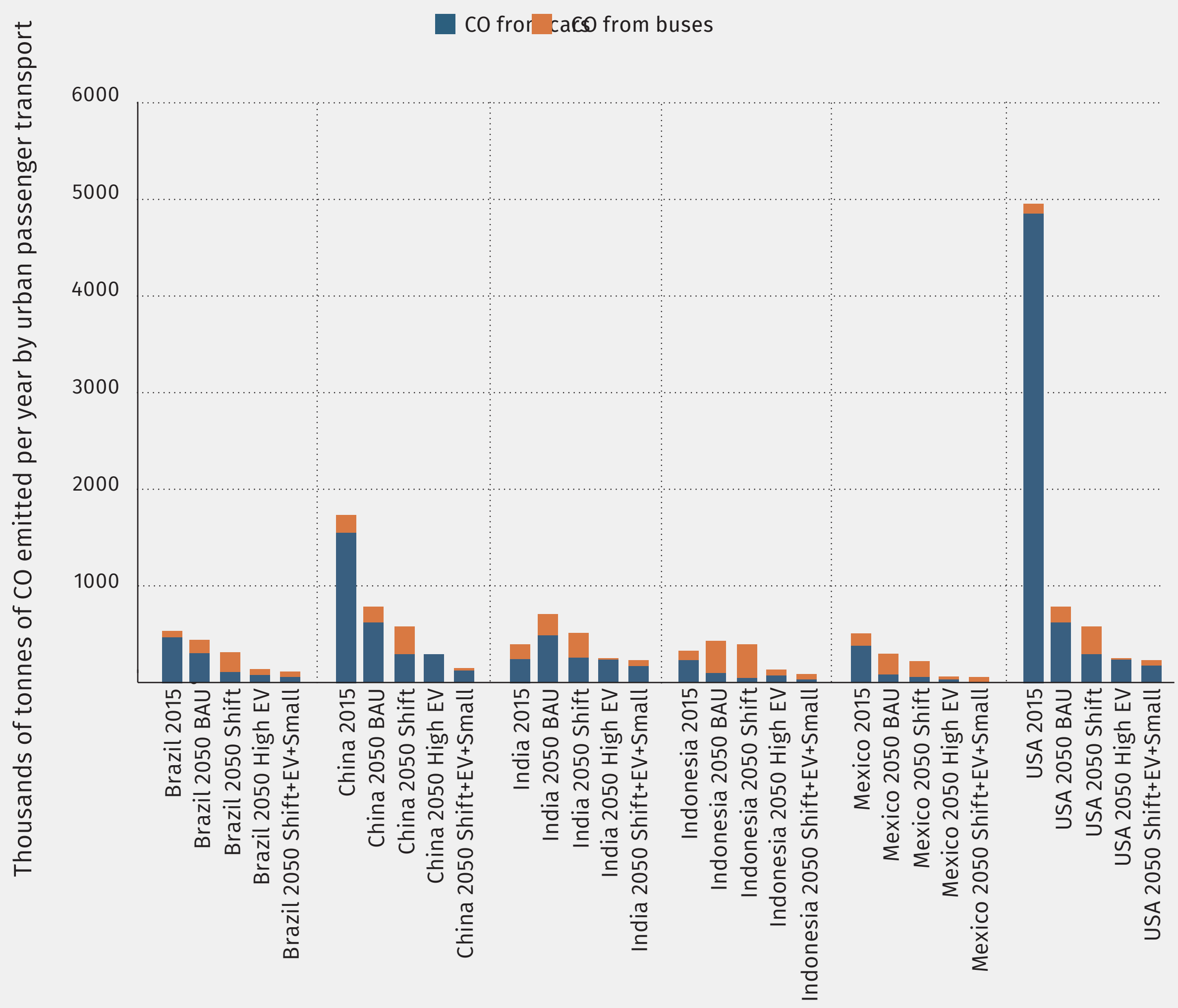


Figure 5.7.d. CO emissions by country, scenario, and year—normalized

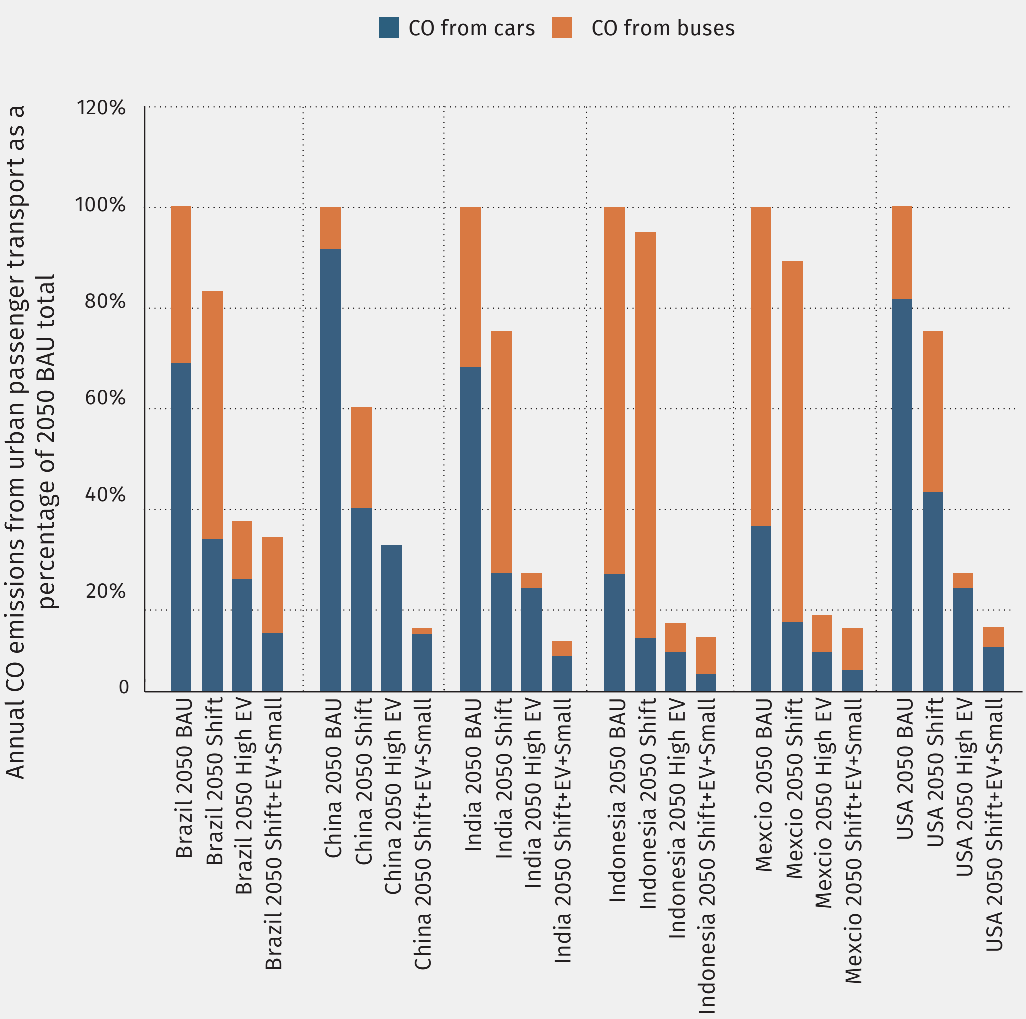
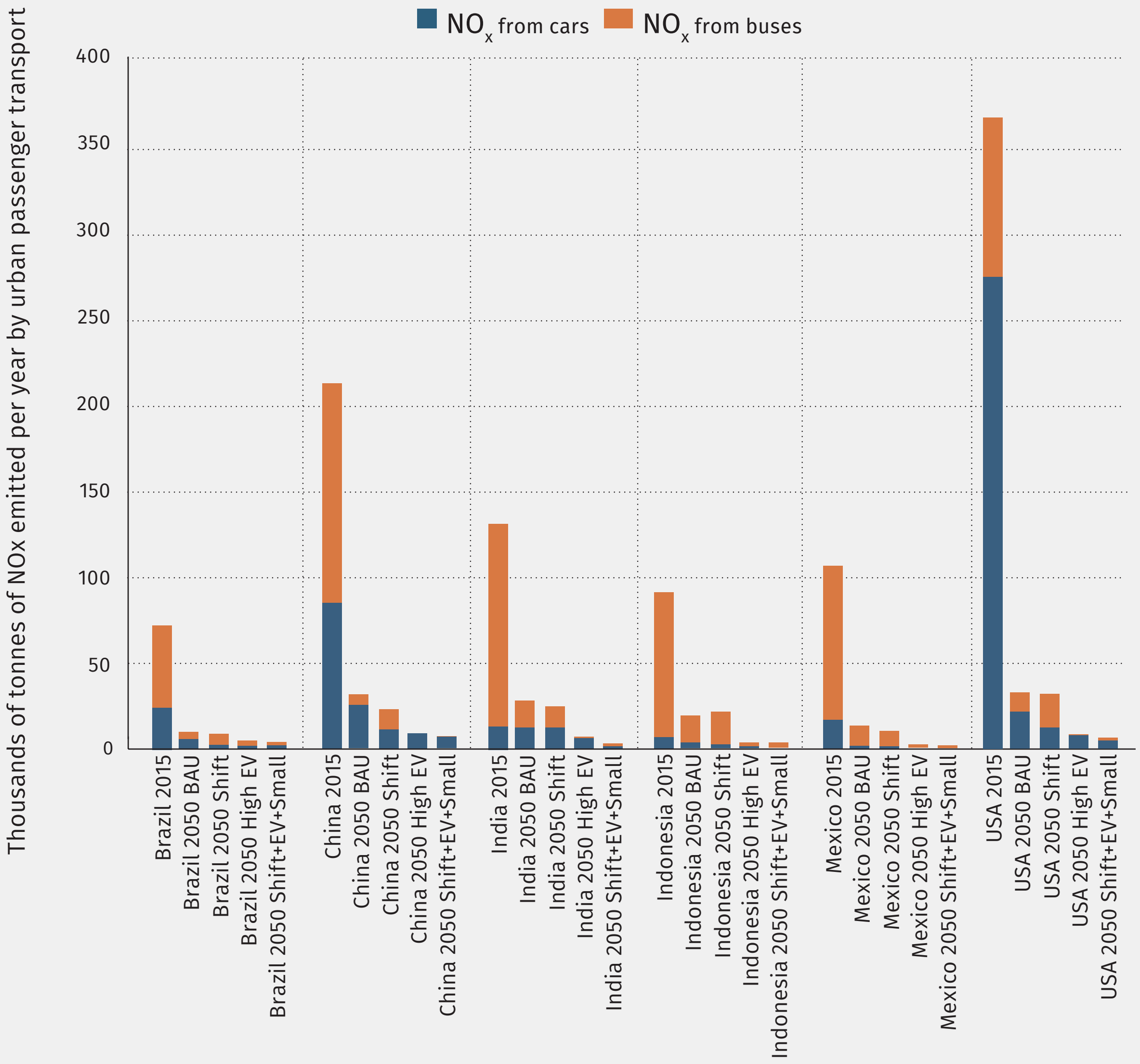


Figure 5.7.e. NO$_x$ emissions by country, scenario, and year



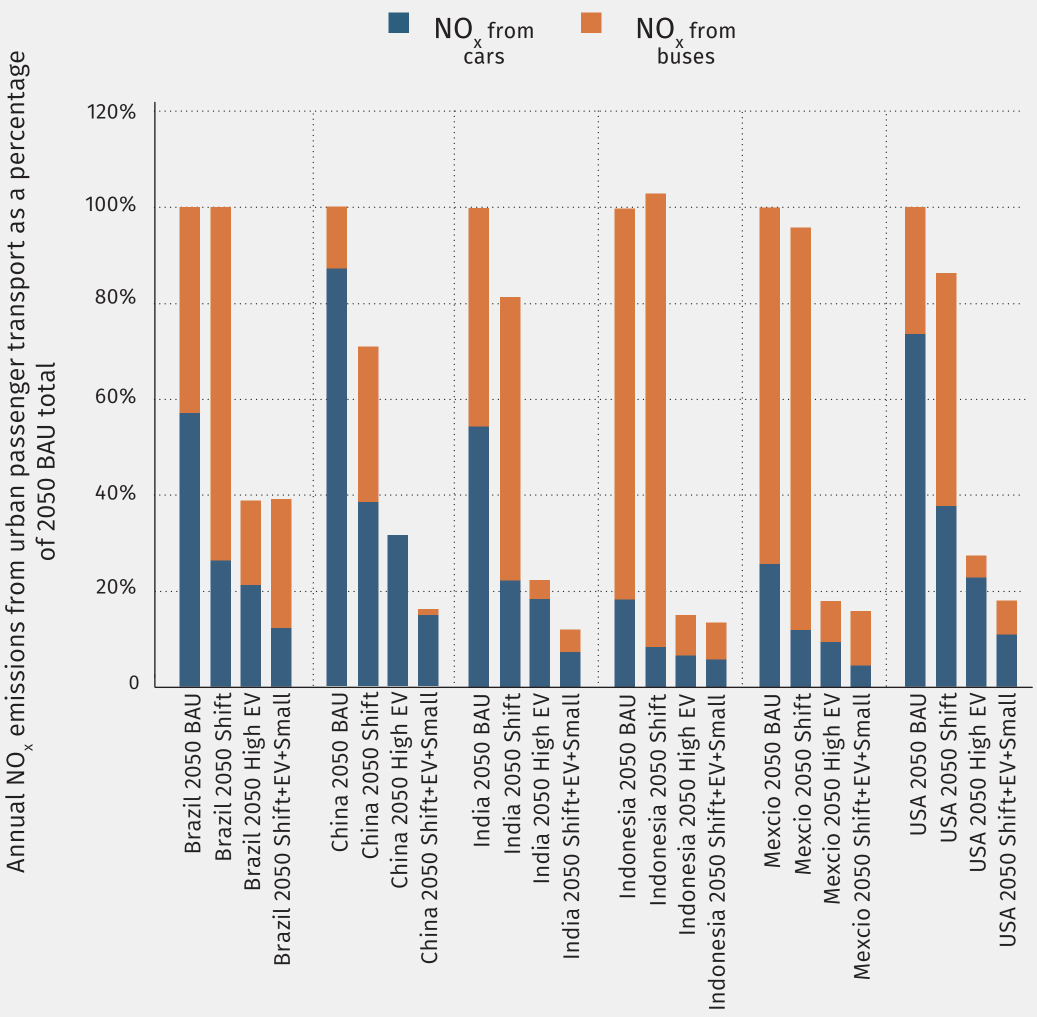


Figure 5.7.f. NO$_x$ emissions by country, scenario, and year—normalized

Although these declines are obvious when the data is visualized in absolute terms (as in Figures 5.7.c and 5.7.e), a different finding is clear when we display the data in terms relative to 2050 *BAU*, as in Figures 5.7.d and 5.7.f. These normalized figures show that in every country the combination of *High EV* and *Mode Shift* and modal shift will result in a much greater reduction than *BAU*. Note that the Shift scenario has a less dramatic reduction in NO$_x$ than in the other pollutants: This is because we assumed that ICE buses are powered by diesel, which is much more NO$_x$-intensive than the gasoline that we assumed would power ICE cars.

As discussed in Section 4.7, we were unable to conduct a sufficiently rigorous analysis of the impacts of pollution levels on public health within the scope of this study. However, it is notable that under the *EV+Shift+Small* scenario, most countries experience a >70% reduction in most pollutants compared to *BAU*. It is also notable that most countries will see a dramatic increase in primary PM2.5 emissions from urban transport under the *BAU* scenario, and many countries will also see an increase in CO emissions.

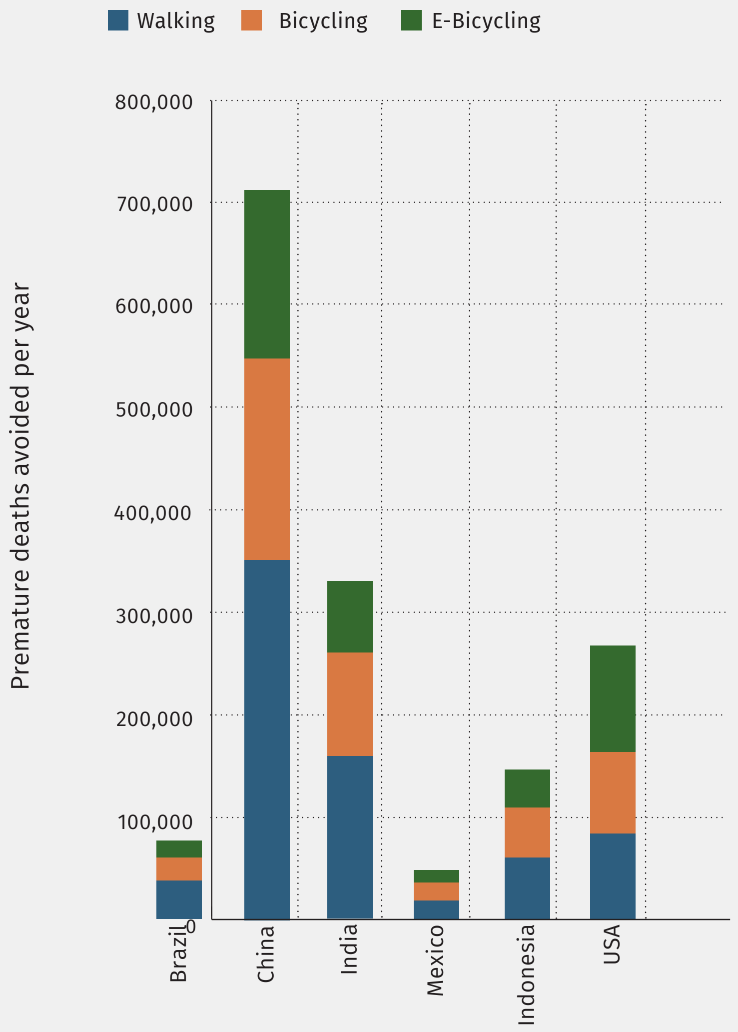
Considering that air pollutant emissions from transportation were responsible for nearly 400,000 global deaths in 2015,[27] we expect that the potential reduction in pollutant emissions under the *EV+Shift+Small* scenario will also save many lives.

5.8. PHYSICAL ACTIVITY AND PUBLIC HEALTH

Urban passenger transport does not only affect public health through air pollution; physical activity is also a major factor. As described in Section 4.6, increased rates of walking and cycling (including e-bicycling) can have a dramatic impact on reduced premature deaths.

Only one of our three scenario variables, *Mode Shift*, includes any changes to levels of walking and cycling, and those changes are the same in all scenarios that include *Mode Shift*. Therefore, in Figure 5.8.a, below, we display these results in terms of the annual number of premature deaths avoided as of 2050 in the comparison between *Mode Shift* scenarios and *BAU*.

Figure 5.8.a. Annual premature deaths avoided by *Mode Shift* scenarios as of 2050, by country



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[27] Anenberg, S., et al. (2019). A Global Snapshot of the Air Pollution–Related Health Impacts of Transportation Sector Emissions in 2010 and 2015. International Council on Clean Transportation: ICCT.

6

CONCLUSIONS

This study demonstrates that a much more sustainable, affordable, and healthy urban transport future is possible—but only if cities and countries embrace comprehensive change across three fronts: *Mode Shift*, *High EV*, and *Small Vehicles*. Strong shifts in each of these aspects will deliver meaningful benefits on their own, but the full potential is only realized when they are pursued together. Our conclusions are as follows:

6.1. REDUCING VEHICLE SIZE IS AN UNDERUSED LEVER

This report is, to our knowledge, the first country-level urban transport outlook to explicitly model different vehicle size scenarios as a core modeling variable and to quantify the effects across multiple impact domains. While earlier studies have documented the rise of SUVs and shifting vehicle size trends, few have examined the implications of reversing these trends in a systematic, multi-country-scenario analysis.

Our findings show that reducing the average size of vehicles—returning market shares to 2020 vehicle sizes—can substantially lower energy use, GHG emissions, battery material demand, and road fatalities. It can provide other urban benefits too, such as reducing parking area requirements and freeing up road space. These benefits are particularly notable when paired with *Mode Shift* and *High EV*. Yet despite these clear advantages, vehicle size remains a largely overlooked policy lever in many national and local transport strategies. Policymakers aiming to build safer, more efficient cities while reducing dependence on scarce battery resources should give serious attention to size-focused interventions, such as regulation, taxation, and consumer incentives.

6.2. MODAL SHIFT, ELECTRIFICATION, AND VEHICLE SIZE REDUCTIONS MUST BE COMBINED FOR MAXIMUM BENEFIT

A combination of *Mode Shift*, *High EV*, and *Small Vehicles* scenarios create far greater impacts than any scenario alone. The most ambitious scenario, which combines all three strategies (*Shift+EV+Small*), results in the greatest benefits. The scenarios combine to create different kinds of impact: For example, *High EV* lowers emissions, but without *Mode Shift*, it does not meaningfully reduce road deaths, particulate pollution, or costs for low-income travelers. *Mode Shift* reduces those harms but does little to reduce the emissions of the remaining vehicle fleet unless *High EV* is also pursued. Similarly, *Small Vehicles* amplifies the energy, safety, and cost savings of the other two variables.

From the perspective of policy implementation, the combination of scenarios may provide good benefits, as we detailed in earlier studies. *Mode Shift* reduces the quantity of electric vehicles, batteries, and electricity that must be produced, shortening the time frame for electrification. Similarly a shift to smaller vehicles also reduces the amount of batteries needed for electrification. Urban transport systems are complex, and single-issue strategies cannot resolve their full set of challenges. A coordinated policy approach is essential: promoting walking, cycling, and public transport; accelerating vehicle electrification; and reversing the trend toward ever-larger vehicles.

6.3. THERE ARE MANY UNQUANTIFIED BENEFITS THAT STRENGTHEN THE CASE FOR REFORM

While this study focused on quantifiable metrics, it is important to recognize that the true benefits of a reformed transport system go far beyond what we were able to model. Smaller vehicles reduce roadway maintenance requirements and the spatial domination of streetscapes; they even take up less space and thereby reduce congestion. *Mode Shift* brings social and psychological benefits, from reduced loneliness and increased social interaction to improved neighborhood vibrancy and inclusiveness. Electrification reduces noise pollution—a growing concern in dense cities, as scientists begin to unravel its implications for public health. Electric buses provide smoother, more comfortable rides for passengers and may be easier to incorporate into an integrated public transport system. Each of these shifts also complements broader goals in land use, housing, and climate resilience.

Perhaps most significantly, these strategies can help cities reclaim space—roadways narrowed by smaller vehicles, parking repurposed for housing or green space, and travel time reallocated toward social and economic life. Such outcomes are difficult to quantify on a global scale but are central to the lived experience of urban sustainability.

This report therefore offers not just a vision of lower emissions and lower costs but of better cities. Achieving that vision will require ambitious, integrated policy action, but the tools and evidence are now clearer than ever.

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