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VISION 2050
STRATEGIES TO ALIGN GLOBAL ROAD TRANSPORT WITH WELL BELOW 2°C

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EXECUTIVE SUMMARY

Since 2020, the world has had a remaining carbon budget of 400 billion tonnes (Gt) of carbon dioxide (CO_2) if we are to have a likely chance of limiting global warming to 1.5°C above pre-industrial levels (Intergovernmental Panel on Climate Change [IPCC], 2021). The same carbon budget for 1.7°C is 700 Gt CO_2 and for 2°C, it is 1,150 Gt CO_2. Road vehicles account for more than 20% of the carbon emissions from human activities, considering both fuel production and combustion. Figure ES-1 shows CO_2 emissions pathways for light- and heavy-duty vehicles that are compatible with the IPCC's carbon budgets if vehicles emit a proportional (21%) share of the economy-wide carbon budget.

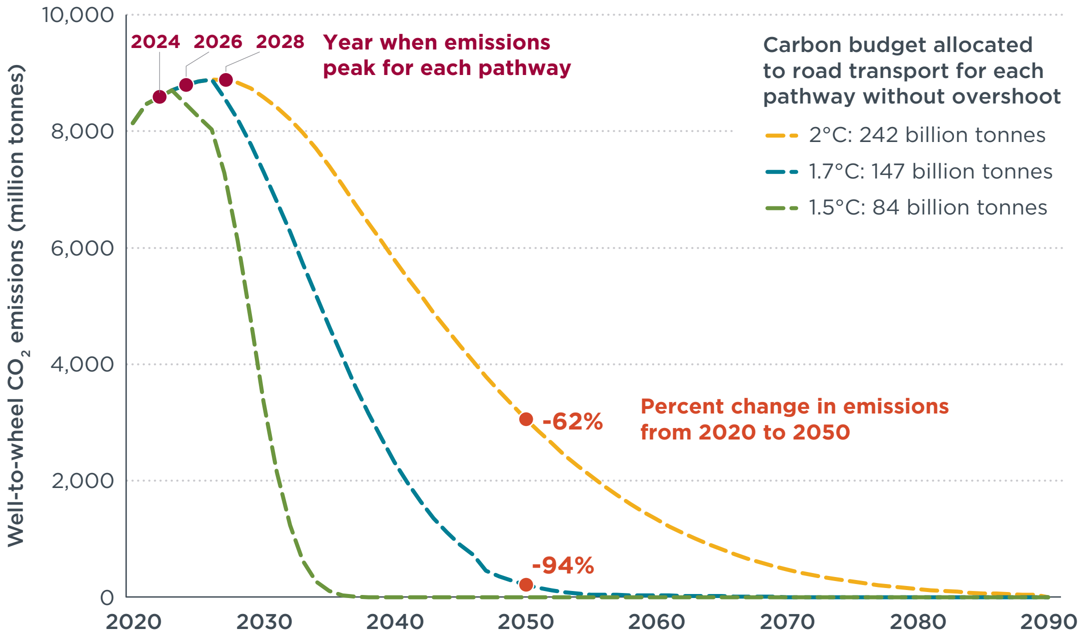

Figure ES-1. Well-to-wheel CO_2 emission pathways for light- and heavy-duty vehicles compatible with 2°C, 1.7°C, and 1.5°C of warming without temperature overshoot (all 67% likelihood).

Modeling by the International Council on Clean Transportation (ICCT) shows that *without any further policy action*, global vehicle CO_2 emissions would exceed even the budget for 2°C. However, a *faster transition to zero-emission vehicles* (battery electric and hydrogen fuel cell vehicles) could peak vehicle emissions by 2027 and align with a 2°C target.

This study explores the potential of a combination of five strategies to further reduce carbon emissions from vehicles. We consulted with other researchers to formulate ambitious but feasible scenarios for road vehicles and then used the ICCT's Roadmap model to explore their potential to align vehicle emissions with a well-below 2°C or 1.5°C goal.

We find that a combination of all five strategies could cut cumulative CO_2 emissions from vehicles in half through 2050 compared with a Baseline scenario. That "All Out" scenario would save 144 Gt CO_2 and align the sector with a warming target well below 2°C (Figure ES-2). These are the five strategies in the All Out scenario:

1. Accelerate the global transition to zero-emission vehicles
2. Maximize the fuel efficiency of any new combustion vehicles sold
3. Replace old combustion vehicles faster
4. Reduce the dependence on cars in urban areas and improve freight logistics
5. Decarbonize the electricity and hydrogen used in zero-emission vehicles

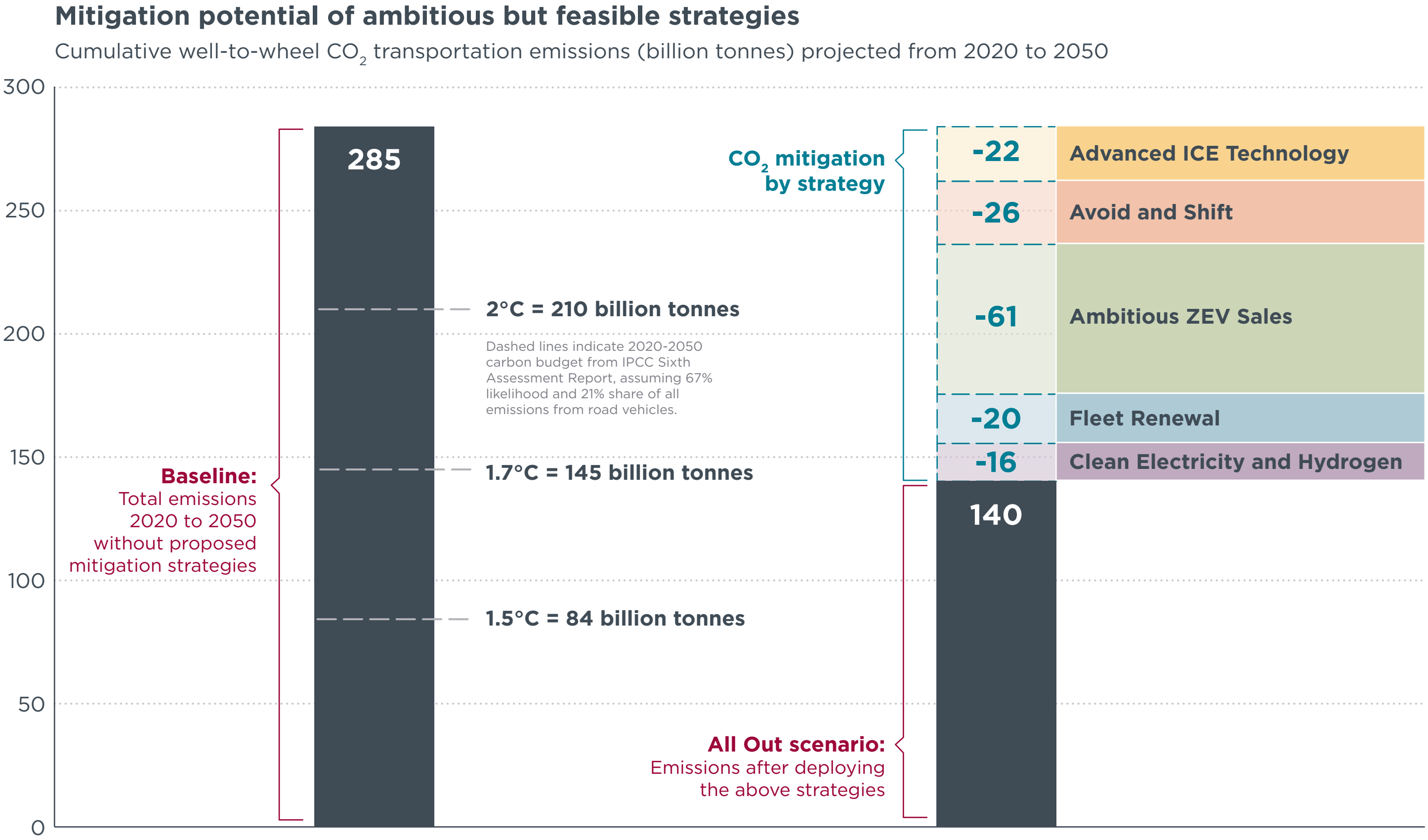

Figure ES-2. Cumulative well-to-wheel CO_2 emissions in the Baseline and All Out scenarios and relative mitigation potential of each strategy, with reference lines for vehicle carbon budgets through 2050 compatible with 1.5°C, 1.7°C, and 2°C targets. Data labels are rounded to the nearest Gt.

Accelerating the global transition to zero-emission vehicles contributes 42% of the emission reductions in the All Out scenario—more than any other two strategies combined. This would require making sure that around 70% of new cars and 50% of new trucks sold by 2030 are electric, and in major markets those percentages increase to 100% for new cars by 2035 and 100% for new trucks by 2040. This scenario also includes actions to shift the international used vehicle market to zero-emission vehicles so that countries that rely significantly on used imports are also part of the strategy to reduce emissions.

Even when we accelerate the transition to zero-emission vehicles, 700 million new gasoline and diesel light- and heavy-duty vehicles will still be sold through 2045. **Adopting the most efficient existing technologies in all combustion vehicles** (like hybrid vehicles) and making vehicles lighter could contribute 15% of the emissions reductions in the All Out scenario. Enacting new or strengthening existing fuel economy standards and greenhouse gas standards and indexing fiscal policies like vehicle purchase fees to vehicle CO_2 emissions performance are proven strategies to increase the uptake of such technologies.

Turnover is a key challenge to rapidly decarbonizing the fleet of vehicles currently on the road; the average light-duty vehicle remains on the road for 18 years and the average heavy-duty vehicle for 16 years. **Complementing the transition to zero-emission vehicles with policies to replace older vehicles faster** contributes 14% of the All Out scenario's emissions reductions; these include measures like fleet-renewal programs, low-emission zones, and vehicle inspection programs.

Reducing people's dependence on cars in urban areas and improving freight logistics contributes 18% of the All Out reductions. Many cities have had success reducing car dependence with strategies such as investing in public transport, building cycling and walking infrastructure, and prioritizing space for people over cars. Similar measures could be emulated or directly replicated in other cities. Similarly, actions to improve freight logistics include improving vehicle routing and increasing vehicle utilization.

Decarbonizing the electricity and hydrogen used in zero-emission vehicles contributes 11% of the All Out reductions. Key actions here include regulatory and fiscal measures that accelerate the adoption of renewables in the grid and ensuring that green hydrogen is produced with additional renewable energy capacity.

Implementing the All Out approach at the pace required to realize these CO_2 emissions benefits would require unprecedented cooperation within and among countries. *Still, additional in-sector strategies and carbon removal technologies that are under development would be needed to supplement the All Out strategies if we are to close the gap with the 1.5°C target.* Whether we can fully close the gap depends on whether the political will exists to implement potent decarbonization measures. But what is certain, to have a chance at limiting warming to 1.5°C, the time to act is now.

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INTRODUCTION

The on-road transportation sector—cars, buses, trucks, and two- and three-wheelers—is responsible for over 20% of anthropogenic carbon dioxide (CO_2) emissions globally. Previous ICCT analysis showed that while ambitious policies to phase out sales of new internal combustion engine (ICE) vehicles could reduce global vehicle emissions in line with a 2°C pathway with 67% confidence, further strategies are needed to close the gap with a 1.5°C pathway (Sen & Miller, 2022). The 1.5°C pathway is crucial, as the Intergovernmental Panel on Climate Change (IPCC) projects limiting warming to that amount is needed to avoid the worst effects of climate change (IPCC, 2018). The carbon budget for the 1.5°C pathway is about one-third of the budget of the 2°C pathway, and even the less-ambitious 1.7°C pathway's carbon budget is about 60% of the budget of the 2°C pathway (Friedlingstein et al., 2022). Thus, aligning global vehicle CO_2 emissions with either a 1.7°C or 1.5°C pathway (both with 67% confidence) would require emission reductions beyond those that come from phasing out sales of new ICE vehicles.

One approach is to accelerate ZEV adoption even more. However, in the Ambitious scenario in the latest ICCT study (Sen & Miller, 2023), sales of new ICE vehicles are phased out by 2035 for light-duty vehicles and 2040 for heavy-duty vehicles in major markets, with a 5-year lag (2040 for light-duty vehicles and 2045 for heavy-duty vehicles) for developing countries that do not have any supporting policies in place at present. These expectations are in line with most of the current literature (e.g., United Nations Framework Convention on Climate Change, 2021; BloombergNEF, 2023; and International Energy Agency [IEA], 2021) and relying on a faster transition would mean pushing the feasibility significantly under the already ambitious set of options. In particular, this would require rapid zero-emission vehicle (ZEV) adoption in low- and middle-income countries (Cazzola & Santos Alfageme, 2023).

We therefore investigate the potential of complementary strategies in this study. Other studies addressing this question tend to focus on a handful of approaches, either separately or grouped as a package. These include **avoid-and-shift measures** for **passenger** and **freight** transport that reduce vehicle travel or shift it to more sustainable modes; for passenger vehicles, this means things such as walking, biking, and public transportation (Institute for Transportation and Development Policy [ITDP], 2021) and for freight vehicles, it means things like improved logistics and potential shift to modes such as rail (Kaack et al., 2018). Another strategy involves **restricting the age of used vehicle imports** to improve air quality and fuel efficiency, and to ensure that more electric vehicles are imported (United Nations Environment Programme [UNEP], 2021). **Promoting fleet renewal by removing older vehicles** and incentivizing purchase of newer electric or more fuel-efficient vehicles is another (Kagawa et al., 2013). There are also efforts to **accelerate the improvement in ICE vehicle technologies** through efficiency standards until a mandated ICE phaseout is in effect (Cazzola et al., 2019). These five, along with ensuring zero-carbon electricity and hydrogen for vehicles, are also the strategies that this study considers for supplementing the accelerated ZEV sales strategy.

The ICCT partnered with several prominent research organizations to leverage their expertise for this analysis. We worked with the ITDP and the International Transport Forum (ITF) on passenger avoid and shift; the IEA on freight avoid and shift and general modeling guidance; and UNEP on used vehicles. Researchers at these organizations provided inputs from their existing research, reviewed ICCT's modeling assumptions, and provided critical feedback on the results and insights from this study.

The next sections describe how we integrated the research of these organizations into the design of this study while considering other literature in the field. After that, we detail the parameters used to model each of the strategies, the underlying data used, the scenarios modeled, and the key results. We conclude with a discussion of the results that also highlights limitations and identifies the scope of future research suggested by this analysis.

LITERATURE REVIEW

Considerable research exists on the five mitigation strategies that are the focus of this study. While an accelerated transition to ZEVs for **used imports** is not explicitly considered in the literature, there is research that quantifies exports of used vehicles and the impact of restrictions on imports of used vehicles by setting limits on age or only allowing certain power train types. UNEP's assessment was that 62 countries have "very good" policies that restrict older vehicle imports (UNEP, 2021). In the European Union (EU), the performance of used vehicles traded among EU Member States improved steadily from 2009 to 2018 with respect to air pollutant and carbon emissions (Velten et al., 2019). Meanwhile, in African countries that adopted used vehicle restrictions, there was not necessarily an increase in sales of new vehicles between 2015 and 2019 (Ayetor et al., 2021).

The **passenger** transport **avoid-and-shift** literature focuses on shifting car travel to public transportation or walking and/or biking through various measures. These include densification and mixed-use and transit-oriented development; implementing low-emission zones, congestion pricing, or parking restrictions in city centers; expanding and subsidizing public transit; and investing in bike lanes, sidewalks, and bus lanes. Most studies found that a comprehensive approach combining the development of multimodal transportation and densification (Lah et al., 2019) with supportive pricing signals (ITF, 2023) can considerably shift activity from cars to more sustainable modes of transportation. When combined with high fleet electrification, this can align the transportation sector with the 2°C pathway (ITDP, 2021). Studies in the United States' Los Angeles Metropolitan Area (Chester et al., 2013) and in Germany's Ruhr Metropolitan Region (Müller & Reutter, 2022) found resulting reductions in urban car use to be 20%–30% and close to 50%, respectively, from passenger transport avoid-and-shift measures.

The **freight avoid-and-shift** literature focuses on improving the logistics efficiency of trucks and on mode shift to rail. Long-term strategies such as improved routing, platooning, data sharing between carriers, and higher vehicle utilization can reduce emissions (Mulholland et al., 2018). However, their adoption needs to make financial sense and come with requisite consumer demand, infrastructure availability, cooperation between organizations, and legal frameworks to ensure this cooperation (Pfoser, 2022). Researchers also evaluated multiple scenarios for mode shift from truck to rail and found that a significant exogenous shift such as government intervention that requires transporters to use the one mode over the other would be needed to substantially reduce energy consumption (Pedinotti-Castelle et al., 2022).

The literature on **ICE technology improvement** can generally be divided into analyses of light-duty and heavy-duty vehicles. This is not surprising, given the differences in vehicle design, operations, and potential for increased technical efficiency. For light-duty vehicles, the analysis has primarily focused on regulations to improve vehicle standards. Fuel efficiency improvement has been shown to be dependent on structural factors such as market concentration, technology cost, and manufacturer heterogenity (Elmer, 2016), and analysis of historical vehicle efficiency trends found that fuel economy standards ensure efficiency improvements that are otherwise largely driven by vehicle segment preferences, prices, and electrification (Teter & Paoli, 2021). For heavy-duty vehicles, it was estimated that new trucks that adopt technology packages that are either already commercialized or will be commercialized by 2030 can reduce fuel consumption by more than one-third (Delgado et al., 2016). In Europe (Basma & Rodríguez, 2023) and the United States (Ragon et al., 2023), ICE efficiency improvements were found to be cost-effective because the higher purchase cost is offset by lower fuel costs and because there are societal benefits from reduced emissions.

Fleet renewal literature has generally analyzed existing programs that offer "cash for clunkers" (Naumov et al., 2023) and similar programs that have been proposed. Policies that support replacing inefficient vehicles with low-emission vehicles (Keith et al., 2019) and that provide tax breaks to incentivize replacement (Laborda & Moral, 2019) have been implemented in several jurisdictions, but the age beyond which vehicles are targeted for fleet renewal varies widely. On an international scale, implementing a 16-year age limit for heavy-duty vehicles in G20 economies could result in significant public health benefits (Jin et al., 2021). An upcoming ICCT paper estimates the greenhouse gas (GHG) and air pollutant emission reductions, subsidy costs, and monetized GHG mitigation and public health benefits of a potential fleet renewal program in Germany (Morrison et al., forthcoming). It finds that incentives for new vehicle purchase would achieve GHG mitigation at costs within the range of Germany's estimated social cost of carbon and lower than the penalties that must be paid by automakers that miss their CO_2 emission standards targets for new vehicle sales. It further finds that fleet renewal incentive policies can have a net social benefit when the public health benefits of reduced air pollution are quantified with the GHG emissions mitigation.

Several recent studies of Paris Agreement-compatible pathways using integrated assessment models (IAM) focused on transportation. In one study, adding transport-specific policies that focus on improving ICE efficiency, accelerating ZEV adoption, lowering fuel carbon content, and reducing vehicle travel to the Energy-Environment-Economy Macro-Economic (E3ME) IAM resulted in emission reductions consistent with a 2°C pathway (Mercure et al., 2018). Even in more top-down analyses that did not specifically model transportation policies such as Luderer and Kriegler (2016) and Kuramochi et al. (2018), rapidly transitioning to ZEVs and reducing travel demand were identified as the key drivers for helping the sector to meet Paris targets. The need for demand-side efforts was also mentioned in meta studies (e.g., Mundaca et al., 2019) and studies that specifically focused on reducing the dependence on carbon removal to meet 1.5°C targets (e.g., Van Vuuren et al., 2018).

Studies that have focused on the road transportation sector's emissions trajectory and alignment with Paris-compatible pathways have generally found that through a combination of most or all the strategies discussed above, including accelerated ZEV transition, fleet renewal, avoid and shift, technology improvement, and improved logistics, alignment with a below 2°C pathway is possible. As mentioned above, an accelerated ZEV transition by itself could align the road transportation sector with the 2°C pathway if most markets phase out sales of new ICE light-duty vehicles by 2035 and sales of new ICE heavy-duty vehicles by 2040 (Sen & Miller, 2022). While moving from a 2°C to a 1.5°C pathway was also achieved by different studies, what is considered compatible with 1.5°C and the corresponding carbon budgets for road transport vary across those studies. Table 1 provides details about some of the studies that achieved alignment with a 1.5°C pathway and outlines the methods adopted to decarbonize the energy system and the assumptions regarding the global carbon budget. These studies applied other mitigation measures in addition to ZEV transition, fleet renewal, technology improvement, and avoid and shift. These include a carbon tax of over $2,000 per tonne of CO_2 in addition to a "low-carbon policy" scenario (Zhang et al., 2018); increased local production of goods (Sharmina et al., 2020); various "improve" strategies (Gota et al., 2019); forced retirement of any fossil fuel vehicles while still allowing the sale of "zero-emission" biofuel vehicles by 2050 (D. S. Teske, 2020); and considerable reduction in travel demand that leads to a nearly flatlining demand for travel in some regions (S. Teske & Niklas, 2022).

Table 1. Analysis of energy modeling methods and carbon budget assumptions in studies that achieved alignment with a 1.5°C pathway.

Study	Summary and assumptions	Decarbonization methods
Luderer et al. (2016)	Study compares various IAM results and thus other sectors are considered. Carbon removal plays the most significant role in achieving the target. For all transportation, cumulative emissions compatible with this pathway between 2011 and 2100 are about 180–250 gigatonnes (Gt) CO_2; because the results are in an IAM context, we assume this is tank-to-wheel emissions. The emissions between 2011 and 2020 were around 75 Gt, and that leaves 105–170 Gt CO_2 that can be emitted. For all transportation, tank-to-wheel emissions account for about 23% of global emissions, and starting from 2021, the global carbon budget for 1.5°C is about 360 Gt CO_2. This means that transportation is allocated a disproportionate share (about 30%–50%) of the remaining budget.	Electrification, fuel efficiency, activity reduction, fuel content switch (e-fuels and biofuels), and measures from other sectors
Kuramochi et al. (2018)	An amalgamation of various IAM results and aims to pick the "best" strategies from each. There is no specific target for the transport sector and nothing quantifying the "best" strategy identified (study only says the last fossil fuel vehicle is sold by 2035), nor is there an overall CO_2 emissions budget identified; however, study indicates that emissions need to peak by 2025 and reach net-zero by around 2040.	Sell last fossil-fuel-powered vehicle by 2035, combined with measures from other sectors
Van Vuuren et al. (2018)	An IAM, and a combination of methods are used apart from reducing transportation emissions. Carbon capture and storage plays a significant role, as do energy efficiency, renewable energy, low population growth, and reduction in agricultural emissions, among other strategies. Net-zero emissions are reached around 2050 with a peak close to 2025. Sector-specific emissions are not reported.	Fuel efficiency, electrification, and activity reduction or shift to zero-emission transportation modes
Gota et al. (2018)	Study combines nationally determined contributions from various countries to create a 1.5°C pathway. The estimated all-transport pathway (tank-to-wheel emissions) has 2050 emissions at around 2 Gt CO_2. An aggregate emissions amount between 2020 (8 Gt CO_2) and 2050 is not specified, but based on the intermediate values for 2030 and 2040 (6.6 Gt CO_2 and 5 Gt CO_2, respectively) and assuming a linear trend, we estimate the cumulative emissions are 160–170 Gt CO_2, excluding those in 2020. This is substantially higher than the 23% of 360 Gt CO_2 estimate for 1.5°C pathway compatibility.	Bottom-up analysis of nationally determined contributions with optimistic outlook. Combines various fuel efficiency, electrification, avoid-and-shift measures.
Sharmina et al. (2020)	Primarily focuses on transportation, but industry also contributes to the achievement of the target. No absolute targets are specified but emissions are expected to peak between 2020 and 2030, then decline to net-zero levels by 2050.	Avoid and shift, electrification, local production to reduce travel, and improvements in load factors
Zhang et al. (2018)	The most aggressive 1.5°C scenario among those reviewed here, this combines aggressive improvement in energy efficiency with rapid electric vehicle sales, high vehicle occupancy, and switch to mass transit. Net-zero emissions are reached around 2050, based on negative emissions technologies, and the transport sector gets close to zero emissions at around 2100. However, only a carbon tax of more than $2,000 per tonne can achieve this. Note that overshooting is allowed in this model: The temperature increase peaks at 1.6°C in 2045 and then drops to 1.4°C in 2100.	High energy efficiency improvement (>50%), rapid electric vehicle adoption, high vehicle occupancy, high use of mass transit, carbon tax
Teske et al. (2021)	1.5°C is given a carbon budget of 110 Gt CO_2 (tank-to-wheel emissions) until 2050 for all transportation modes. This is significantly higher than what is expected if the 23% of 360 Gt CO_2 assumption is used. Road transport CO_2 emissions reach zero by 2050 without the aid of carbon capture and storage.	Road transport travel to be flat between 2020 and 2050, use only zero-emission fuels by 2050, phase out ICE sales by 2030, mandatory 2% improvement in efficiency standards every year

SCENARIO DESIGN AND METHODS

The following seven strategies were considered to reduce on-road transportation CO_2 emissions:

» Accelerating the transition of new vehicle sales to ZEVs

» Accelerating the transition of used vehicle imports to ZEVs

» Further deployment of ICE efficiency technology for new light-duty vehicles

» Further deployment of ICE efficiency technology for new heavy-duty vehicles

» Passenger vehicle avoid-and-shift measures in urban areas

» Freight vehicle avoid-and-shift measures and operational efficiency improvements

» Fleet renewal strategies to shift vehicle activity from older ICE vehicles to new vehicles

A detailed discussion of how each of these strategies was implemented is in the expanded methodology document published under a separate cover. The exception is the first measure, accelerating new ZEV sales adoption; that is based on Sen and Miller (2023; henceforth referred to simply as Sen and Miller) and full details are in that paper.

SCENARIOS

Six scenarios were constructed: Baseline, Ambitious ZEV Sales, Ambitious ICE Technology, Avoid and Shift, Fleet Renewal, and All Out. Table 2 provides the key highlights of the scenarios, and the subsequent subsections discuss some of the details regarding how they were constructed. Historical and projected vehicle CO_2 emissions for each of the six scenarios were calculated using version 2.2 of ICCT's Roadmap Model (ICCT, 2022).

The level of ambition chosen in each of these strategies was designed to reflect options that are ambitious but within the realm of technological and political feasibility in terms of implementation through 2050. As much as possible, this study adopted methods and model measures that are near the middle of the range of ambitious scenarios formulated by other researchers. While the results are presented between 2020 and 2050, all scenarios (and temperature pathways) have the same historical inputs and emission results from 2020 to 2022.

Table 2. Summary of the six scenarios constructed for this study.

Scenario	Description
Baseline	Baseline ZEV transition based on adopted policies and conservative market development
Advanced ICE Technology	Technologically feasible **improvement in ICE vehicle efficiency globally**
Avoid and Shift	Worldwide **reduction of passenger car travel** in metropolitan areas to match similar cities in the same world regions in which there is less vehicle travel, and **reduction of freight vehicle travel and load factor** through improvement in freight logistics and operations
Ambitious ZEV Sales	Worldwide **phaseout of new ICE sales by 2045**, with faster phaseout in major markets and **phaseout of used ICE imports with appropriate lags** for both light- and heavy-duty vehicles
Fleet Renewal	Worldwide fleet renewal measures to **phase out vehicles over a certain age** from the fleet
All Out	Everything above + Net-Zero Electricity Grid + 100% Green Hydrogen by 2050

Baseline

The Baseline scenario is outlined in Sen and Miller and accounts for the projected effects of adopted policies and anticipated market developments affecting ZEV sales through 2050. Importantly, the Baseline scenario is not a forecast of the future, but rather a plausible pathway of what could happen in the absence of new policies. It serves as a reference case to evaluate the benefits of further policy actions. Adopted policies are modeled based on ICCT's policy analysis in each region and market potential is based on a combination of ICCT studies, the IEA's Stated Policies Scenario (STEPS; IEA, 2020), and expert judgment, with the aim of reflecting plausible market growth in the absence of further policies. Market development in the absence of adopted policies is cautiously optimistic, and the Baseline scenario assumes ZEV adoption proceeds globally, albeit with a lag in countries that have not yet adopted vehicle efficiency standards or other policies to promote ZEVs. We assumed that adopted policies are kept in place and complied with, not rolled back or partially implemented. For electricity grid emissions, emission factors from STEPS are used. For hydrogen production emissions, emission factors are based on previous ICCT analysis (Bieker, 2021). In every other scenario, unless otherwise specified, the same assumptions for electricity grid and hydrogen production emission factors are used.

Advanced ICE Technology

The Advanced ICE Technology development scenario is paired with the Baseline assumptions and both light-duty and heavy-duty technology developments are considered. For light-duty vehicles, the energy intensity of ICE vehicles improves according to feasible technological pathways using technological innovations that are currently available. Six representative regions are chosen and based on these, the pathways for all other regions are defined (see the expanded methodology document published under a separate cover for mapping). The six regions are the United States, the European Union, China, Japan, South Korea, and India. These are the six largest light-duty vehicle markets and relatively comprehensive data on fleet characteristics (Shen et al., 2023) and potential technological efficiency pathways (Lutsey, 2018) is available. Using the National Highway Traffic Safety Administration's Corporate Average Fuel Economy (CAFE) model (National Highway Traffic Safety Administration, 2012), technological pathways are modeled. Strong hybrid engine technology (Tran et al., 2021) was chosen along with packages to reduce aerodynamic drag and glider weight by more than 20%. Energy efficiency improvement in 2035 compared to 2020 ranges from 24% to 42%; the variability across regions arises primarily from differences in the initial energy intensity in 2020, and the higher percentage improvements are generally achieved in regions with high initial fuel consumption (Figure 1).

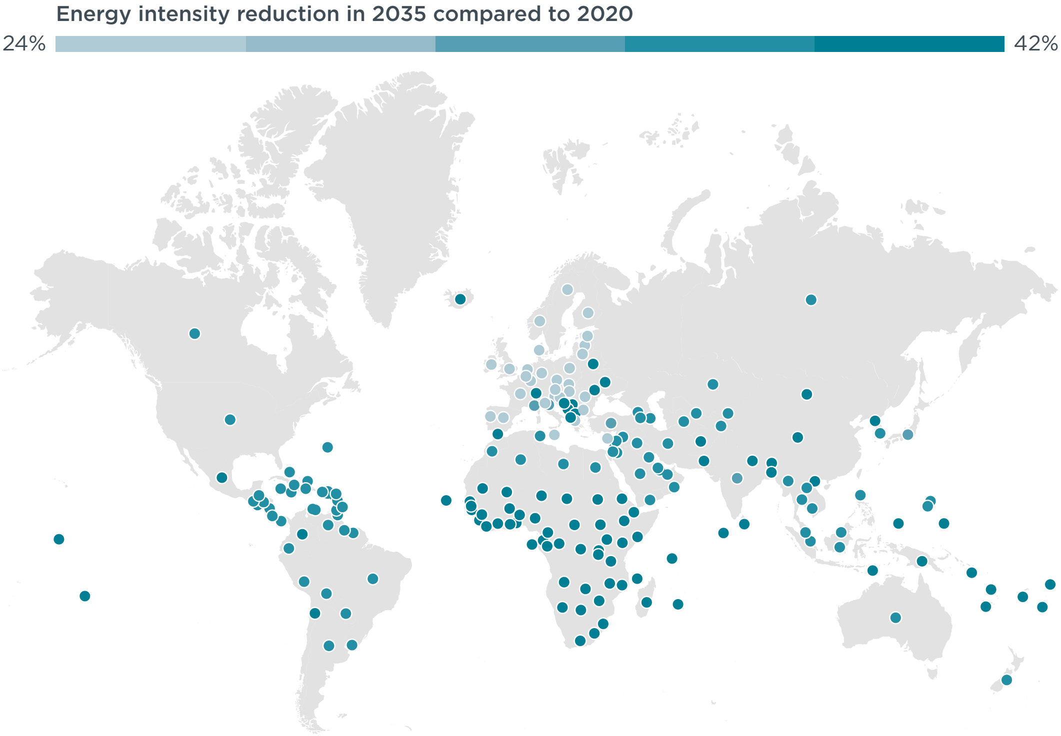

Figure 1. Global energy intensity reduction of new light-duty ICE vehicles in 2035 compared to 2020 in the Advanced ICE Technology scenario.

We considered several ICCT studies in developing the assumptions for heavy-duty vehicles (Figure 2). For the United States, a study projected post-2027 (i.e., after Phase 2) energy intensity reductions from 10% for heavy-duty tractors to over 20% for most other vehicle types (Ragon et al., 2023). For India, a technology potential and cost effectiveness study for heavy-duty vehicles is used (Yadav et al., 2023). Per that study, a 40%–50% reduction in energy intensity by 2030 can be achieved, depending on the vehicle type, by using the strongest vehicle package; the strongest package included strong hybridization with low-rolling-resistance tires and reduced aerodynamic drag. For the European Union, an analysis of decarbonization pathways (Basma & Rodríguez, 2023) is used to determine the technology potential, and the maximum potential ranges from 23%–39%, depending on the diesel truck class. For every other region, we use a 2016 ICCT analysis of global HDV technology potential (Delgado et al., 2016) in which the maximum technology improvement potential estimated ranges between 30% and 36% for rigid trucks and 40% and 52% for tractor-trailers. These efficiency improvements are phased in by 2035.

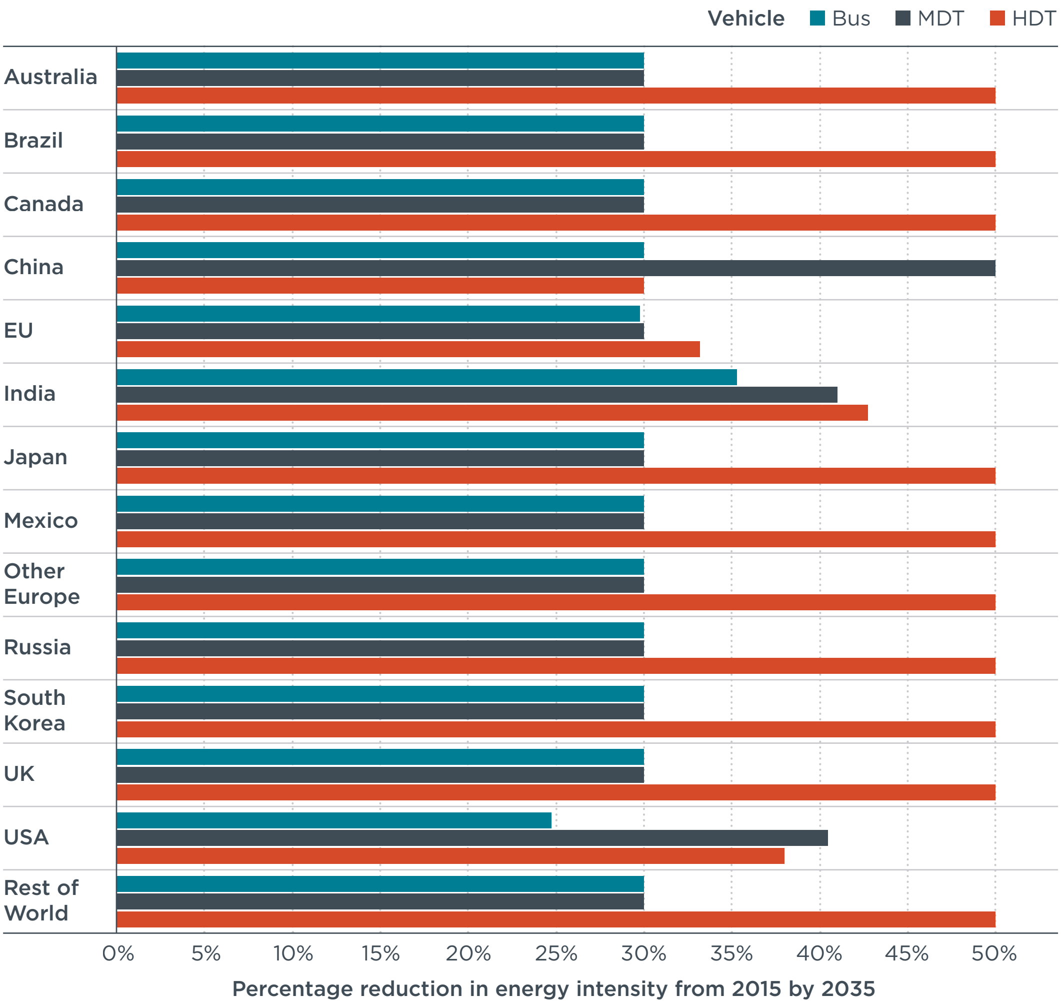

Figure 2. Global energy intensity reduction of new heavy-duty vehicles in 2035 compared to 2015 in the Advanced ICE Technology scenario.

Avoid and Shift

The Avoid and Shift scenario combines Baseline assumptions with fewer passenger and freight kilometers traveled. This reduces vehicle activity for both vehicle segments.

For **passenger travel**, a city-level database from ITF (ITF, 2023) is utilized to group similar cities by region and population (Table 3). This database has passenger kilometers traveled for each city in 2022 and then Baseline and "High Ambition" avoid-and-shift scenarios for 2050; the High Ambition scenario assumes less growth in travel than the Baseline. The database also has population data for these cities, including population projections. Each city is ranked in terms of passenger kilometers per capita for car travel (pkm per capita) in 2050 for the Baseline and High Ambition avoid-and-shift scenarios. These cities are grouped together into "Super Regions" based on similar geographic and socioeconomic characteristics and then binned into population groups. A new scenario, the ICCT Shift scenario, is created by adjusting the percentile distribution of cities with higher per capita passenger kilometers travel to resemble a city that had lower pkm per capita in the Baseline (Table 4). For example, in a group of U.S. cities, a 35 percentile shift in the ICCT Shift scenario would make Miami's pkm per capita resemble that of New York in the Baseline (in terms of vehicle kilometers traveled [VKT] in Table 5). The idea is to provide policymakers in a group of cities that are likely to have similar geographic and population characteristics with concrete examples that they can seek to emulate. The percentile shift chosen for the ICCT Shift scenario varies by region, as not all regions will have similar capacity to reduce pkm per capita, and the shifts are designed to ensure that the final regional reduction results are in between those of ITF's High Ambition scenario and ITDP's Compact City Scenario (ITDP, 2021), which had even more aggressive assumptions in terms of the potential for urban avoid and shift. It is assumed that the rate of reduction of pkm is slower in the early years, and only 25% of the total reduction potential to 2050 is achieved between 2022 and 2030. Between 2030 and 2040, 50% of the total potential is achieved, and the remainder is achieved between 2040 and 2050. We assume that passenger travel shifts to zero-emission modes such as walking, cycling, or zero-emission public transit. The global reduction in passenger car travel in 2050 is 37% compared to the Baseline scenario.

Table 3. Frequency distribution of the number of cities in each Super Region and population group.

Super Region	<100,000	<500,000	<1,000,000	<5,000,000	≥5,000,000	Total
Africa	199	1,443	298	83	20	2,043
ASEAN	99	412	47	20	10	588
Asia high-income	26	38	5	13	4	86
China	84	966	175	98	25	1,348
Europe	237	532	80	71	8	928
India	1,039	961	59	52	12	2,123
Latin America	562	241	33	36	5	877
Other Asia-Pacific	290	379	116	174	30	989
Other high-income	3	149	44	45	11	252
Total	2,539	5,121	857	592	125	9,234

Table 4. Percentile shift assumed for cities in each population group within Super Regions.

Super Region	<100,000	<500,000	<1,000,000	<5,000,000	≥5,000,000
Africa	25	30	35	40	45
ASEAN	35	35	35	35	50
Asia high-income	30	30	35	35	40
China	35	35	35	35	35
Europe	20	20	20	25	25
India	40	40	45	50	50
Latin America	35	35	35	40	40
Other Asia- Pacific	30	30	30	30	30
Other high-income	30	30	30	35	35

Table 5. City pairs where percentile shift results in City A in the shifted scenario resembling City B's kilometers traveled by car per person in the Baseline, by Super Region.

Super Region	City duos (A – B)	Percentile shift	Absolute shift km per capita	Percent reduction in VKT per capita
Africa	Cairo – Casablanca	45	1,817 – 694	62%
ASEAN	Bandung – Manila	40	668 – 510	24%
Asia high-income	Seoul – Tokyo	40	2,255 – 1,130	50%
China	Chaozhou – Qingdao	35	749 – 446	40%
Europe	London – Amsterdam	25	9,742 – 5,556	43%
India	Pune – Chennai	50	1,005 – 571	43%
Latin America	Buenos Aires – Lima	40	2,735 – 2,461	10%
Other Asia-Pacific	Dhaka – Multan	30	2,998 – 1,499	50%
Other high-income	Miami – New York	35	13,322 – 7,260	45%

For **freight travel,** the calculations are based on the IEA's Future of Trucks (Teter et al., 2017) report, with modifications when certain scenarios are achieved and to account for urban/nonurban travel mix. The IEA study has three scenarios: 4°C compatible, 2°C compatible, and "well-below" 2°C compatible. In each scenario, the target numbers for travel reduction and load factor improvement are assumed to be achieved by 2060. In this study, we assume these improvements on an accelerated time frame, with the 2°C compatible improvements achieved by 2040 and the well-below 2°C compatible improvements achieved by 2050. Starting from 2022, linear achievements to the 2040 value are assumed and then again between 2040 and 2050, linear achievements are assumed. The global improvements by year, geography, and vehicle type are listed in Table 6.

Table 6. Global improvements in freight travel and load factor by year, geography, and vehicle type.

Year	Geography	Vehicle type	VKT improvement (percentage decrease from Baseline)	Load factor improvement (percentage increase from Baseline)
2040	Urban	LCV	19	13
2040	Nonurban	LCV	6	13
2040	Urban	MDT	25	13
2040	Nonurban	MDT	21	13
2040	Both	HDT	21	13
2050	Urban	LCV	22	16
2050	Nonurban	LCV	7	16
2050	Urban	MDT	30	16
2050	Nonurban	MDT	25	16
2050	Both	HDT	25	16

Due to the differences in urban/nonurban travel split by vehicle category across countries, the final reduction in freight vehicle VKT varies across countries, as shown in Figure 3 for year 2050. The global average is 23%.

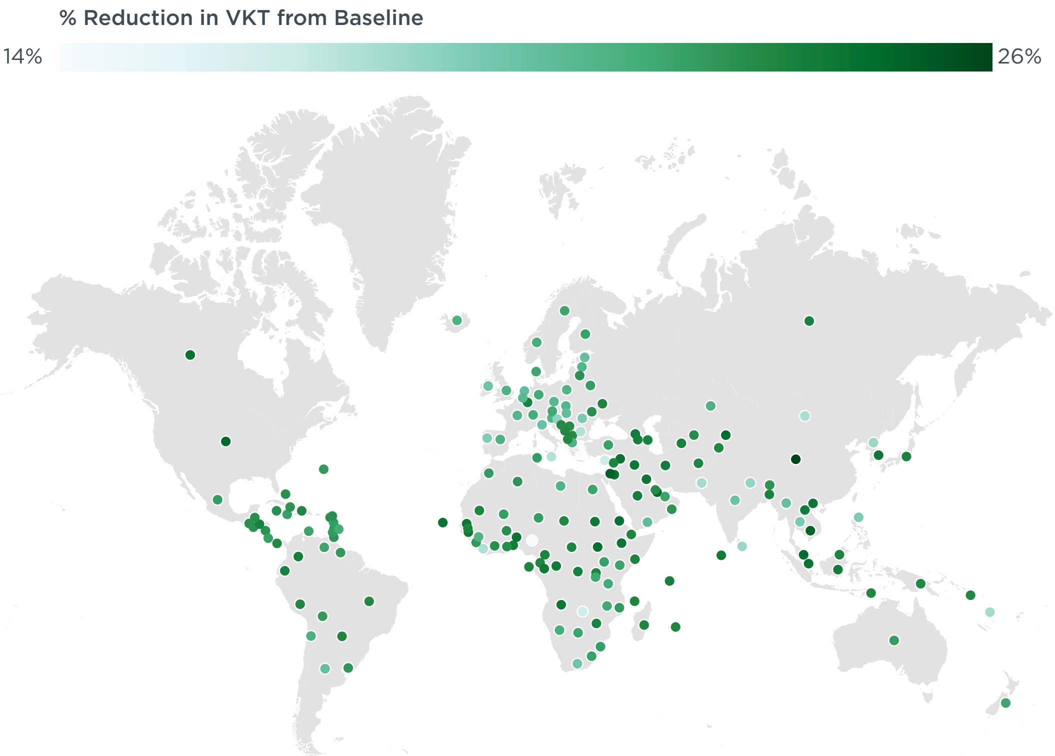

Figure 3. Percent reduction in freight VKT from Baseline achieved by freight avoid-and-shift measures in 2050.

Ambitious ZEV Sales

The Ambitious ZEV Sales scenario follows Sen and Miller in defining the trajectory of new vehicle sales and adds a restriction on used vehicle imports. For new vehicles, an accelerated global transition to ZEVs is assumed, with all countries phasing out ICE vehicle sales no later than 2045. Leading electric vehicle markets with existing ambitious policies (the United States, China, the European Economic Area, and Canada) are expected to do this faster: by 2035 for light-duty vehicles and 2040 for heavy-duty vehicles. A second set of markets (India, Mexico, Japan, and South Korea) are assumed to phase out sales of ICE light-duty vehicles by 2040 and all vehicles by 2045. All other countries are assumed to have ZEVs be 100% of new vehicle sales by 2045, with a few exceptions; the exceptions include countries such as Chile, New Zealand, Singapore, and Ukraine, and such countries have either already signed a more ambitious international commitment (i.e., the ZEV Declaration or the Global Memorandum of Understanding on Zero-Emission Medium- and Heavy-Duty Vehicles), or have a national policy that is more ambitious than a 2045 phaseout. These are placed on an accelerated timeline consistent with those commitments.

In addition, detailed trade flows of used vehicles were simulated based on a UNEP (2021) database that tracks global used vehicle imports of light-duty vehicles by more than 200 countries and territories from major export markets including the United States, European Union, Japan, and South Korea. For heavy-duty vehicles, the approximate share of used imports in the vehicle fleet is based on IEA's MoMo (IEA, 2018) database. An import age limit of 5 years for light-duty vehicles and 8 years for heavy-duty vehicles is assumed in this accelerated time frame. The age limit is based on the current median of light-duty vehicle age restrictions globally. A 3-year dispensation for Africa is provided based on UNEP's recommendations; this allows vehicle imports of up to 8 years of age for light-duty vehicles and 11 years for heavy-duty vehicles and is due to relatively lax import regulations compared with the rest of the world and because vehicles certified to lagging emission standards with outdated emission control technologies are still being produced and sold on the continent. The power train share of used vehicles in the target country from 2030 onward is determined by the source (vehicle-exporting) markets. For example, if Afghanistan imports 80% of its vehicles from the European Union and 20% from the United States, and the vehicles that are exported from those regions are 60% and 20% ZEVs, respectively, then the share of ZEVs imported by Afghanistan is 52%. Pairing the restrictions on used vehicles with the ambitious new vehicle sales scenario ensures that the full ZEV transition of used imports is achieved no later than the year implied by the age limit specified. In the Afghanistan example, if the European Union achieves a 100% ZEV sales share for new vehicles by 2035 and the United States does the same by 2040, then Afghanistan will achieve a 100% ZEV share of used imports by 2045 at the latest. From 2020 to 2030, UNEP and IEA's estimates of current power train shares of used imports are used.

The Ambitious ZEV Sales scenario uses the same assumptions regarding hydrogen production as the other scenarios specified above, but uses electricity grid emission factors consistent with IEA's Announced Pledges Scenario, under the assumption that the grid will also be cleaner alongside advancements in ZEV regulations (IEA, 2021).

Table 7 displays the regional breakdown of used vehicle ZEV sales shares between 2025 and 2050 for light-duty vehicles and heavy-duty vehicles in the Ambitious ZEV Sales scenario.

Table 7. Used zero-emission vehicle powertrain shares in the Ambitious ZEV Sales scenario by region.

	HDV					LDV				
	2030	2035	2040	2045	2050	2030	2035	2040	2045	2050
Africa and Middle East	1%	11%	51%	84%	98%	11%	59%	91%	99%	100%
Asia	1%	9%	69%	89%	99%	18%	64%	91%	100%	100%
Europe	2%	19%	62%	87%	99%	38%	95%	99%	100%	100%
Latin America	3%	19%	67%	88%	99%	22%	68%	96%	100%	100%

Fleet Renewal

To maximize the replacement of older ICE vehicles with newer ZEV vehicles, fleet renewal policies are applied in conjunction with the Ambitious ZEV Sales scenario instead of the Baseline scenario. We assume that when older vehicles are removed from the fleet, they are replaced by new vehicles that have the efficiency levels and ZEV shares assumed for new vehicle sales. For example, if the new vehicles sold are 60% ICE and 40% ZEVs, then vehicles that replace the older vehicles will also be sold in the same proportion. The demand for passenger or freight travel that would have been met by those older vehicles is instead met by new vehicles that consume less gasoline and diesel. (There is an argument to be made for only allowing replacement by electric vehicles, but making that assumption creates a disadvantage in the earlier years of the program when a large stock of older vehicles must be retired but an equivalent number of electric vehicles is not available.) No assumptions are made regarding the difference in annual VKT between older vehicles and newer ones.

The light-duty vehicle fleet renewal program is designed based on an upcoming ICCT paper (Morrison et al., forthcoming) which found that the societal benefits from mitigating GHG and air pollutant emissions outweighed the costs of incentivizing new vehicle purchase if the average age of vehicles removed from the fleet was 14 years or more for diesel vehicles and 20 years or more for gasoline vehicles.

The heavy-duty vehicle fleet renewal program is designed based on the G20 air quality analysis (Jin et al., 2021) prepared by the ICCT; here the removal age was set at 16, and that is in line with the average retirement age of heavy-duty vehicles. For both light and heavy vehicles, following the recommendation of UNEP, a removal age of 19 years for African countries was modeled. The fleet renewal program is phased in gradually across all world regions between 2026 and 2030, starting with 20% of all eligible vehicles to be removed from the fleet in 2026, 40% in 2027, and so on until all eligible vehicles are removed in 2030 and beyond. The 2030 target is chosen in order to maximize the chance of stabilizing emissions and be consistent with the well-below 2°C target by removing as many older vehicles as possible (Tanaka & O'Neill, 2018).

This scenario uses the same electricity grid and hydrogen production emission factors as the Ambitious ZEV Sales scenario.

Globally, this results in a significant reshuffling of VKT by different powertrains by 2030 (Figure 4). For both light-duty and heavy-duty vehicles, there is an increase in the VKT share of ZEV powertrain because activity from older vehicles is largely replaced by new ZEVs.

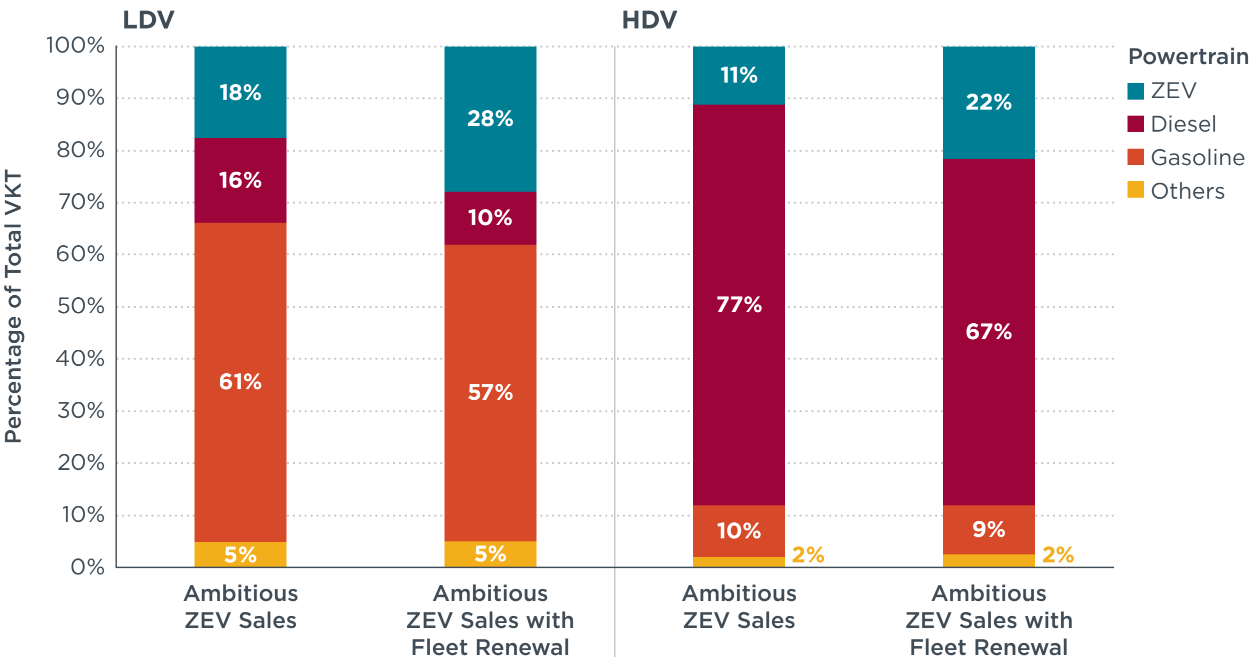

Figure 4. Share of total VKT in 2030 by powertrain and vehicle type, with and without Fleet Renewal.

All Out

The All Out scenario combines the other scenarios—Ambitious ZEV Sales, Advanced ICE Technology, Avoid and Shift, and Fleet Renewal—with cleaner electricity and hydrogen production pathways. For electricity grid emission factors, IEA's Net Zero Emissions scenario is used, and every country in the world reaches 100% clean electricity grid by 2050. For hydrogen production emission factors, Bieker (2021) held the mix of hydrogen production sources (i.e., green, blue, and grey, in descending order of emissions intensity) constant for each country from 2030. This scenario assumes that the mix will become increasingly cleaner after 2030 through a linear progression until 2050, when 100% of the hydrogen produced is green hydrogen.

EMISSION TRAJECTORIES

Here we compare the annual and cumulative emissions from each of the above scenarios with Paris-compatible emission trajectories (Sen & Miller, 2023). Transportation budgets are calculated based on shares of global emissions and emissions counted include well-to-tank emissions arising from both upstream fuel extraction and processing and electricity generation. While the literature generally only considers tank-to-wheel emissions for the transportation sector when trying to align emission trajectories with Paris-compatible temperature pathways, this may lead to significant undervaluation of the transportation sector's impact, especially in cases where other sectors are not explicitly modeled. This is because the well-to-tank emissions incurred by generating electricity and producing hydrogen to power ZEVs will increase in future years as these vehicles penetrate the vehicle fleet. Though the well-to-wheel emissions of ZEVs are already substantially lower than those of ICE vehicles (Bieker, 2021), well-to-tank emissions' share of overall well-to-wheel emissions is expected to increase, even as overall well-to-wheel emissions decline (Teter & Paoli, 2021). Therefore, the carbon budget for transport emissions in Sen and Miller and in the present study includes both well-to-tank and tank-to-wheel emissions.

Given the relative ease of reducing emissions from road transport compared with other sectors, there is discussion in the literature about whether a lower or higher share than the current share of emissions should be assigned to road transport (S. Teske et al., 2022; Napp et al., 2019). Such considerations are beyond the scope of our study and as a result, solely the present-day share is considered when allocating a portion of the carbon budget to road transport and generating the pathways. (See the Results section, below, for a few exceptions related to the All Out scenario and a hypothetical case in which no new vehicle is sold after 2023.)

The total anthropogenic carbon budgets are based on IPCC estimates for warming to be limited to 2°C with a 67% likelihood of success, and for that the remaining global carbon budget from 2020 onward is around 1,150 gigatonnes (Gt) CO_2. In 2020, well-to-wheel emissions from road transport were around 8 Gt CO_2, out of about 39 Gt CO_2 emitted overall. Assuming a 21% share of emissions for on-road vehicles, as has been the trend in recent years, the remaining budget is approximately 242 Gt CO_2 from 2020. We assume that the net-zero date is 2090, and an exponential curve fit leaves a budget of approximately 210 Gt CO_2 between 2020 and 2050.

For a 67% chance of limiting warming to 1.5°C, the available budget between 2020 and 2050 is much smaller—around 84 Gt CO_2 when assuming the same 21% share for vehicles—and an exponential pathway consumes most of the budget by 2035 and reaches net zero in 2040. For the 1.7°C case with a 67% chance and with the same 21% share, the remaining budget between 2020 and 2050 is around 145 Gt CO_2 following an exponential pathway. The 1.7°C pathway is set to consume the leftover budget of 2 Gt by 2070. Figure 5 summarizes these three pathways.

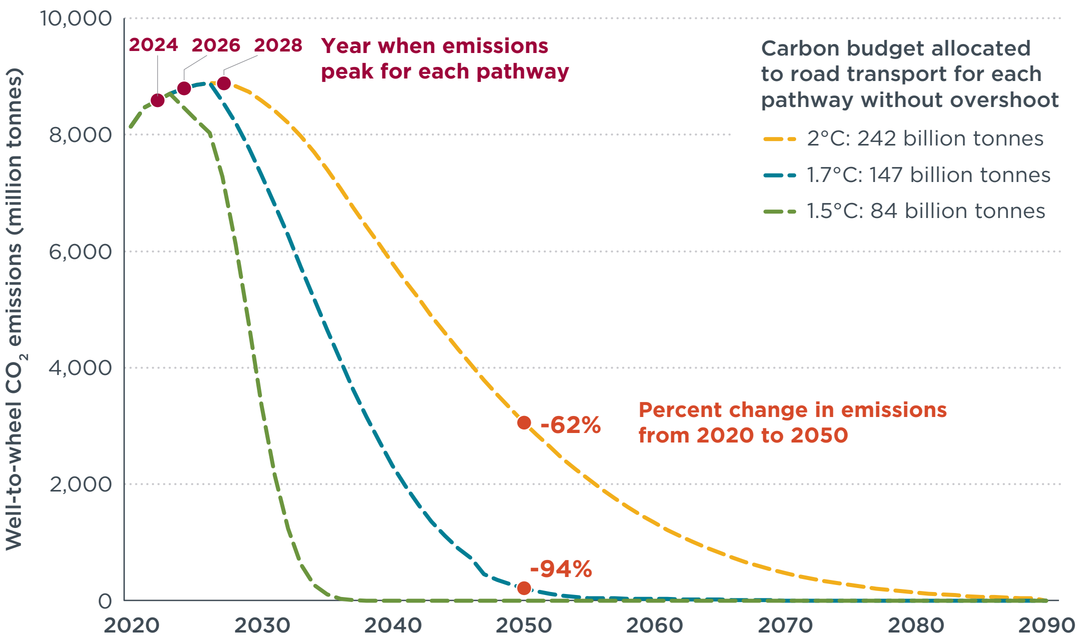

Figure 5. Well-to-wheel CO_2 emission pathways for on-road vehicles compatible with 2°C, 1.7°C, and 1.5°C of warming (all 67% likelihood).

RESULTS

ANNUAL EMISSION TRENDS

Emissions in the Baseline scenario in 2050 are 21% higher than in 2020 (Figure 6). Emissions from every other scenario in 2050 are lower than those in 2020. We find that Avoid and Shift and Advanced ICE Technology have similar trajectories, but the former has greater long-term emissions reduction potential. This is expected because new vehicles are increasingly non-ICE even in the Baseline, and that dampens the long-term emissions reduction potential of the Advanced ICE Technology scenario. Through 2030, both Avoid and Shift and Advanced ICE Technology achieve a similar or even slightly higher rate of emissions reduction compared with Ambitious ZEV Sales. This underscores the effectiveness of such measures to reduce emissions independent of ZEV sales. In the long-term, though, the Ambitious ZEV Sales scenario for new and used vehicles delivers the largest reduction in emissions, 71% lower compared to 2020. Adding Fleet Renewal policies that are phased in between 2026 and 2030 further reduces emissions, and 2050 emissions are 81% lower than 2020 emissions. Adding Avoid and Shift, Advanced ICE Technology, Fleet Renewal, and Net-Zero Electricity Generation and 100% Green Hydrogen Production to Ambitious ZEV Sales in the All Out scenario reduces emissions in 2050 by 97% compared to 2020. This shows the combined effect of strategies that on their own are unlikely to close the gap to net-zero emissions by 2050.

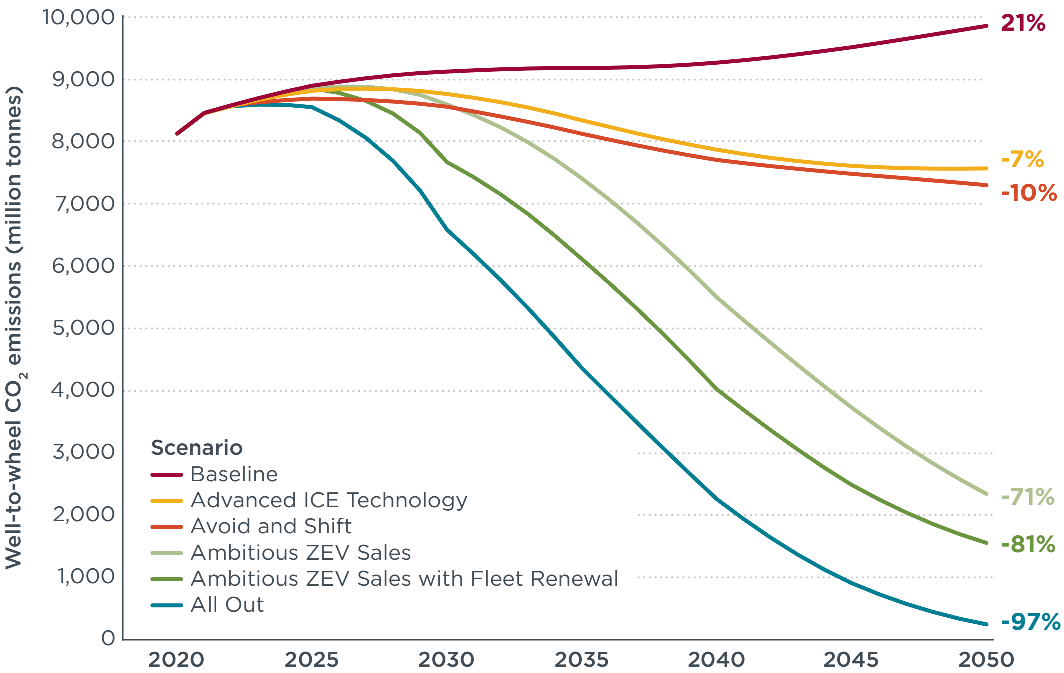

Figure 6. Annual well-to-wheel CO_2 emissions in million tonnes by scenario, with each strategy implemented individually except for Ambitious ZEV Sales with Fleet Renewal (those two strategies) and All Out (all strategies).

COMPATIBILITY WITH PARIS AGREEMENT TEMPERATURE PATHWAYS

Comparing the cumulative emissions from different scenarios with the three Paris-compatible pathways demonstrates the importance of combining strategies to achieve maximum reduction in emissions. There are 285 Gt of cumulative emissions in the Baseline scenario (2020–2050) and the All Out scenario avoids 144 Gt of these emissions. The reduction in cumulative emissions from the Baseline by the Avoid and Shift, Advanced ICE Technology, and Ambitious ZEV Sales scenarios are 26 Gt, 22 Gt, and 61 Gt, respectively. We evaluated the incremental impact of Fleet Renewal on top of the Ambitious ZEV Sales scenario because large-scale fleet renewal policies are considerably more effective in reducing emissions when combined with stringent policies to accelerate the transition of new vehicle sales to ZEVs. When Ambitious ZEV Sales is combined with Fleet Renewal, an additional 20 Gt of CO_2 emissions can be avoided. Combining all these strategies, including Net-Zero Electricity Grid and 100% Green Hydrogen production, leads to the aforementioned total mitigation potential in the All Out scenario of 144 Gt CO_2 and that is enough to reduce cumulative emissions to below the budget for the 1.7°C-compatible pathway. A further 40% reduction in cumulative emissions would be needed to align with a 1.5°C pathway while avoiding overshoot and if the probability of achievement remains at 67% and road transport's share of emissions remains at 21%. The All Out scenario could be considered to align with the 1.5°C pathway if we lower the likelihood of achievement from 67% to 50% and increase the sectoral emissions share to 29%. Alternatively, if we keep a 67% confidence in achievement but increase the sector share to 36%, the All Out scenario could align with the 1.5°C pathway. As discussed earlier, considerations of whether other sectors would be able to reduce emissions quickly enough to allow road transport to use a larger share of the remaining carbon budget are beyond the scope of this study.

To illustrate the "locked-in" emissions of the current road fleet, a hypothetical scenario where no new vehicles are sold beyond 2023 was also considered, and this is without any additional measures implemented. We find that cumulative well-to-wheel emissions between 2020 and 2050 from this measure are 130 Gt, only 10 Gt less than the All Out estimate. This shows that on one hand, using a combination of strategies to reduce CO_2 emissions could be almost as effective as taking a drastic measure such as halting all new vehicle sales. However, it also demonstrates that even something as aggressive as stopping new vehicle sales entirely is not sufficient for alignment with the 1.5°C pathway.

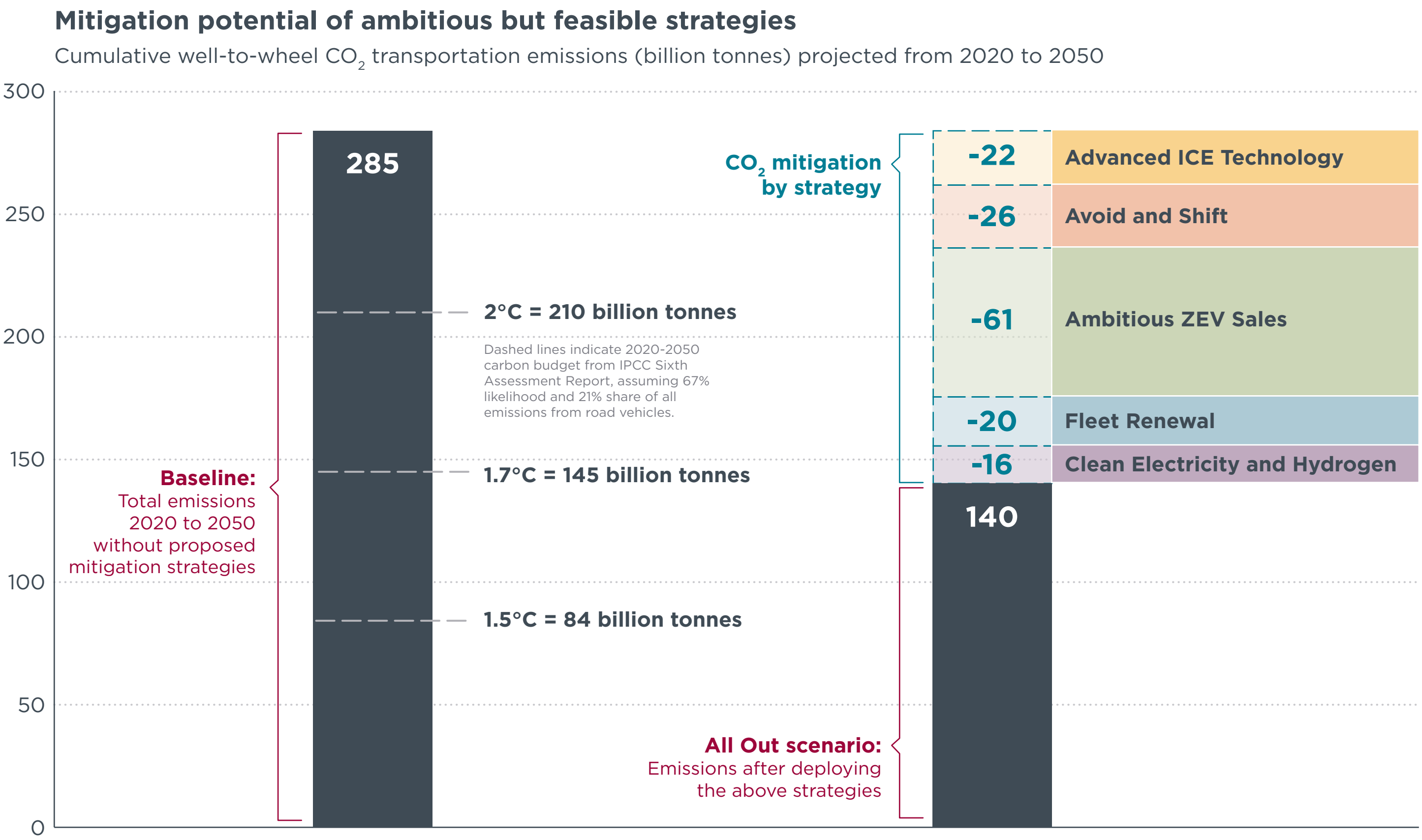

Figure 7. Cumulative well-to-wheel CO_2 emissions in the Baseline and All Out scenarios and relative mitigation potential of each strategy, with reference lines for vehicle carbon budgets through 2050 compatible with 1.5°C, 1.7°C, and 2°C targets. Data labels are rounded to the nearest Gt.

REGIONAL AND RESIDUAL EMISSIONS

Residual emissions in the All Out scenario vary from 40% to 60% of the original cumulative Baseline emissions, depending on region.[1] The reductions from the Baseline are primarily achieved through Ambitious ZEV Sales, although cleaning the electricity grid and hydrogen production processes also plays a significant role, especially in China, Africa, and the Middle East. Fleet Renewal plays a role comparable to the combined effects of Avoid and Shift and Advanced ICE Technology in the European Union and the United Kingdom because these markets have relatively older vehicle fleets. Across regions, Avoid and Shift generally leads to a slightly larger reduction in emissions than Advanced ICE Technology, but the latter is marginally more important in ASEAN countries and India.

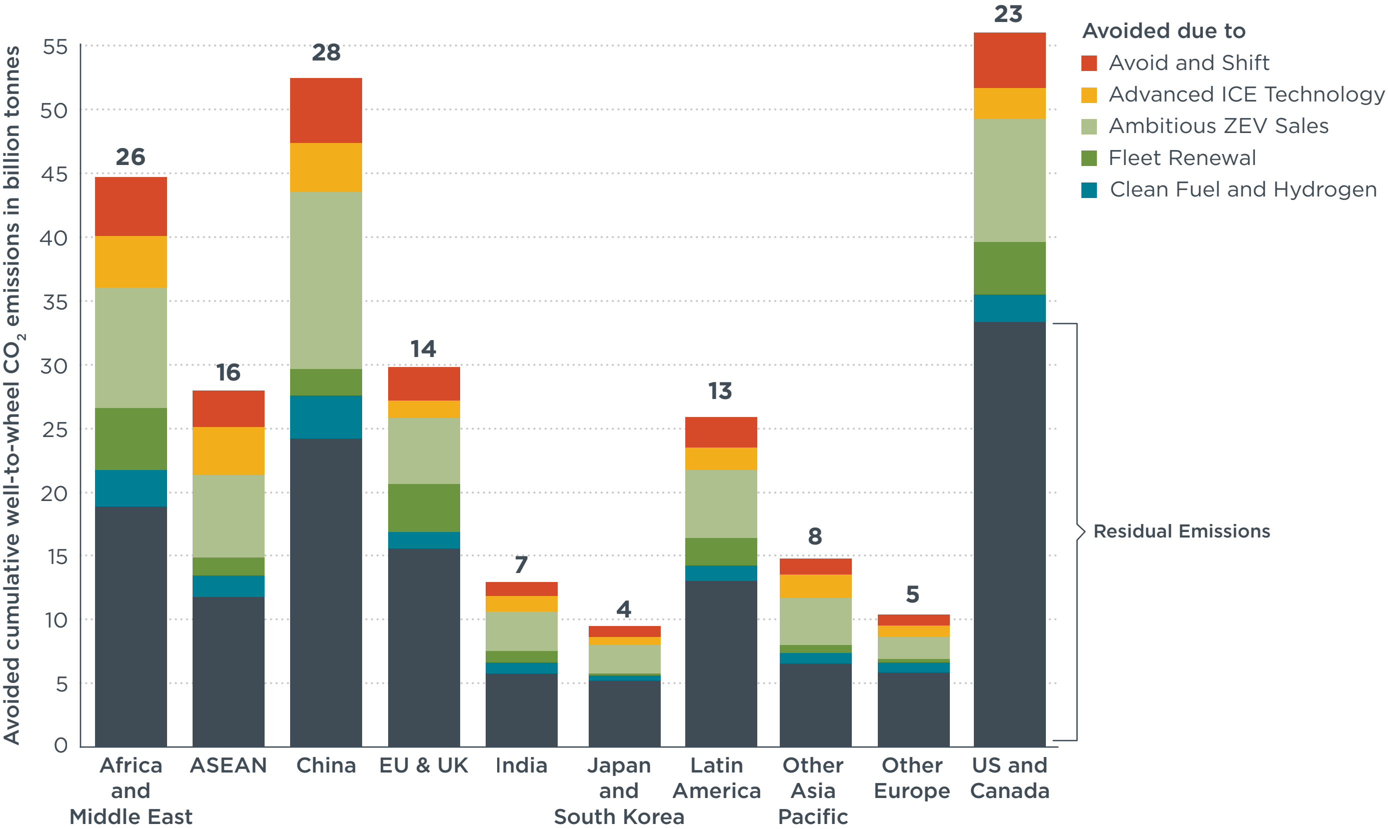

Figure 8. Cumulative avoided well-to-wheel CO_2 emissions through 2050 compared to Baseline by region and scenario, and residual emissions in the All Out scenario. Data labels show cumulative mitigation potential of the All Out scenario.

Light-duty vehicles are the predominant source of residual emissions in the All Out scenario, and the mix of light and heavy vehicles' contribution to residual emissions stays largely constant through 2050. Conventional ICE vehicles and plug-in hybrid electric vehicles (PHEVs) continue to be responsible for a large chunk of the emissions from light-duty vehicles. Any remaining ZEV-related emissions by 2050 are from hydrogen combustion, as electricity generation is net zero across all regions in All Out.

Further reduction in the emissions of light-duty vehicles beyond those modeled in All Out might be possible through (1) more-stringent fleet renewal regulations (in our study, gasoline vehicles are allowed 20 years of lifetime, higher than the average age for light-duty vehicles, and this affects the number of older vehicles on the road

1 Residual emissions may be defined as those for which abatement remains uneconomical or technically infeasible under the assumptions of a specific model and mitigation scenario (Luderer et al., 2018).

significantly because gasoline vehicles are predominantly light-duty vehicles); (2) more-stringent avoid-and-shift measures; or (3) including PHEVs in a fleet-renewal program in addition to ICE vehicles. Also, assuming 100% electrification is not possible for heavy-duty vehicles, then there is a greater need to achieve net-zero hydrogen production for those vehicles.

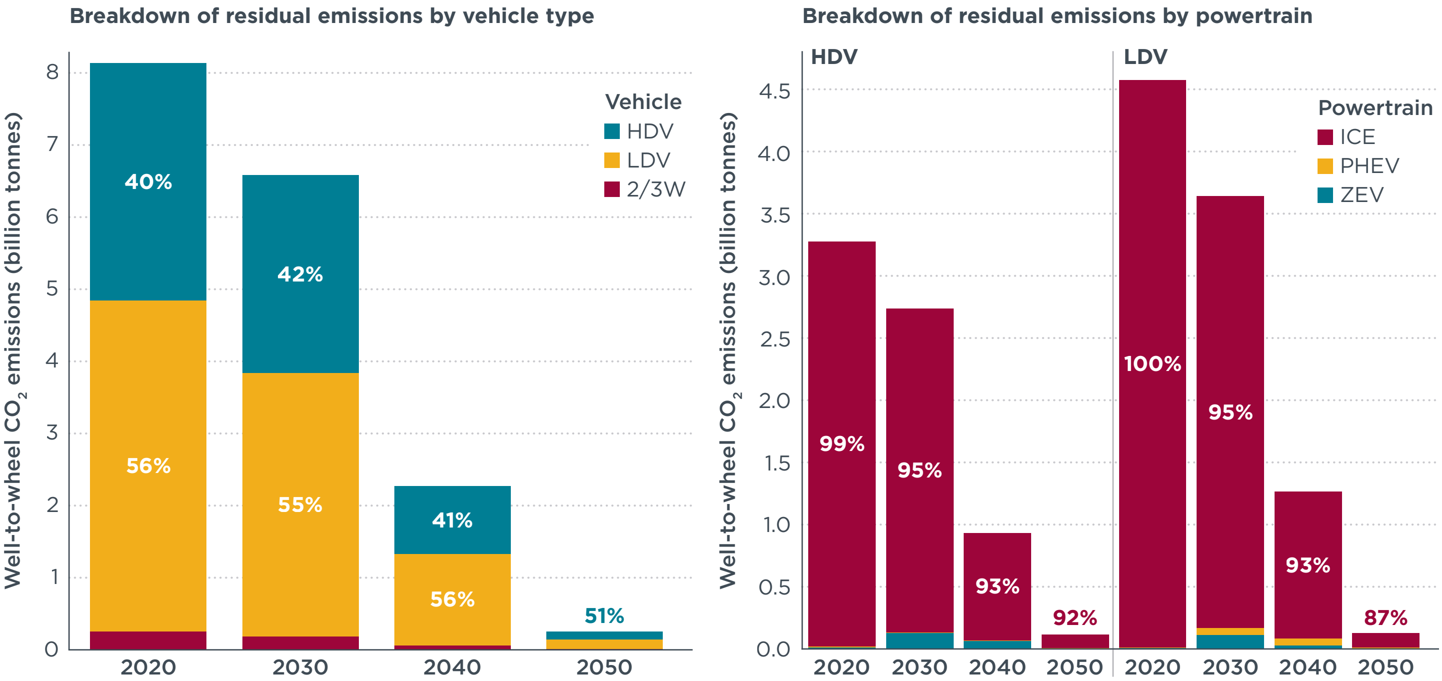

Figure 9. Residual well-to-wheel CO_2 emissions by vehicle type and powertrain type in the All Out scenario. Data labels on the left panel show the emissions by vehicle type. Data labels on the right panel show the share of emissions from ICE vehicles.

DISCUSSION

KEY HIGHLIGHTS

Sen and Miller demonstrated that a scenario of Ambitious ZEV Sales encompassing a full phaseout of sales of new non-ZEV vehicles globally by 2045 can ensure that the road transport emissions trajectory is compatible with a below-2°C pathway without overshoot. This study shows that a combination of additional strategies could further reduce emissions in line with a 1.7°C pathway: ICE technology improvement to reduce energy intensity, avoid-and-shift measures to reduce passenger and freight activity, limiting the age of used vehicle imports, fleet renewal to reduce the number of older ICE vehicles on the road, and ensuring a net-zero electricity grid as well as 100% green hydrogen production processes for fuel cell electric vehicles.

Advanced ICE Technology improvements such as strong hybridization of the engine and reducing drag and glider weight to reduce energy intensity are especially effective pre-2030, and during that time, their impact on emission reductions is comparable to that of the Ambitious ZEV Sales scenario. Although ICEs are generally phased out between 2035 and 2045, there is still significant impact from their performance for years to come, as most ICEs that are sold before a phaseout still remain in the fleet by 2050. Independent of order of implementation, **the cumulative mitigation potential of ICE efficiency technology improvement is estimated to be around 22 billion tonnes.**

Avoid and Shift measures are also important in the latter half of the analysis period, as it is expected to take at least a decade to fully implement several measures, including building infrastructure for walking and cycling, building or expanding mass transit projects, and improving logistics for freight vehicles. Independent of order of implementation, the **cumulative mitigation potential of the avoid-and-shift measures that we evaluated is estimated to be around 26 billion tonnes.**

Ambitious ZEV Sales for new vehicles combined with restricting the age of used vehicle sales to no more than 5 years for light-duty vehicles and no more than 8 years for heavy-duty vehicles (both with a three-year dispensation for Africa) **could avoid 61 billion tonnes** in cumulative CO_2 emissions globally.

Fleet Renewal measures could accelerate the global CO_2 emission reduction benefits of ZEVs by approximately 4 years and ultimately lead to a 10-percentage-point increase in emission reductions in 2050 (relative to 2020) compared to Ambitious ZEV Sales without Fleet Renewal. The fleet renewal program evaluated in this study is phased in between 2026 and 2030 and most older vehicles are removed from the fleet and replaced with new vehicles in line with the average efficiency and powertrain type of sales in that year. While in some markets ICEs are still predominant in sales of new vehicles during the initial years of the program, older vehicles replaced after 2035 are increasingly likely to be ZEVs and this magnifies the emissions benefits. **The cumulative mitigation potential of fleet renewal measures implemented alongside the Ambitious ZEV Sales strategy is estimated to be around 20 billion tonnes.**

A **net-zero electricity grid** following the IEA's Net Zero Emissions scenario and a strategy to ensure that all hydrogen produced to power fuel cell electric vehicles is **green hydrogen** by 2050 could avoid **16 billion tonnes of cumulative CO_2 emissions**. This is an important piece of the puzzle for reaching net-zero emissions targets because ZEVs will also need to have near-zero well-to-tank emissions.

An All Out scenario combining all of the above **could bring global road transport CO_2 emissions in line with a 1.7°C pathway**. This is similar to what a previous ICCT study (Graver et al., 2022) found is achievable for the aviation sector, but is still far from a pathway that aligns with 1.5°C. The sizeable work that remains is underscored by another finding of this study, that absent further policy measures, projected CO_2

emissions from ***vehicles that are already on the road today*** would exceed the limited carbon budget remaining to avoid overshoot of 1.5°C. Indeed, the cumulative emissions from selling no new vehicles going forward are only 10 billion tonnes lower than the All Out scenario when no other measures are implemented. This demonstrates the effectiveness of the strategies that we evaluated in driving rapid CO_2 emission reductions, but also highlights the scale of the challenge in reducing emissions from new and used vehicles in time to avoid overshoot of 1.5°C. While some additional strategies that could be considered in future studies are mentioned below, carbon removal technologies may also need to play a role if in-sector efforts are not able to bridge this gap.

FUTURE RESEARCH

Alignment with the 1.5°C pathway requires near-zero emissions from vehicles globally before 2040, if we are strict about adhering to a 67% probability of achieving the limited warming, maintaining the same share for road transport in the carbon budget, and an exponential shape to the pathway without overshoot. Though these parameters have been relaxed in other studies to achieve alignment with the 1.5°C pathway, that is not desirable when seeking to maximize the likelihood of success without relying on other sectors to make up the difference. To reduce the gap with the 1.5°C pathway, future research could evaluate the potential of further in-sector strategies beyond those that we have assessed here, including more ambitious variants of these strategies as well as additional strategies like shifting trucks to rail and right-sizing vehicles to improve energy efficiency.

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