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EXPANDED METHODOLOGY:

DATA AND METHODS OF ANALYSIS USED IN DEVELOPING STRATEGIES TO ALIGN GLOBAL ROAD TRANSPORT WITH WELL BELOW 2°C

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INTRODUCTION

This document provides details of the parameters used to construct the scenarios in the report, *Vision 2050: Strategies to Align Global Road Transport with Well Below 2°C*. The scenarios were constructed with the support of an external advisory group that provided data and scenario design inputs. The key parameters are Passenger Avoid and Shift, Freight Avoid and Shift, Light-Duty Vehicle Internal Combustion Engine (ICE) Technology Improvement, Heavy-Duty Vehicle Internal Combustion Engine (ICE) Technology Improvement, Fleet Renewal, and Used Vehicles. In this expanded methodology document, the base data and any assumptions used to construct scenarios based on that data are discussed along with detailed tables and figures. Additionally, regional results for cumulative emissions reductions in the scenarios using these parameters are included in Table 12 at the end.

PASSENGER AVOID AND SHIFT

The ICCT analysis incorporates databases from *ITF Transport Outlook 2023* (International Transport Forum [ITF], 2023) that benchmark passenger activity. The ITF study explored two scenarios, Current Ambition and High Ambition, to examine the potential consequences of future transportation policies on demand and emissions until 2050. We present here a brief outline of the methods and assumptions underpinning these scenarios. We did not directly adopt these methods but used them as a point of reference in our work.

The Current Ambition scenario offers insights into the possible evolution of transport demand and emissions if existing transport policies remain unchanged. It takes a business-as-usual perspective and projects the potential effects of current commitments, including those made under the Paris Agreement. The main assumptions for urban passenger demand under this scenario include the gradual implementation of measures based on existing policies. These measures include prices for things such as congestion, parking, and carbon; the introduction of road-access restrictions for vehicles; and investments in bicycle and pedestrian infrastructure combined with stronger enforcement of regulatory measures related to these modes. In addition, transit-oriented design and land-use planning are gradually implemented to increase population density in some regions.

In contrast, the High Ambition scenario assumes a pathway in which policymakers take proactive actions to expedite the decarbonization of the transport sector; some policies are implemented on an accelerated timeline and others are implemented at increased scale. This scenario models the impact of specific policy objectives such as promoting alternative transportation options, improving public transport services, enhancing infrastructure for walking and cycling, and moving freight more efficiently. The main assumptions involving urban passenger demand are the implementation of comprehensive strategies to promote sustainable modes and clean vehicles. It involves introducing pricing measures, road-access restrictions, and improved alternatives to reduce car dominance. Regulatory measures enhance urban safety, and land-use and transport planning facilitate greater accessibility and increased population density. The scenario prioritizes public transport enhancements, cycling infrastructure, and teleworking in supportive industries.

For the ICCT analysis, we obtained an ITF database that has information for 9,234 cities in 187 countries. The database includes the total number of actual and projected kilometers traveled per mode and year from 2015 to 2050 for 18 passenger transport modes; it also has population numbers and a homogeneous assumption of the number of trips per person. The changes in the kilometers traveled per mode until 2050 reflect the assumptions of implementing current policies or more ambitious policies. Table 1 summarizes the basic structure of the ITF database.

Table 1. Main structure and content of the ITF database used for the ICCT Passenger Avoid and Shift scenario.

Information	Description
Time frame for the assumptions	2015 to 2050 for both the Current Ambition and High Ambition scenarios
Cities	9,237 in total, identified by city ID and city name
Countries	187 in total, identified by country ISO codes
Regions	Europe: European Economic Area and surrounding countries, including candidates to join the European Union ENEA: East and Northeast Asia LAC: Latin America and the Caribbean MENA: Middle East and North Africa SEA: Southeast Asia SSA: Sub-Saharan Africa SSWA: South and Southwest Asia TAP: Transition economies and other Asia-Pacific countries UCAN: United States, Canada, Australia, and New Zealand
Passenger transport modes	Walk, bike, motorbike, car, taxi, rail, metro, light rail, bus, bus rapid transit, informal bus transit, three-wheeler public transit vehicles, scooter, shared bike, ridesharing, shared motorbike, carsharing, charter buses
Trips	Number is based on a common assumption of a fixed number of trips per capita across all cities
Population	Actual and projected population for each city from 2015 to 2050

To derive our shift scenario, we calculated the kilometers traveled per person by car in each city and grouped that information with other cities according to population and region. We grouped countries into bigger regions when necessary, because a sufficient number of cities within each group was essential to the analysis; otherwise, no shift would occur or a shift would require a reduction in travel to a level not seen in cities of similar size and socioeconomic group. Our Super Regions were created based on proximity and socioeconomic development. The regions in each Super Region are shown in Figure 1.

Figure 1. Regions in each Super Region.

We created population groups to capture cities with similar density, infrastructure, and land-use characteristics. While population is not a comprehensive proxy for density and land-use differences, cities within the same population group are more likely to exhibit similar traits compared with significantly larger or smaller cities. The population groups were defined as more than 5 million people, 1 million to 5 million, 500,000 to 1 million, 100,000 to 500,000, and 10,000 to 100,000. Cities smaller than 10,000 were excluded from the analysis due to their limited representation in the database. Table 2 summarizes the frequency distribution of cities within the Super Regions and population groups.

Table 2. Number of cities and distribution within 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

The underlying logic of our approach is to simulate a hypothetical change in the use of passenger cars in a certain city, assuming that it would have fewer vehicle kilometers traveled (VKT) per capita in 2050 compared with the business-as-usual scenario. To estimate a realistic potential decline or shift in VKT, we first ranked all the cities in each population-region group by VKT per capita in 2050 using data from the *ITF Transport Outlook 2023* Current Ambition scenario. We then assumed that every city in the same population group in a Super Region would shift toward another city in the same group with fewer kilometers driven by passenger cars. Next, we determined the percentile shift, in other words, how much each population group in each Super Region would move within the previous Current Ambition or Baseline ranking based on its new VKT (Table 3). A city in a region-group that was in the 75th percentile that undergoes a shift of 25 would, as a result, have the same VKT as a city in the region-group in the Baseline 50th percentile. This percentile shift or new percentile ranking in each group points to the percentage reduction in VKT per capita, which is the percentage change in kilometers traveled by cars per person in 2050 in the ICCT Shift scenario compared to the Baseline. This is a way for governments to understand the extent of the shift modeled because it gives real-world examples of cities that perform better on this indicator (car pkm per capita). Examples are provided in the next section.

Table 3. 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

To validate our estimates of the potential for transformation across all Super Regions, we compared our percentage reduction in VKT per capita with the ambitious *High Shift* scenario presented by the Institute for Transportation and Development Policy (ITDP) in its report, *The Compact City Scenario – Electrified* (Fulton et al., 2021). The scenario envisions prioritizing public transit, cycling, and walking infrastructure alongside sustainable land-use policies and traffic-reduction strategies. This results in reduced car use in high-income countries and slower growth in driving in low- and middle-income countries. The comparison with ITDP allowed us to gauge whether our methodology was impacted by limitations such as having cities within a specific group being excessively influenced by even a minor percentile shift. The percentage shifts in the ITDP scenario were used to establish a ceiling for the percentile shift imposed on our city groups in each Super Region. We see in Table 4 that generally our estimates are between the ITF and ITDP estimates, with the latter being on the ambitious side.

Table 4. Reductions in kilometers traveled by cars per capita in the ITDP, ICCT, and ITF studies.

Region	ITDP Compact Cities	ICCT (this study)	ITF Transport Outlook 2023
United States	38%	24%	13%
OECD Europe	44%	42%	33%
China	54%	39%	26%
India	57%	38%	38%
Brazil	57%	36%	24%
Other Americas	55%	30%	24%
Africa/Middle East	62%	39%	18%
Other Europe/Asia	54%	36%	32%

MAIN CHANGES IN CITIES AND COUNTRIES

Table 5 summarizes the changes in total kilometers traveled by cars per person for a city in a given Super Region due to a percentile shift and the new city it resembles from ITF's Current Ambition scenario. As an example, for Africa, in the ITF's Current Ambition (Baseline) scenario, the projected per capita distance driven using passenger cars in Cairo in 2050 is 1,817 km. When applying a 45 percentile shift in the percentile distribution of African cities with a population above 5 million, the projected per capita distance driven by passenger cars in Cairo is reduced to 694 km. This aligns with the same per capita distance driven in Casablanca, a city in the same population group, in 2050 in the Baseline scenario. Through the ICCT Shift scenario, our approach envisions Cairo resembling Casablanca by 2050. The same logic is applied to the other city duos.

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%

The city-level results can be aggregated at a country level (Figure 2). Globally, we see most of the reduction from the Baseline occurs in Africa and Europe. This does not necessarily mean a decrease in passenger car activity in these regions, but rather a slower growth in activity compared to the Baseline scenario.

Figure 2. Reduction in passenger car activity compared to the Baseline by country/region.

The ICCT's Avoid and Shift scenario served as an input for calculating estimates in emissions reduction; we use version 2.2 of the ICCT's Roadmap model (ICCT, 2022) and assume a decrease in kilometers traveled per vehicle (VKTpVeh). Note that other parameters, such as the vehicle stock, could be utilized to simulate reductions in car use within future scenarios. To conduct a sensitivity analysis and understand how changing the vehicle stock instead could impact total emissions, we simulated two alternative scenarios. The first scenario focused on changes in the stock alone, and the second combined changes in VKTpVeh and vehicle stock. We selected a sample of countries[1] that accounted for 80% of global passenger car VKT for the sensitivity analysis, using the Ambitious ZEV Sales scenario.

- If we assume VKTpVeh remains unchanged, the resulting CO_2 emissions are 3.39 billion tonnes.
- If we assume that stock does not change and the entirety of the travel demand is accomplished through reduction in VKTpVeh, the resulting CO_2 emissions are 3.37 billion tonnes.
- If we split the difference—take the same fraction of VKTpVeh and stock shift—the resulting CO_2 emissions are 3.38 billion tonnes.

The resulting difference is about 1% between the reduction-in-VKTpVeh-only case and the two other cases. Given the operational simplicity of the reduction-in-VKTpVeh-only case, that one is chosen.

1 In descending order of passenger car vehicle km traveled in 2050: China, United States, India, Pakistan, Thailand, Indonesia, Germany, France, Saudi Arabia, Italy, Mexico, Japan, Malaysia, United Kingdom, Brazil, Iran, Canada, Poland, Russia, Egypt, Nigeria, and South Korea.

FREIGHT AVOID AND SHIFT

The Freight Avoid and Shift calculations are based on a report from the International Energy Agency (IEA), *The Future of Trucks* (Teter et al., 2017), with modifications when certain scenarios are achieved and to account for urban/nonurban travel mix.

For reducing travel and improving load factor, the following measures can be taken.

- **Routing efficiency:** Find the shortest route and avoid congestion.
- **Last-mile efficiency:** Avoid times of congestion and predict dynamic demand.
- **Backhauling:** Deliver cargo on return trips to maximize load and reduce travel.
- **Vehicle utilization:** Utilize higher payloads, which affects load factor.
- **Consolidation centers:** Set up centers to group shipments for delivery into one region.
- **Co-loading:** Ship similar types of products together.
- **Co-modality:** Use other forms of transport for part of the travel whenever efficient.
- **Crowdsourced logistics:** Use individual citizens as couriers for last mile.
- **Physical internet:** Share a system to track logistical resources of all providers to maximize efficient use, which affects both logistics and load factor.

In the analysis, these affect vehicles in a similar fashion. However, not every vehicle is affected by these measures. For example, backhauling only affects medium- and heavy-duty trucks (MDT and HDT) and not light commercial vehicles (LCVs), but the impact of backhauling on MDTs and HDTs are the same. As expected, the impact is much higher for LCVs and MDTs in urban settings.

The IEA study has three scenarios: a 4°C compatible one, a 2°C compatible one, and a "well-below" 2°C compatible one. 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 that these improvements will be accelerated, and the 2°C compatible assumptions will be achieved by 2040 and the well below 2°C compatible assumptions will be achieved by 2050. Starting from 2022, linear achievements until the 2040 value are assumed. Linear achievements are assumed again between 2040 and 2050. Table 6 summarizes the improvements possible by 2040 and by 2050 by deploying various strategies for different vehicle types.

Table 6. Percentage decrease in vehicle kilometers traveled (VKT) or increase in load factor due to Freight Avoid and Shift strategies by strategy, parameter, year, and vehicles affected.

Strategy	Parameter	Vehicles	2040 improvement	2050 improvement
Routing efficiency	VKT	All on-road freight	5.6%	6%
Last-mile efficiency	VKT	Urban LCV/MDT	2.8%	3.5%
Vehicle utilization	Load factor	All on-road freight	6.8%	8.4%
Backhauling	VKT	All MDT/HDT	2.8%	3.5%
Consolidation center	VKT	Urban LCV/MDT	2.8%	3.5%
Co-loading	VKT	All MDT/HDT	5.6%	7%
Co-modality	VKT	Nonurban MDT/HDT	1.9%	2.3%
Crowdsourced logistics	VKT	Urban LCV/MDT	1.9%	2.3%
Physical internet	VKT and load factor	All on-road freight	7.1% each	8.8% each

The improvement potential is calculated for each vehicle, geographic type (urban/nonurban), year, and parameter (VKT or load factor) by subtracting the percentage change value from the i^{th} improvement measure from 1. Then the resulting values from all such subtractions are multiplied. The combined multiplied value is then subtracted from 1 to get the aggregated improvement potential.

Improvement potential = 1 – [product of (1 – all improvement measures applicable)]

The assumption here is that in the Baseline scenario of this study (unlike the 4°C scenario from IEA), no such improvements are made, so we do not need to scale the potential relative to the Baseline values. Table 7 summarizes the improvements that are modeled for all categories at a global level.

Table 7. 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 difference in urban/nonurban travel split globally, the final numbers are different on a country-by-country basis for VKT improvement, as is captured in Figure 3.

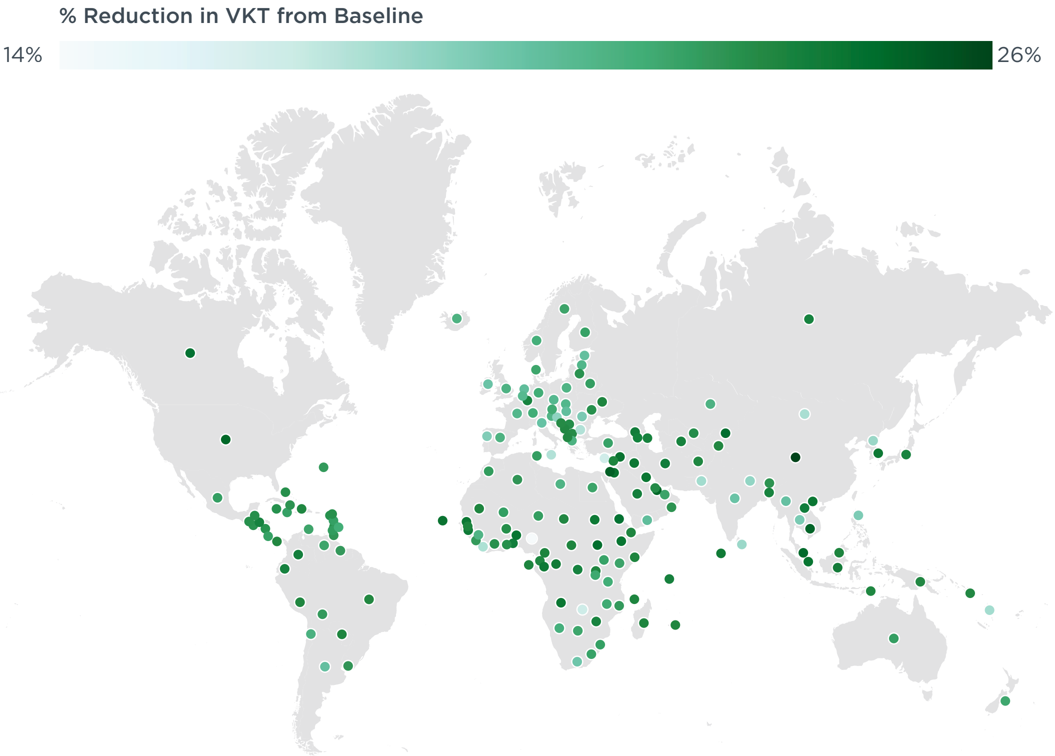

Figure 3. Percent reduction in freight VKT from Baseline achieved by freight avoid-and-shift measures in 2050.

LIGHT-DUTY VEHICLE INTERNAL COMBUSTION ENGINE (ICE) TECHNOLOGY IMPROVEMENT

To model ICE technology improvement for light-duty vehicles (LDVs), we start with the 2020 baseline energy intensity and apply a ratio for future years. For example, if Canada's 2020 gasoline car energy intensity was 3.2 MJ per km and we predict a 10% reduction in fuel consumption in 2025, we model this as a ratio of 0.9, which reduces energy intensity to 2.88 MJ per km.

It is not practical to model the potential improvement trajectory for every country in the world. As a result, six "representative" regions are chosen: the United States, the European Union, China, Japan, South Korea, and India. These are six of the biggest automobile markets in the world and there is both relatively good historical data for them (Shen et al., 2023) and an understanding of what future potential technology might look like (e.g., Lutsey et al., 2017; Meszler et al., 2017; He & Bandivadekar, 2013).

TECHNOLOGY PACKAGE

The technology package that was modeled for LDV ICE vehicles is a strong hybrid engine with a road-load technology that maximizes ways of reducing the impact of drag and mass. This is the target for all markets. However, they all have different starting points in terms of current fuel efficiency and, by extension, what a representative new vehicle—an exemplar—looks like in that market. For each vehicle class (light-duty passenger cars and trucks) an exemplar vehicle is chosen that represents the vehicle on which advanced technology improvements should be applied. The technology package selection and modeling is done using the Corporate Average Fuel Economy (CAFE) model set by the National Highway Traffic Safety Administration (National Highway Traffic Safety Administration, 2012). The engine technology chosen is HCR2, which is a high compression-ratio engine (Atkinson cycle) with cylinder deactivation. Three road-load technologies are assumed: the AD20 (20% drag reduction), MR5 (20% reduction in glider weight), and in some cases, MR6 (28.2% reduction in glider weight). Note that all three technology options are considered marketable by the National Highway Traffic Safety Administration but not necessarily cost-effective. However, since the objective of the study is to maximize technological feasibility rather than economic feasibility based on current conditions, these options were chosen. The focus of this improvement is on all nonelectric vehicles, including all ICE vehicles and self-charging hybrids without plug-in technology.

Based on the analysis, the maximum improvement for gasoline vehicles is around 50%–57% from the 2020 baseline, with the improvement potential being on the higher end for smaller and medium-size vehicles. For diesel vehicles, the maximum potential is around 56%. However, not all countries will reach this improvement potential based on their starting trajectory and because they only have 15 to 20 years to implement ICE energy-efficiency technology improvement measures.

COST CURVES

The cost curves are calculated based on the combined powertrain/road-load technology options and separating out the effect of each option is impractical for most cases. Vehicles are redesigned annually to allow for improvements in energy intensity until 2035 for advanced markets (essentially the six representative regions plus other major countries such as the United Kingdom and Canada) and 2040 for other markets. If nonelectric vehicles are no longer sold before this period (in some advanced scenarios, some of the larger markets will phase out nonelectric vehicles before 2035) then the trajectory is not adjusted, and it is assumed that the last nonelectric vehicle sold will not have the most advanced ICE technology package. Cost curves vary by basic vehicle type (cars and light trucks) and by fuel type (gasoline and diesel) and no other region-specific factors are considered. Learning curves for the reduction in costs over time were developed from the same CAFE modeling runs used to derive the basic cost curves. The U.S. dollar value is 2018.

The cost curves model how expensive would it to be attain a certain level of fuel consumption given a certain vehicle type. For example, it is cheaper to attain the same level of fuel consumption for a small car than for a large pickup truck.

Here is how the cost is calculated:

Cost = (Slope x (Fuel consumption certification in gallons per 100 miles^exponent)) + Intercept

The exponent (negative values greater than 1) is higher for smaller vehicles, which indicates that they have a smaller penalty for higher fuel consumption. They also have lower slope but higher intercept values (all intercept values are negative), which indicates that their baseline fuel consumption is achieved at a much lower cost. Technology improvement limits are assumed based on the technology package simulation results, and as a result no category of vehicle can improve indefinitely. An example of cost curves for gasoline vehicles is shown in Figure 4.

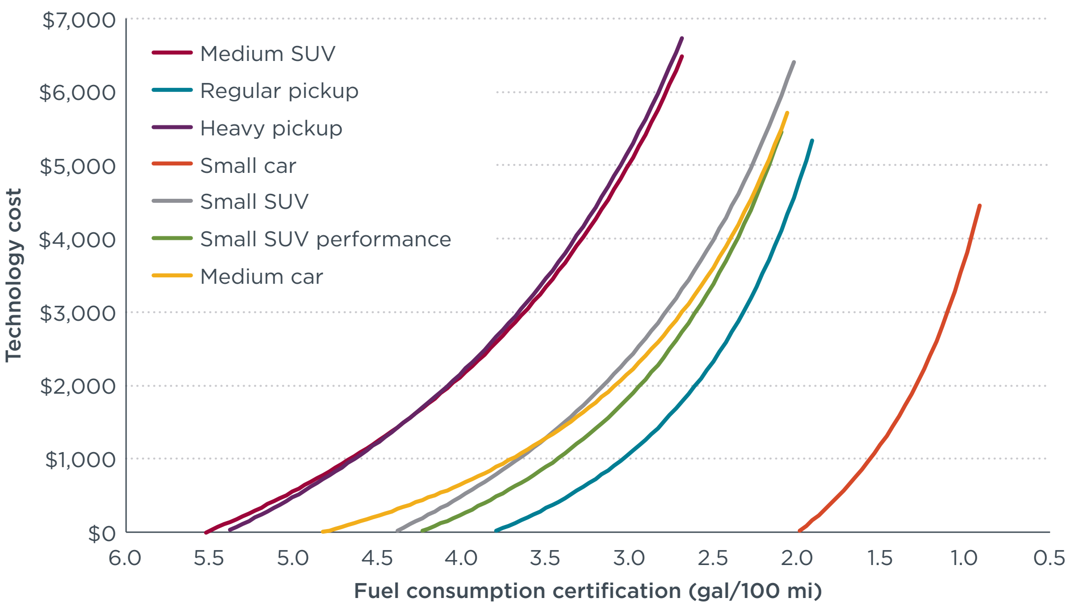

Figure 4. Cost curves of gasoline-vehicle fuel consumption.

As an example, let us consider the cost curve of the regular pickup. The pickup's fuel consumption range starts at around 3.8 gal/100 miles (approximately 3.12 MJ/km). The cost curve for the pickup has an intercept of -1645, an exponent of -2.09, and a slope of 27238. This means that to reach fuel consumption certification of approximately 3.0 gal/100 miles, the cost equals = (27238 * 3 ^ -2.09) -1645 = $1,080. Conceptually this means that to improve the fuel consumption rate of a pickup from 3.8 gal/100 miles to 3 gal/100 miles, or approximately 21%, the cost of doing so is $1,080.

BASELINE TECHNOLOGY

An initial difficulty is to figure out how much of the technology pathway being adopted is already in the new vehicles sold in different markets. That is not clear just by looking at fuel-efficiency values; fuel efficiencies are lower in the United States, where larger cars and trucks are more popular than in the European Union. Thus, to create an equitable "no tech" baseline, a "maximum tech" analysis is done on the exemplar vehicles as is. Then we figure out the implied "no tech" baseline for each cost curve class by applying the "maximum tech" reduction percentage to the observed "maximum tech" fuel consumption and check the difference with the fuel economy we get from this exercise versus the actual starting value. The difference implies that some of the technology is already built into the present-day vehicles sold, and it ranges from 15%–26%. To extend the baseline tech consumption estimate to the other areas, the weight-adjusted baseline fuel consumption in each of the six representative regions is compared against the certified fuel consumption data for the six representative regions in 2020. The representative region that has the least percentage of deviation from the fuel consumption of the target country gets assigned to that country. Figure 5 shows the mapping of the six representative regions to other countries.

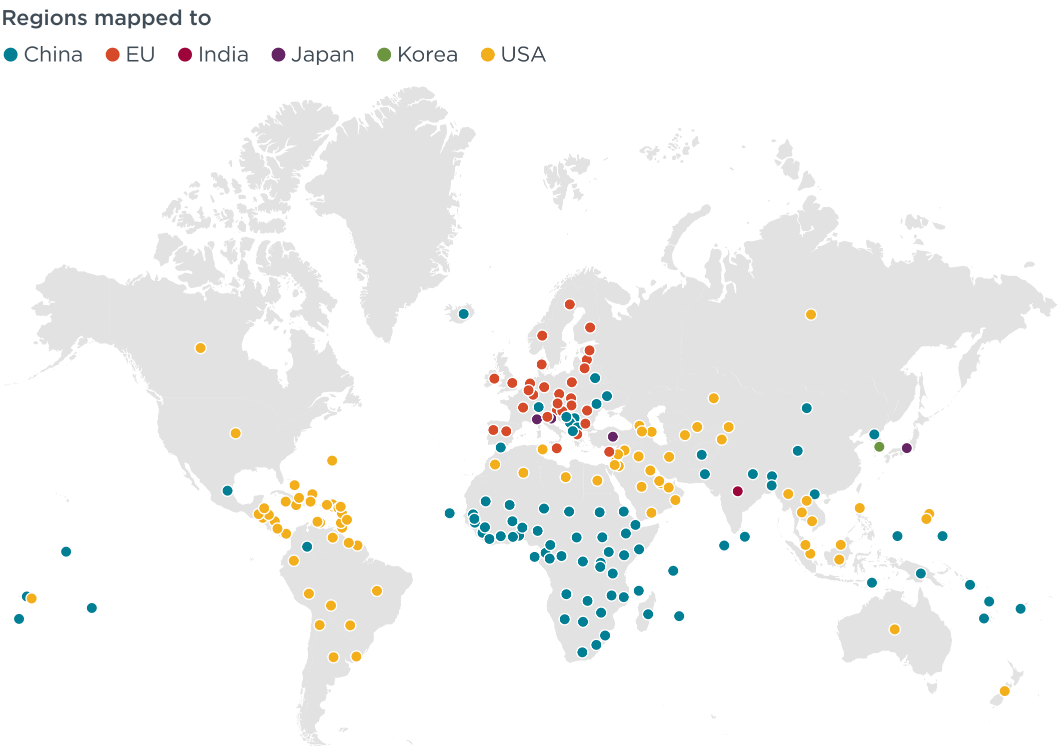

Figure 5. Mapping the six representative regions to other countries/regions.

The resulting global energy intensity for LDVs in 2050 is between 0.58 and 0.76 times the value in 2020 (Figure 6), signifying a range of improvement between 24% and 42% over the 2020 baseline.

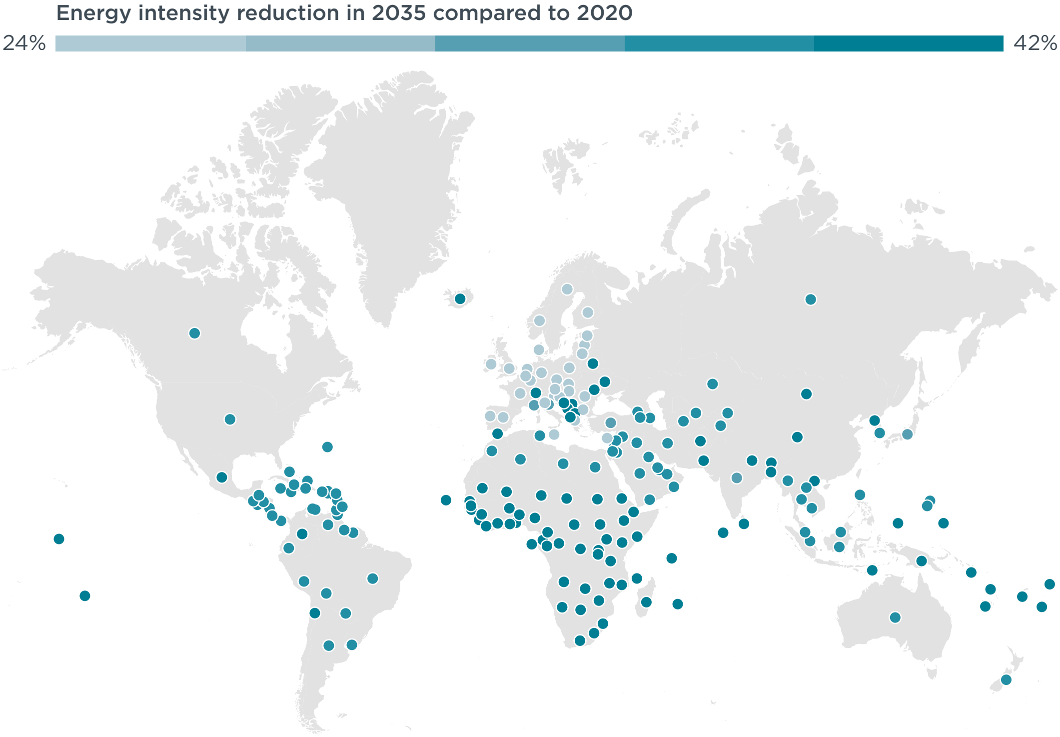

Figure 6. Global energy intensity improvement of new light-duty ICE vehicles in 2035 compared to 2020 in the Ambitious ICE Technology scenario.

HEAVY-DUTY VEHICLE INTERNAL COMBUSTION ENGINE (ICE) TECHNOLOGY IMPROVEMENT

The heavy-duty vehicle (HDV) improvements are based on existing ICCT studies. For the United States, the U.S. Phase 3 Benefits Assessment study is used (Ragon et al., 2023). From this study, the gains made after 2027 (after Phase 2) are estimated to be between 10% for heavy-duty tractors to over 20% for most other vehicle types (Table 8).

Table 8. Summary of heavy-duty ICE efficiency improvements in the United States by vehicle class. Reprinted from Ragon et al. (2023).

Class	Type	2027 EPA regulatory target		ICCT post-2027 ICE potential		Post-2027 efficiency ICE improvement potential	
Tractor trucks		gCO_2/ton-mile		gCO_2/ton-mile		Efficiency improvement	
Class 7 tractor	Low roof	96.2		72.5		25%	
	Mid roof	103.4		78.6		24%	
	High roof	100.0		76.4		24%	
Class 8 tractor (day cab)	Low roof	73.4		56.2		23%	
	Mid roof	78.0		60.2		23%	
	High roof	75.7		58.9		22%	
Class 8 tractor (sleeper cab)	Low roof	64.1		48.6		24%	
	Mid roof	69.6		53.2		24%	
	High roof*	64.3		49.7		23%	
Heavy-haul tractor		48.3		43.6		10%	
Vocational vehicles		gCO_2/ton-mile		gCO_2/ton-mile		Efficiency improvement	
		Diesel	Gasoline	Diesel	Gasoline	Diesel	Gasoline
Class 4–5	Urban	367	413	280	316	24%	24%
	Multi-purpose	330	372	249	278	25%	25%
	Regional	291	319	212	226	27%	29%
Class 6–7	Urban	258	297	191	222	26%	25%
	Multi-purpose*	235	268	172	195	27%	27%
	Regional	218	247	153	170	30%	31%
Class 8	Urban	269	297	226	222	16%	25%
	Multi-purpose	230	268	199	195	14%	27%
	Regional	189	247	160	170	15%	31%

* A full cost-effectiveness analysis of the various efficiency technology packages was performed for those HDV segments in Buysse et al. (2021).

For India, the technology potential and cost-effectiveness study of 2023 is used (Yadav et al., 2023). Per this study, 39%–49% of the decrease in energy intensity can be achieved, depending on the vehicle type, by using the strongest vehicle package. The strongest package includes strong hybridization with low-rolling-resistance tires and reduced aerodynamic drag (Table 9).

Table 9. Summary of heavy-duty ICE efficiency improvements in India by vehicle type.

Vehicle type	Percentage reduction in energy intensity in 2030 compared with 2020
Rigid trucks <12 tonnes	41%
Rigid trucks 12–16 tonnes	44%
Rigid trucks 16–28 tonnes	39%
Rigid trucks >28 tonnes	44%
Tractor-trailers	49%

For the European Union, the 2023 analysis of decarbonization pathways (Basma & Rodríguez, 2023) is used to determine the technology potential. The maximum potential ranges from 23%–39% depending on the diesel truck class (Table 10).

Table 10. Summary of heavy-duty ICE efficiency improvements in the European Union by truck group. Reprinted from Basma & Rodríguez (2023).

Group	Maximum CO_2 reduction potential by 2025 relative to 2016 (%)	Maximum CO_2 reduction potential by 2030 relative to 2016 (%)
0	25.22%	27.71%
1	25.60%	28.13%
2	25.55%	28.08%
3	29.24%	32.13%
4 - UD	24.34%	26.74%
4 - RD	35.88%	39.43%
4 - LH	29.51%	32.67%
5 - RD	30.64%	33.92%
5 - LH	29.09%	32.35%
9 - RD	35.89%	39.40%
9 - LH	30.54%	33.75%
10 - RD	31.38%	34.64%
10 - LH	30.10%	33.37%
11	20.68%	22.72%
12	21.03%	23.31%
16	29.73%	32.63%

For every other region, we used the 2016 ICCT analysis of global HDV technology potential (Delgado et al., 2016). The technology potential is calculated based on the U.S. SuperTruck program (Delgado & Lutsey, 2014) or the U.S. Environmental Protection Agency's best estimates and then scaled to various markets. In this analysis, estimates from the Delgado et al. (2016) study are used for the following regions: Latin America (including Brazil and Mexico), Canada, Japan, South Korea, Australia, non-EU Europe, and Russia. In addition, a global average is also calculated. The maximum technology-improvement potential that was estimated ranges from 30%–36% for rigid trucks and 40%–52% for tractor-trailers. For tractor-trailers, the region with the highest reduction potential is China, and for rigid trucks, Latin America, Asia-Pacific, Middle East, and Africa have the most potential (Figure 8).

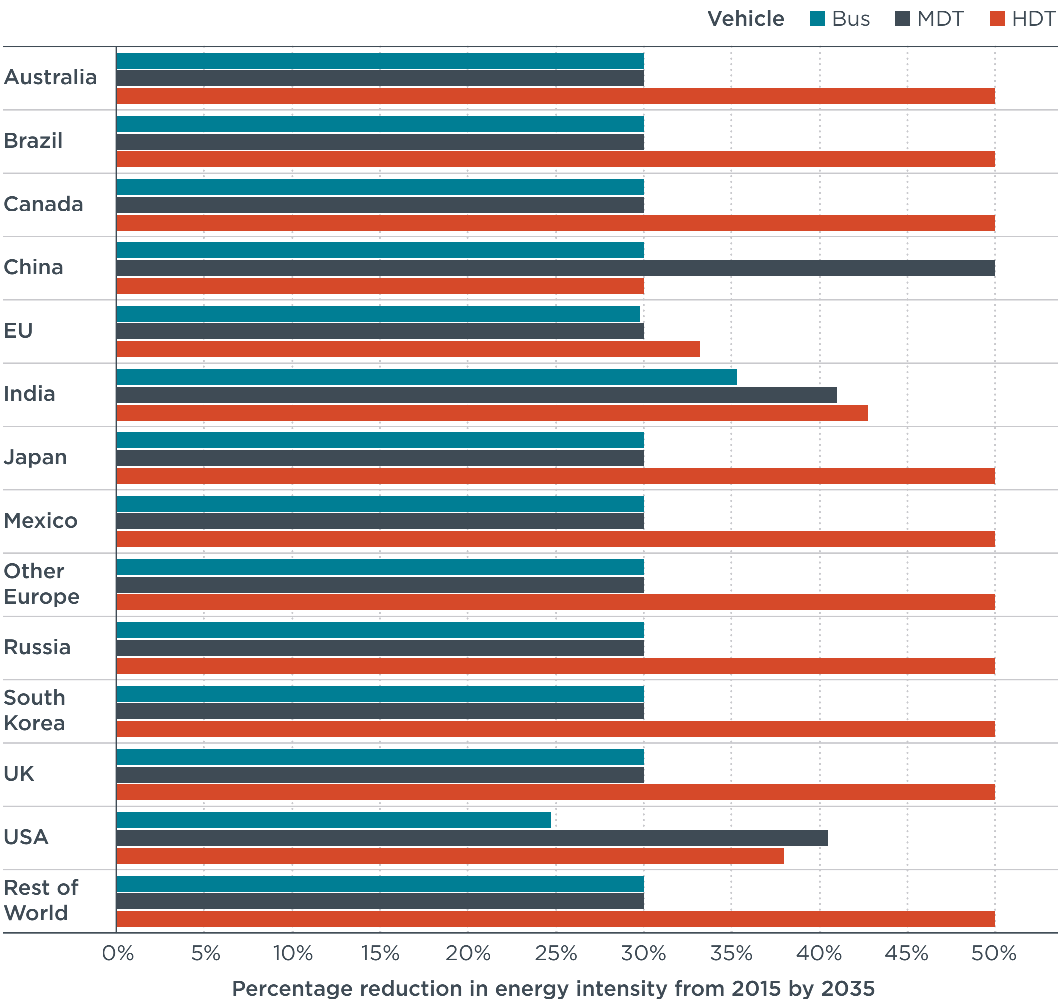

Figure 7. Global energy intensity reduction of new heavy-duty vehicles in 2035 compared to 2015 in the Advanced ICE Technology scenario.

FLEET RENEWAL

Fleet renewal policies either mandate or incentivize the retirement of vehicles after a certain age or restrict their activity, and these usually happen well ahead of their natural turnover schedule. For example, if a vehicle has a 30-year lifespan, then a fleet-renewal policy might mandate that vehicles more than 15 years old cannot remain in the fleet. The assumption is that this would not significantly change travel demand; owners of the retired vehicles would still need to meet their annual mileage requirement using the same category of vehicle, such as passenger cars. The replacement vehicles are expected to be cleaner than the retired vehicles, both in terms of local pollutant emissions and likely also in GHG emissions.

Two types of fleet-renewal interventions are considered in this study. The first, for LDVs, is based on the forthcoming ICCT paper by Morrison et al. which designed a program for LDV stock in Germany. This followed a renewal program that was utilized in Germany between 2007 and 2008 and paid owners of vehicles that were at least 9 years old to get rid of their older vehicles and subsidized the purchase of new ones. Morrison et al. (forthcoming) found that it would be cost-effective from a societal benefits standpoint to remove vehicles from the fleet older than 14 years for diesel vehicles and older than 20 years for gasoline vehicles. Looking at the global LDV fleet in the Roadmap model, we find that the average age of vehicles is around 18. Hence, if countries were to adopt fleet-renewal programs with similar age criteria, the vehicles targeted by these programs would be older than the average in the Baseline scenario. We follow Morrison et al. (forthcoming) in setting the gasoline vehicle removal age for this hypothetical program at 20 years.

For HDVs, the renewal policy is based on the analysis of air pollution from HDVs in G20 economies (Jin et al., 2021) prepared by the ICCT in 2021. The authors evaluated the impacts of hypothetical fleet-renewal programs that targeted heavy-duty diesel vehicles older than 16 years and assumed that such programs would be implemented after markets require Euro VI or better emission standards for all new vehicle sales. We find that for the global HDV fleet in Roadmap, this is consistent with the average age of vehicles. Hence, similar to the program evaluated for LDVs, the vehicles targeted by the hypothetical HDV fleet-renewal program would also be older than the average in the Baseline scenario.

Vehicles in African countries are older than the global average, so we assume the age thresholds set by hypothetical fleet-renewal programs in Africa would be extended by 3 years for both vehicle types. The fleet-renewal program starts in 2026 under the assumption that it would take governments at least 3 years to set up such a scheme. It is also prudent to wait until zero-emission vehicles make up a substantial share of new vehicle sales before implementing a large-scale fleet-renewal program. This is important because the study assumes that the activity of the vehicles removed from the fleet will be replaced with newly purchased vehicles. For example, if 10,000 km of activity of vehicles removed from the fleet needs to be replaced through the purchase of new vehicles, and in that year the sales of new vehicles are 70% ICE and 30% ZEV, then 7,000 km of vehicle activity would be replaced with ICE vehicles and 3,000 km would be replaced with ZEV vehicles. Finally, to prevent a rapid shock to the system in the first year, the fleet-renewal program is phased in over 5 years, between 2026 and 2030. In the first year, 20% of the vehicles that are eligible for removal are assumed to be removed, starting with the oldest vehicles. In each subsequent year, there is a 20% increase in this number until 2030, when the program is fully implemented. The literature points to the need to substantially reduce emissions by 2030 in order to have a 67% probability of meeting a well-below 2°C target (Tanaka & O'Neill, 2018), and thus any policy designed to phase out older vehicles from the fleet must be fully in effect by then.

USED VEHICLES

Data related to used vehicles is taken from a dataset provided by United Nations Environment Programme (UNEP) that has sales data from 2015–2020 for the four largest exporters of used vehicles: the European Union, the United States, Japan, and South Korea. The dataset contains aggregated data for all LDVs and more than 200 importing countries and regions are covered (UNEP, 2021).

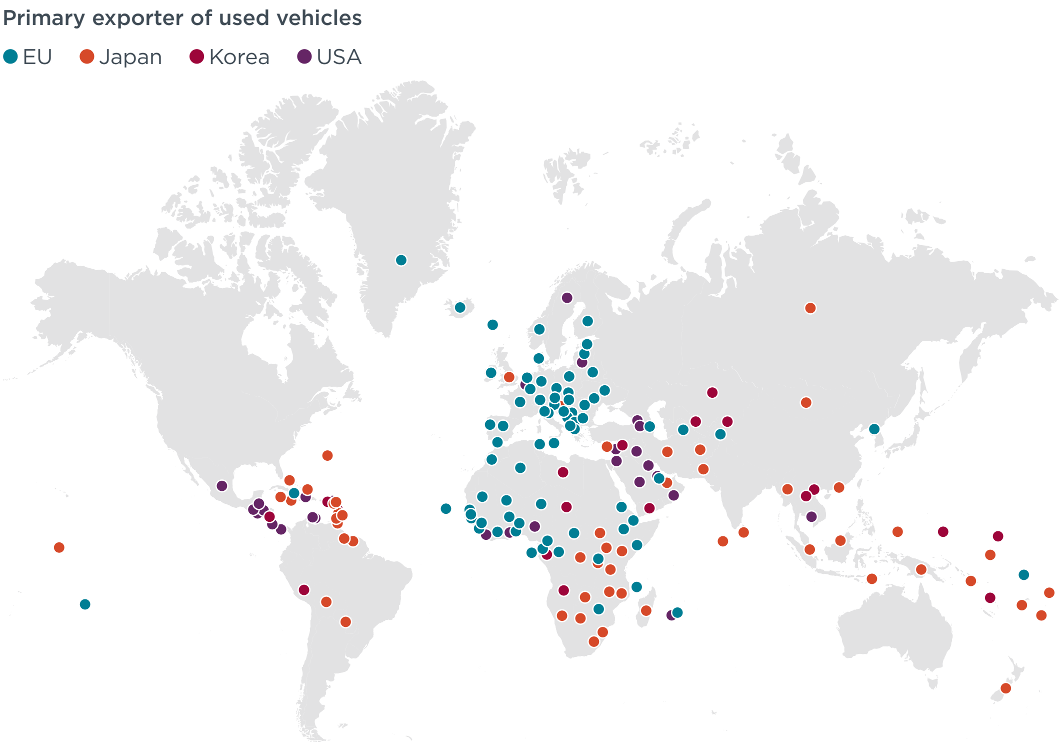

Figure 8. Map of countries/regions shaded by their primary source of used vehicle imports.

Based on our analysis of the UNEP dataset, either an EU Member State or the United Kingdom is the largest source of used imports for 80 importing countries; for 64 importers, Japan is the largest source, the United States is the primary source for 39 importers, and South Korea is the largest source for 22 importers (Figure 9).

Of the countries and territories that tended to import most of their vehicles from Europe, 68 were based either in Africa (29) or in Europe (39), including EU countries that exported used vehicles to another Member State. For Japan, a somewhat even split exists between exports to countries and territories in Asia-Pacific (24), Latin America (17), and Africa (16). For the United States, about half of exports go to countries in Latin America with the rest are split about evenly between Europe, the Middle East, Africa, and Asia-Pacific. For South Korea, exports predominantly go to Asia-Pacific countries (10).

To determine the age of used vehicles when they enter the importing country's vehicle fleet, we developed a used vehicle entry-age restriction dataset based on ICCT research and supplemented by UNEP's report, *Used Vehicles and the Environment – Progress and Updates 2021* (UNEP, 2021). For countries that do not ban used imports but lack any defined age or emission standards limit for such imports, an upper limit of 10 years for LDVs and 15 years for HDVs was assumed, based on the average entry ages from the existing dataset plus a few years (Figure 10).

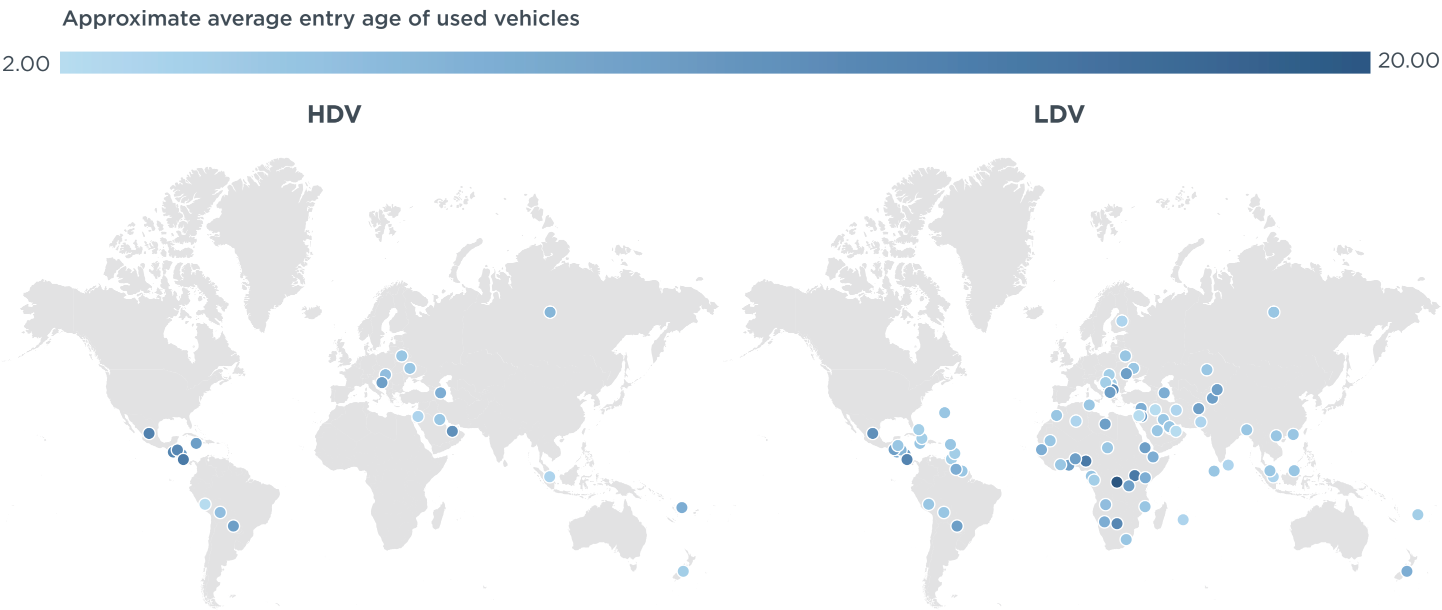

Figure 9. Approximate entry age of used vehicles by country/region and vehicle type.

The powertrain shares of used vehicles were inferred from the powertrain share of new vehicles sold in the source countries over the past 5 years. For countries that import used vehicles from multiple sources, the powertrain shares are weighted by the share of each source country for that importer. The source share from 2021 onward is determined by averaging the share between 2015 and 2020.

As an example, country X imports 60% of its used vehicles from the European Union and 40% from Japan. Five years ago, the EU's powertrain share was 50% gasoline and 50% diesel, and Japan's powertrain share was 95% gasoline and 5% diesel. If the average entry age of these used vehicles is 5 years old, then the share of used powertrains imported by country X would be 68% gasoline (0.6*0.5 + 0.4*0.95) and 32% diesel (0.6*0.5 + 0.4*0.05).

Table 11 shows the projected zero-emission vehicle sales share for used vehicle imports by region from 2030 to 2050 for LDVs and HDVs under the Ambitious ZEV Sales scenario. In this scenario, countries are assumed to preferentially import used zero-emission vehicles (as opposed to used ICEs), and it leads to a reduction in the average age of used vehicle imports. In this scenario, we assume a maximum entry age of 5 years for LDVs and 8 years for HDVs, except for Africa, where we assume a maximum entry age of 8 years for LDVs and 11 years for HDVs. The *de facto* age limit is based on the current median of import age restrictions globally—5 years for LDVs and 8 years for HDVs.

Table 11. Regional breakdown of zero-emission vehicle powertrain shares for used vehicle imports in the Ambitious ZEV Sales scenario.

	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%

The ratio of used imports to new vehicle sales is determined by Roadmap using IEA's Mobility Model (MoMo) database, which applies a stock balance approach to estimate the historic number of used vehicle imports in each MoMo database region. For the European Union, this data is supplanted by research from Ecologic (Velten et al., 2019) with modifications by the ICCT (Buysse et al., 2021).

REGIONAL BREAKDOWN OF CUMULATIVE EMISSIONS AVOIDED BY STRATEGY

Applying all the strategies considered in the analysis results in reductions from the Baseline scenario of 144 billion tonnes between 2020 and 2050. This reduces cumulative emissions from the Baseline by half. These are primarily achieved through efforts in the Ambitious ZEV Sales scenario, although decarbonizing both the electricity grid and the production of hydrogen 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 for passenger and freight vehicles 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 and India.

Table 12. Cumulative emissions avoided from Baseline by region and strategy (billion tonnes).

Region	Advanced ICE Technology	Passenger Avoid and Shift	Freight Avoid and Shift	Ambitious ZEV Sales	Fleet Renewal	Clean Fuel and Hydrogen	Total by region
Africa and Middle East	4.0	2.7	1.9	9.5	4.8	2.8	**25.7**
ASEAN	3.7	1.3	1.6	6.5	1.3	1.8	**16.2**
China	3.9	3.1	2.0	13.9	2.1	3.4	**28.4**
EU & UK	1.4	1.4	1.2	5.2	3.8	1.3	**14.3**
India	1.2	0.4	0.6	3.1	0.9	0.9	**7.1**
Japan and South Korea	0.7	0.4	0.4	2.2	0.2	0.4	**4.3**
Latin America	1.8	1.1	1.3	5.3	2.2	1.2	**12.9**
Other Asia Pacific	1.8	0.4	0.8	3.7	0.6	0.8	**8.1**
Other Europe	0.9	0.5	0.3	1.7	0.3	0.7	**4.4**
US and Canada	2.4	2.6	1.7	9.7	4.1	2.1	**22.6**
Total by strategy	**21.8**	**13.9**	**11.8**	**60.8**	**20.3**	**15.4**	**144.0**

Avoided Cumulative Emissions from Baseline (billion tonnes)

0.20 13.90

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