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THE CO_2 STANDARDS REQUIRED FOR TRUCKS AND BUSES FOR EUROPE TO MEET ITS CLIMATE TARGETS

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EXECUTIVE SUMMARY

The European Commission will review the currently adopted CO_2 emission standards for heavy-duty vehicles (HDVs) in 2022. This study seeks to inform the strengthening of standards that this revision requires in order to align the HDV sector with the European Climate Law, which strives to achieve climate neutrality by 2050.

The European Commission has identified a necessary CO_2 emissions reduction of 90% by 2050 relative to 1990 across all transport modes to align with this law. Our analysis depicts the contribution of emissions reduction that the HDV sector must make to comply with this target—through achieving a 98% reduction by 2050 relative to 2019. This reduction is based on the existing decarbonization commitments of the remaining transport modes, such as marine and aviation.

We model two scenarios representing the current CO_2 standards for trucks (Adopted Policies) and the milestones set by the Commission's strategy to decarbonize transport (Sustainable and Smart Mobility Strategy). Neither of these scenarios is sufficient to comply with the European Climate Law.

We also model a scenario enshrining recent announcements from major HDV manufacturers committing to a zero-emission vehicle transition, which would nearly align the HDV sector with the European Climate Law (Manufacturer Aligned Zero Emission Targets) and the additional reduction targets necessary to comply with the long-term climate commitment of the Commission (European Climate Law).

With regard to the regulatory design of the CO_2 standard, we assume that in all scenarios, with the exception of Adopted Policies, the scope of the CO_2 standard is extended to cover all HDVs; that the credit/debt system is extended in its current form through to 2050; that targets continue to be set in 5-year intervals; and that the fleet-wide multipliers for zero- and low-emission vehicles are phased out beyond 2030.

The currently adopted HDV CO_2 standard would produce an 8% increase in CO_2e emissions across the total fleet by 2050 relative to 2019, therefore failing to contribute toward meeting the commitments set by the European Climate Law. Despite the intentions behind the Sustainable and Smart Mobility Strategy, the 2030 and 2050 milestones also fail to deliver the necessary deep decarbonization cuts, achieving an 78% reduction over the same period.

The future zero-emission vehicle adoption levels that HDV manufacturers have said they anticipate, if achieved and supplemented by consistent efficiency improvements, would correspond to an emission reduction of 96% by 2050 relative to 2019—closely in line with the goal of the European Climate Law. However, these manufacturer goals only represent their strategic vision and binding regulation is likely necessary to realize these reductions in emissions. Manufacturers' targets represent the minimum level of stringency that the European Commission should consider in the review of the CO_2 standards; the HDV CO_2 standard, which applies to new vehicles, acts as the main policy lever to enshrine these manufacturer-led commitments into binding regulation.

Increasing the target established in the HDV CO_2 standard from the current 30% reduction required by 2030 relative to the 2019/2020 baseline to 60% in 2030, and introducing reduction targets of 90% in 2035 and 100% in 2040, are necessary steps to make these manufacturer-led goals a reality (Figure ES1). Of note, all major HDV manufacturers in the European Union have pledged that all vehicle sales will be fossil-free by 2040. We estimate that the availability of low-carbon fuels compatible with the internal combustion engine will be insufficient to decarbonize the road transport sector. Thus, we model these manufacturer announcements for technology transition under an optimistic assumption that "fossil-free" denotes zero-emission vehicles only, thus presenting the upper bound of the CO_2 reduction potential of this commitment.

Setting a standard with an ambition lower than these recommended values could fail to impel manufacturers to deliver deep cuts in decarbonization.

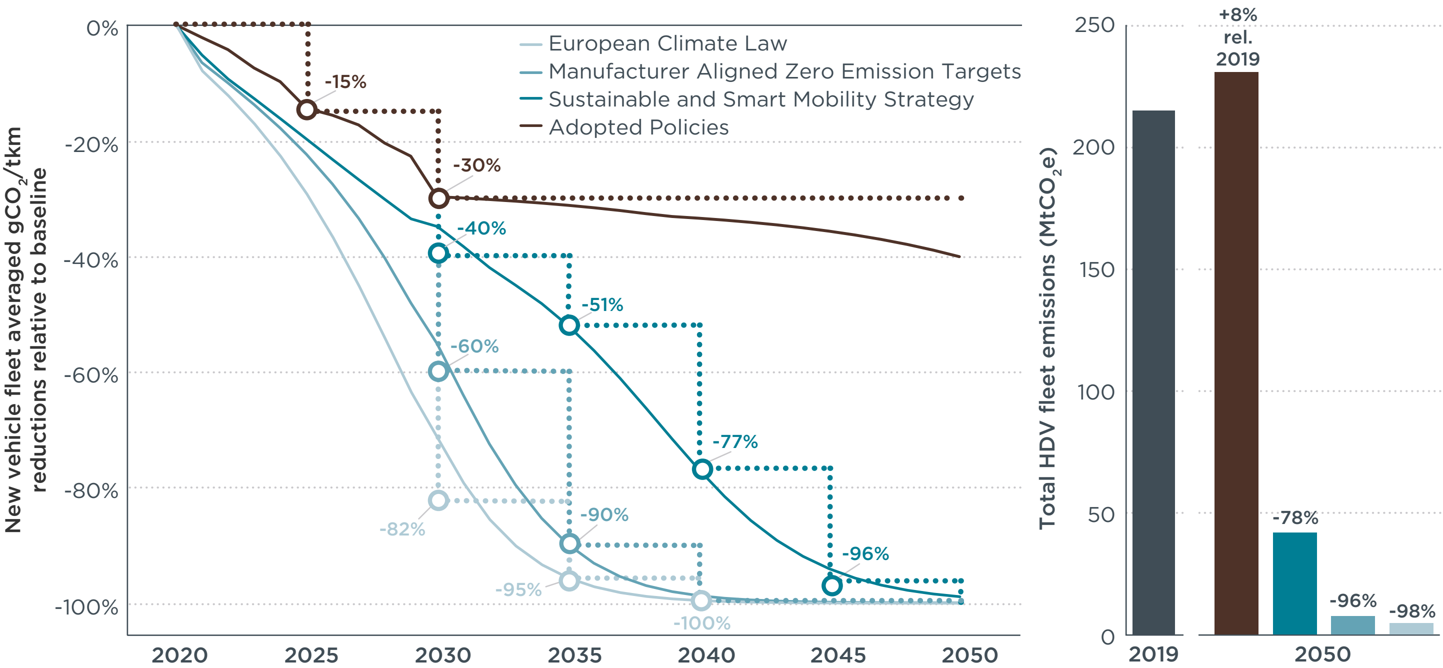

Figure ES1. New vehicle fleet average CO_2 emissions relative to 2020 baseline with corresponding 5-year targets by Scenario (left) and overall HDV emissions in 2050 in $MtCO_2e$ relative to 2019 (right).

Reducing HDV CO_2 emissions by 98% by 2050 relative to 2019 and ensuring full compliance with the European Climate Law will require a stricter level of ambition: 82% in 2030, 95% in 2035, and 100% in 2040. The current regulatory framework sets targets in 5-year steps, but a full ICE phase-out is required by 2038 for full compliance. While presenting a similar level of annual emissions in 2050, the cumulative CO_2e savings from the European Climate Law scenario are 12% (418 million tonnes) greater than the Manufacturer Aligned Zero Emission Targets, shown in Table ES1.

Table ES1. Cumulative HDV emissions reductions and relative changes compared to 2019. CO_2 reductions consistent with the European Climate Law are shown in green.

Scenario	New HDV CO_2 target (vs. 2019/2020) 2030	2035	2040	HDV CO_2e emissions savings (vs. 2019)[a] 2030	2050	Cumulative CO_2e reduction by 2050 compared to Adopted Policies (million tonnes)
Adopted Policies	-30%	-30%	-30%	**+4%**	**+8%**	-
Sustainable and Smart Mobility Strategy	-40%	-51%	-77%	**-3%**	**-78%**	1,897
Manufacturer Aligned Zero Emission Targets	-60%	-90%	-100%	**-10%**	**-96%**	3,080
European Climate Law	-82%	-95%	-100%	**-19%**	**-98%**	3,498

[a] The economy-wide target for 2030 is at least -55%. The HDV contribution required by 2050 is -98%.

The European Climate Law scenario achieves a 19% emission reduction in 2030 relative to 2019, compared to a 10% reduction in the Manufacturer Aligned Zero Emission Target scenario. Europe has an economy-wide target to reduce overall emissions by 55% by 2030 relative to 1990; Stepping up the ambition of the HDV CO_2 regulation can aid in achieving this target.

Strengthening the CO_2 standards for trucks and buses is a necessary step to set the EU on a path toward climate neutrality. An ambitious proposal by the European

Commission to increase the HDV CO_2 standard to a reduction of at least 60% in 2030, introduce a phase-out date for combustion-powered trucks and buses of no later than 2040, and establish interim targets will send a powerful signal to manufacturers and shape European industrial strategy to secure its leading role in the global transition to zero-emission mobility.

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INTRODUCTION

In June 2021, the European Commission, the European Parliament, and the European Council adopted the European Climate Law. The law legally commits the European Union (EU) to achieving climate neutrality by 2050 (European Commission, 2021a). Acknowledging the crucial role that the transport sector will play in meeting this target, the Commission outlined future steps to transform the EU transport system in its Sustainable and Smart Mobility Strategy released in December 2020 (European Commission, 2020). This strategy states that the transport sector should achieve a 90% reduction in greenhouse gas (GHG) emissions by 2050, relative to 1990, to align with the climate neutrality goal.

Heavy-duty vehicles (HDV), which are trucks and buses with gross vehicle weights above 3.5 tonnes, pose a unique challenge against meeting this target. The sector is responsible for over one quarter of transport-related CO_2 emission across the 27 Member States of the European Union (EU-27), despite accounting for only 2.5% of road vehicle annual sales (European Environment Area [EEA], 2021a). Yet policies that target GHGs from the sector are nascent, and the market for zero-emission HDVs (ZE-HDVs) is still in its infancy, accounting for just 0.66% of HDV sales in 2019 (see Figure 1) (IHS Markit, 2021). Although the number of zero-emission truck models available for sale has grown in recent years, actual sales still lag those of the light-duty sector (Basma and Rodriguez, 2021).

The European Commission implemented the first regulation mandating a reduction in CO_2 emissions for new HDVs in the EU-27 in 2019 (European Commission, 2019). This standard aims to reduce average CO_2 emissions from new trucks in key segments, representing approximately 65% of HDV sales, by 15% in 2025 and by 30% in 2030, relative to a 2019/2020 baseline. By comparison, CO_2 standards have applied to cars and vans for over a decade, and the Commission has recently proposed that all new cars and vans must be zero-emission vehicles (ZEVs) by 2035 (European Commission, 2021b).

	Light-duty vehicles		Heavy-duty vehicles		
	Cars	Vans	Buses	Medium trucks	Heavy trucks
CO_2 Regulation [1] reduction in gCO_2/km relative to 2021 [2] reduction in gCO_2/tkm relative to a 2019/2020 baseline	(EU) 2019/631 Regulation -15% in 2025[1] -37.5% in 2030[1] Fit for 55 Proposal -55% in 2030[1] -100% in 2035[1]	(EU) 2019/631 Regulation -15% in 2025[1] -31% in 2030[1] Fit for 55 Proposal -50% in 2030[1] -100% in 2035[1]	Not covered under HDV CO_2 Regulation (EU) 2019/1242		(EU) 2019/1242 Regulation -15% in 2025[2] -30% in 2030[2] Only applicable to ~65% of total heavyduty vehicle sales
Total sales and ZEV sales share	13M Sales 1.9% ZEV Share	2M 1.0%	0.04M 4.1%	0.11M 0.7%	0.23M 0.04%
CO_2 emissions share	61% of Road Transport CO_2	11%	4%	0.7%	22%
Number of ZEV models	41	8	86	4	16

Figure 1. 2019 EU-27 Vehicle Statistics. HDV sales data for Bulgaria are excluded. Sources: EEA (2021a), EEA (2021b), EEA (2021c), CalStart (2021), EV Volumes (2021), IHS Markit (2021).

The European Commission has not yet set post-2030 emission targets for HDVs, so a gap exists between the CO_2 standards currently in place and those that will restrict the sector's emissions in line with the European Climate Law. At the end of 2022, the Commission will reassess the 2030 target, as well as consider setting longer-term targets for 2035 and 2040 and possibly extending the standard to vehicle classes not currently covered, such as medium-duty trucks, buses, coaches, and trailers. The review presents a possibility to amend or abolish certain mechanisms of the regulation, such as the zero- and low-emission vehicle (ZLEV) factor and the credit/debt system. The development of the upcoming proposal offers a crucial opportunity to adopt more stringent CO_2 standards to align the HDV sector with the aims of the European Climate Law.

In this paper, we present recommendations to narrow the gap between the 2050 climate neutrality goal of the European Climate Law and what the current standards can achieve by revising and extending the scope of CO_2 standards to varying degrees. We first present the different scenarios and the modeling approach we use to evaluate them. We then present the findings from this analytical exercise, followed by our recommendations on how to align the HDV CO_2 standards with the 2050 goal.

SCENARIO OVERVIEW

We define four scenarios in this analysis. First, we model the expected long-term CO_2 tailpipe emission reductions from the current CO_2 standards in Europe under Adopted Policies. Then, we identify three additional scenarios for the HDV CO_2 standards, with different levels of stringency from 2030 to 2040. These scenarios are consistent with the levels of ambition that the European Commission and HDV manufacturers have announced.

The first additional scenario considers the milestones that the European Commission put forward in its Sustainable and Smart Mobility Strategy (European Commission, 2020), which indicated the Commission's ambition for future policies. The second scenario aligns with the sales targets that European HDV manufacturers have announced. The third scenario considers what level of ambition would achieve a 90% reduction across all transport emissions by 2050 relative to 1990, as specified in the European Climate Law. In all cases, we assess the level of stringency required of the CO_2 regulation to ensure adherence to these targets.

With the exception of the Adopted Policies scenario, the scenarios assume that the energy efficiency of new combustion-powered trucks and buses will improve at an annual rate of approximately 3% until their technology potential is exhausted. In reality, a constant efficiency improvement is unlikely. Once investment into ZE-HDV technologies becomes a more cost-effective compliance option with high demand, HDV manufacturers may cease making investments into improving the efficiency of combustion engines. Nevertheless, investments in aerodynamics, tires, and advanced driving assistance systems are expected to continue, as they would benefit both ZE-HDVs and internal combustion engine (ICE) vehicles. Therefore, we select a 3% annual improvement rate in line with what the CO_2 regulation currently requires if ZE-HDVs do not achieve a sizeable market penetration. Table 1 presents a brief description of each of these scenarios.

Table 1. Definition of scenarios

Scenario	Description	Efficiency improvements in combustion-powered HDVs
Adopted Policies	The energy efficiency of regulated HDVs improves in line with CO_2 standards. The uptake of ZEVs is low until 2030 and accelerates gradually thereafter. The ZLEV factor can slightly reduce the efficiency improvements needed in combustion-powered HDVs to achieve compliance in 2025 and 2030.	Regulated HDVs: Up to 15% reduction by 2025 rel. 2020[a] Up to 30% reduction by 2030 rel. 2020[a] Unregulated HDVs: 0.5% reduction annually
Sustainable and Smart Mobility Strategy	Matches the milestones set by the Sustainable and Smart Mobility Strategy: 80,000 ZEV trucks in 2030 Nearly all buses in operation are zero-emission by 2050 Nearly all HDVs sold in 2050 are ZEVs	3% annual efficiency improvement across all classes until efficiency limit is reached
Manufacturer-Aligned Zero Emission Targets	Accounts for ambitions of manufacturers for ZE-HDV share targets in 2030 and 2040. Differing ambitions among manufacturers are weighted across their sales share.	3% annual efficiency improvement across all classes until efficiency limit is reached
European Climate Law	98% CO_2 reduction in 2050 across all HDV classes relative to 1990	3% annual efficiency improvement across all classes until efficiency limit is reached

[a]The efficiency improvement required of ICE HDVs under the Adopted Policy scenario depends on the share of ZE-HDVs in each vehicle class, due to the specific contribution of ZE-HDVs towards manufacturer CO_2 targets.

The main distinction between scenarios is the pace of ZE-HDV uptake. We apply diffusion theory outlined by Rogers, E.M. (1962) to model the technology adoption curve of ZE-HDVs. This theory proposes that the general rate of adoption of an innovative technology follows an S-curve distribution, driven first by the slow initial uptake of the technology by early adopters, gradually increasing in rate as the technology achieves large-scale market acceptance, and slowing as the technology fully diffuses. In the case of vehicle technologies, the adoption curve of ZEVs depends on a variety of factors, including model availability, recharging and refueling convenience, driving practices, environmental concern, and total cost of ownership (McCollum et al., 2017). Thus, modeling consumer choice heavily relies on consumer-driven data, such as stated preference surveys, or on existing market data for alternative powertrain uptake. Such data are rare for the HDV sector. In the absence of these data, we represent this technology diffusion using a Weibull Distribution curve, defined by Equation 1, where *m* is the vehicle class, *r* is the country, *t* is the year, α defines the rate of increase of the adoption curve from 0-100%, β defines the year on which 50% ZEV sales are achieved, and δ is a correction factor applied to countries to align the distribution function with the country's base year ZEV share[1]:

$$ZEV\ Share_{m,r,t} = \frac{1}{1 + e^{-(\alpha_m \times (t - \beta_m + \delta_{m,r}))}}$$

As such, δ is defined by Equation 2, where *BY* is the base year—2020 in the case of this analysis:

$$\delta_{m,r} = \beta_m - \ln\left[\frac{1 - ZEV\ Share_{m,r,BY}}{ZEV\ Share_{m,r,BY}}\right] - \ln[\alpha_m] - BY$$

It should be noted that these diffusions curves represent an idealized version of technology adoption and may not follow such a trend in practice. While S-curve adoptions have been evident in the light-duty sector in Europe (Diaz et al., 2021), the nascent nature of the ZE-HDV market complicates affirmation that the heavy-duty sector will mimic the light-duty sector. Running costs heavily influence operators of HDV fleets, and the uptake of ZE-HDVs may accelerate faster than the light-duty sector once total cost of ownership parity is reached with their diesel counterparts. Conversely, bottlenecks in supply chains and infrastructure installations could slow ZE-HDV adoption.

Recent market data of the emergence of ZEVs vary across different vehicle categories, as illustrated by the relatively high share of zero-emission buses (4.1% in 2019) compared to heavy trucks (0.04%) (IHS Markit, 2021). To account for this variability, we differentiate the ZEV adoption rate across three vehicle groupings based on their assumed speed of ZEV adoption—fast transition, medium transition, and slow transition vehicles. Medium and light trucks, defined as VECTO group 0,[2] as well as buses, are defined as vehicles with a fast transition. Predominantly urban and regional drive cycle, defined as VECTO groups 1, 2, 3, 4-UD, 4-RD, 5-RD, 6, 9-RD, and 10-RD, are defined as medium transition vehicles. Vehicles with a typically long-haul duty cycle or heavy construction trucks, defined as VECTO classes 4-LH, 5-LH, 7, 8, 9-LH, 10-LH, 11, 12, 13, 14, 15, 16, and 17, are defined as slow transition vehicles. Table 3 explains the characteristics of these vehicle types . Figure 2 shows the ZE-HDV sales shares for each scenario and vehicle grouping. A table of the shares for each scenario and vehicle group is available in Appendix D. We describe the determination of these curves in the following sections.

1 For example, a country might have a ZEV uptake of 5% in 2020. An assumed Weibull Distribution that outputs a 0% ZEV share in 2020 and a 5% share in 2025 would thus underestimate the actual ZEV share. Our correction factor shifts the Weibull Distribution to align the baseline with the corresponding point of the curve while keeping the same slope parameters—in this case, taking the value of 5, i.e., 2025–2020.

2 HDVs in Europe are categorized in 18 groups in accordance with the CO_2 certification regulation (EU) 2017/2400, based on their technically permissible maximum laden weight, chassis configuration, and axle configuration. The CO_2 standard (EU) 2019/1242 delineates further among regulated vehicles by mission profile—Urban Delivery (UD), Regional Delivery (RD), and Long-Haul (LH).

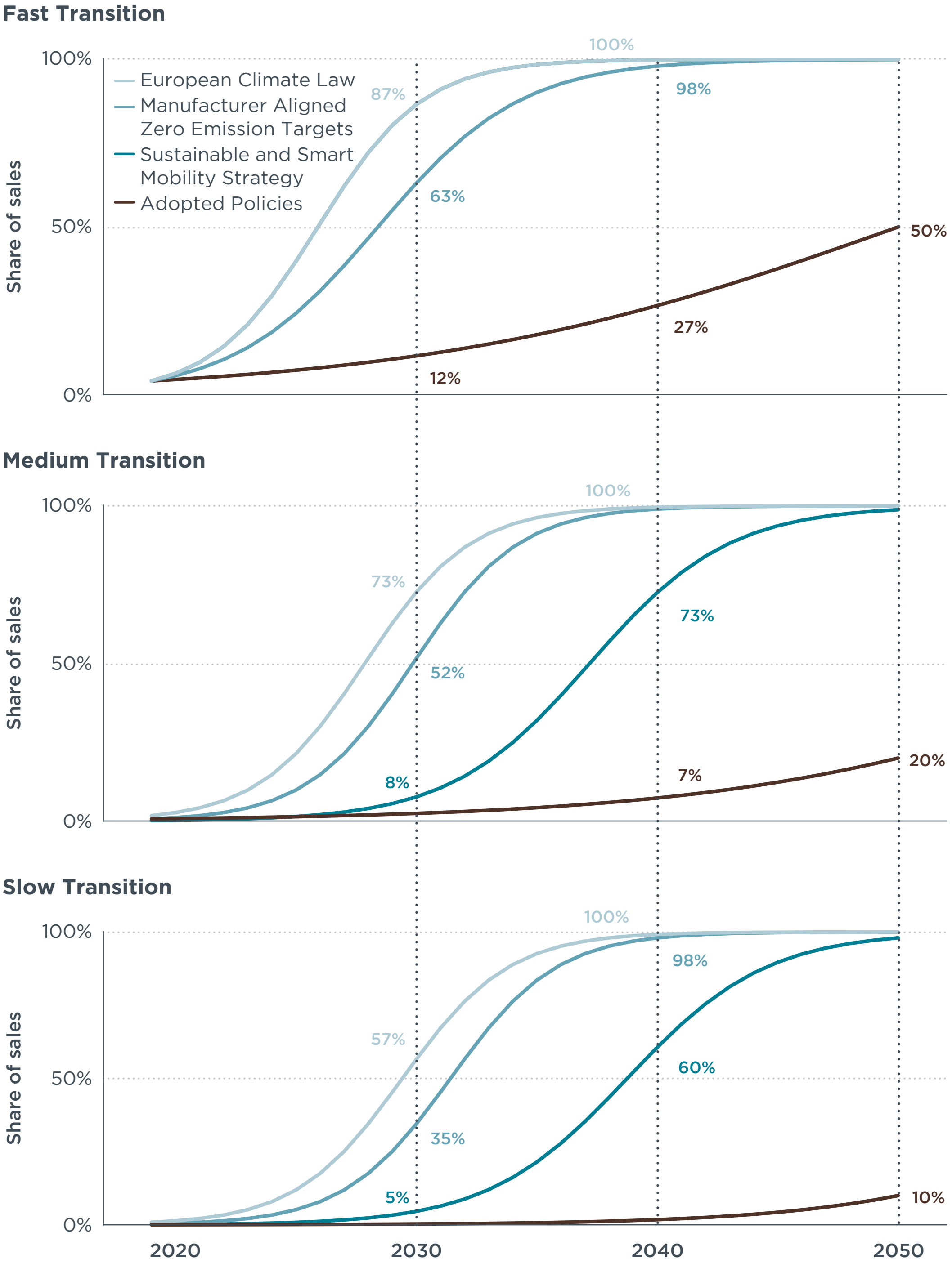

Figure 2. ZEV sales share by the anticipated speed of transition and scenario. Note: The ZEV adoption of fast transition vehicles in the European Climate Law scenario is set equal to the Sustainable and Smart Mobility Strategy Scenario and is not visible on the chart as a result.

These ZE-HDV technology adoption curves are defined by parameters to align with the scenarios defined in Table 1.

ADOPTED POLICIES

Under our Adopted Policies scenario, we model the efficiency improvements of regulated HDVs to comply with the standards in the current CO_2 regulation, i.e., a reduction in CO_2 of 15% by 2025 and 30% by 2030 relative to a 2019/2020 baseline. The implementation of the light-duty vehicle (LDV) CO_2 standard has shown that manufacturers do not follow a linear emission reduction trajectory. Instead, they ramp up reductions in the year before the standard takes effect (Wappelhorst et al., 2021). We model the efficiency improvements in HDVs to follow a similar trajectory in complying with the CO_2 standard for 2025 and 2030. We assume the efficiency of unregulated HDVs improves by 0.5% per annum based on Dallmann and Jin (2020).

For ZEV adoption, we apply a gradual uptake in the share of ZE-HDVs. The purchase price disparity between ZE-HDVs and combustion-powered HDVs is expected to narrow across the EU in the coming decades, while the total cost of ownership over a 5-year period for electric long-haul tractor-trailers is already at parity with that of their diesel counterparts in some countries. Parity is expected to be reached across other EU Member States in the coming decade (Basma, Saboori, & Rodriguez, 2021). This narrowing in purchase price and total cost of ownership is partially driven by the upward trend in the prices of conventional diesel trucks due to the technology investments necessary to comply with CO_2 emission standards and anticipated compliance costs with the upcoming Euro VII standards (Ragon and Rodríguez, 2021a). In addition, the price of ZE-HDVs is expected to fall in the future due predominantly to reduced battery prices (Basma, Saboori, & Rodriguez, 2021) and reductions in required battery capacity in the case of wide deployment of electric road systems. However, these cost reductions for ZE-HDVs are also expected to be proportional to production volumes due to economies of scale and paired with a parallel increase in availability of charging infrastructure. In the absence of a strong regulatory pull from stringent CO_2 standards and infrastructure deployment, we assume that the narrowing of this price disparity will be insufficient to create strong ZE-HDV demand in the coming decades, resulting in a modest increase in ZE-HDV sales shares to 10% of new heavy trucks, 20% of new medium trucks, and 50% of new buses in 2050. These values carry a high degree of uncertainty as, in the absence of regulatory pull, the uptake of ZE-HDVs is subject to a variety of factors that are difficult to capture without detailed consumer choice models. We therefore choose the final share values to align with the base assumption used in a recent ICCT analysis that captures the expected uptake of ZE-HDVs based on current country-wide targets (Miller et al., 2021).

SUSTAINABLE AND SMART MOBILITY STRATEGY

In December 2020, the European Commission published the Sustainable and Smart Mobility Strategy (European Commission, 2020). This strategy outlined a series of milestones that would align the EU transport system with the ambition of the European Climate Law and achieve a 90% reduction in emissions by 2050 relative to 1990. With respect to the HDV sector, the strategy set three key milestones toward this target:

» By 2030, 80,000 zero-tailpipe-emission lorries will be in circulation[3]

» By 2050, nearly all sales of lorries will be zero-tailpipe-emission

» By 2050, nearly all bus operations will be zero-tailpipe-emission

For medium and heavy trucks, we apply ZEV adoption curves necessary to achieve 80,000 zero-emission lorries in 2030, interpreting "lorries" to cover both medium and heavy freight trucks, while also achieving nearly full ZEV share (assumed as 98%) by 2050. For buses, we apply an adoption curve corresponding to the 2019 baseline EU bus ZEV share of 4.1% and a 98% ZEV stock by 2050.

MANUFACTURER ALIGNED ZERO EMISSION TARGETS

Globally, a many HDV manufacturers have started to indicate their willingness to shift to zero-emission technologies. As of July 2021, 19 leading manufacturers representing 45% of the global HDV market had made announcements committing to carbon

3 This represents approximately 1.3% of the total EU-27 fleet in 2019.

neutrality and more ZE-HDV sales (Garcia Coyne, MacDonnell, & Façanha, 2021). In Europe, all major manufacturers operating in the EU-27 have already announced targets to ramp up the production of ZE-HDVs. These targets present various levels of ambition, as shown in Table 2. A joint declaration of all major truck manufacturers, however, sets a minimum level of ambition through a commitment to sell only fossil-free commercial vehicles by 2040 (ACEA & PIK, 2020).

"Fossil-free" in this commitment, does not necessarily constrain the manufacturers to ZEVs alone and could technically also include combustion-engine vehicles powered with biofuels and synthetic fuels. However, in this analysis, we assume that "fossil-free" denotes ZEVs only, thus presenting the upper bound of the CO_2 reduction potential from a tank-to-wheel perspective. Some manufacturers have made additional announcements beyond this commitment: Daimler and Scania have separately committed to selling only zero-emission trucks by 2039 and 2040, respectively.

Table 2. Manufacturer announcements for the phase-in of zero-emission and fossil-free HDVs.

	Manufacturer	2025	2030	2039	2040	Source	2019 Sales Share
Fleet Zero-Emission Vehicle Targets	**DAF**	-	-	-	100%	(ACEA and PIK, 2020)	18%
	Iveco	-	-	-	100%	(ACEA and PIK, 2020)	6%
	MAN	-	40% LH 60% RD	-	100%	(MAN, 2021); (ACEA and PIK, 2020)	15%
	Daimler Trucks	-	60%[a]	100%	100%	(Daimler AG, 2021); (ACEA and PIK, 2020)	18%
	Renault Trucks	10%	35%	-	100%	(Renault Trucks, 2020); (Renault Trucks, 2021); (ACEA and PIK, 2020)	9%
	Scania	10%	50%	-	100%	(Scania, 2021); (ACEA and PIK, 2020); (Dutch Ministry for the Environment and CALSTART, 2021)	18%
	Volvo Trucks	7%	50%	-	100%	(Volvo Trucks, 2021); (ACEA and PIK, 2020)	16%

Note. LH = Long-Haul. RD = Regional Delivery.
[a]The 2030 Daimler announcement is phrased as "up to 60%."

While manufacturers broadly agree, under the joint commitment, to sell only fossil-free vehicles by 2040, their targets for the preceding years vary. To account for this variability, we weight each manufacturer's individual target in 2030 by their respective sales share to generate an average target across all HDV manufacturers. We differentiate the ambition across vehicle transition types by assuming the ambition of the medium transition vehicles to be 50% greater than that of slow transition vehicles in 2030. This assumption aligns with the targets set by MAN (2021), which indicate that delivery trucks achieve a 50% greater sales share of ZEVs than do long-haul trucks.

This weighting results in a zero-emission vehicle sales target of 35% by 2030 for slow transition vehicles, i.e., heavy trucks, and a target of 52% for medium transition vehicles. We create a ZEV adoption curve for these truck categories that corresponds to these respective shares of zero-emission vehicles in 2030 and a 100% share in 2040, resulting in an average ZEV share of 41% for all trucks by 2030.

To date, only MAN has provided a target for buses, pledging that half of its sales will be buses that run on alternative drives by 2025, which may not necessarily refer to ZEVs. ACEA's pledge for 2040 does not mention buses, but because the adoption of zero-emission buses has greatly outpaced that of HDVs, we assume that the fast transition vehicles also reach a 100% ZE-HDV share by 2040. Thus, we apply an adoption curve that corresponds to the baseline EU bus ZEV share of 4.1% in 2019 and achieves 100% ZEV share by 2040. This assumption corresponds to a ZEV bus sales share of 63% in 2030.

EUROPEAN CLIMATE LAW

According to the European Commission, the transport sector should reduce CO_2 emissions by 90% relative to 1990 levels to comply with the European Climate Law (European Commission, 2020). The Commission has not set a specific target for HDVs to comply with this transport-wide reduction. However, long-term targets have been announced for all other major transport segments (i.e., passenger cars, vans, aviation, and navigation), taking the form of legally binding regulations, strategic milestones, or proposals by the Commission upon which the European Council and Parliament must still agree. These ambitions indicate that:

- All new cars and vans will be zero-emission in 2035 (European Commission, 2021b);
- Nearly all cars and vans in operation will be zero-emission in 2050 (European Commission, 2020);
- Sixty-three percent of all aviation fuel will be sustainable in 2050 (European Commission, 2021c); and
- Between 86% and 88% of the international maritime transport fuel mix will consist of renewable and low carbon fuels in 2050 (European Commission, 2021d).

Applying the emissions reporting to the United Nations Framework Convention on Climate Change (UNFCCC) from the EEA (2021a) to these targets, the HDV sector would need to reduce its total fleet emissions by a minimum of 98% below 2019 levels for the entire transport sector to comply with an overall 90% reduction in emissions (see Figure 3).

Considering that the sales targets of zero-emission HDVs in the Sustainable and Smart Mobility Strategy only near 100% by 2050—that is, many combustion-powered HDVs will still be in circulation until closer to mid-century—the pathway outlined for the HDV sector by the strategy is clearly incompatible with the requirements of the European Climate Law, and ambition must increase.

The uncertainty of the future performance of other transport sectors induces a high level of variability for the actual required contribution of emissions reduction by HDVs. The final target for HDVs is highly dependent on LDVs—which constitute the largest share of current transport emissions—nearly fully decarbonizing by 2050, which already presents a significant challenge (Buysse et al., 2021). It also depends on the extent to which efficiency improvements offset activity growth in the aviation and maritime sectors and the extent to which renewable and low-carbon maritime fuels result in zero tailpipe emissions.

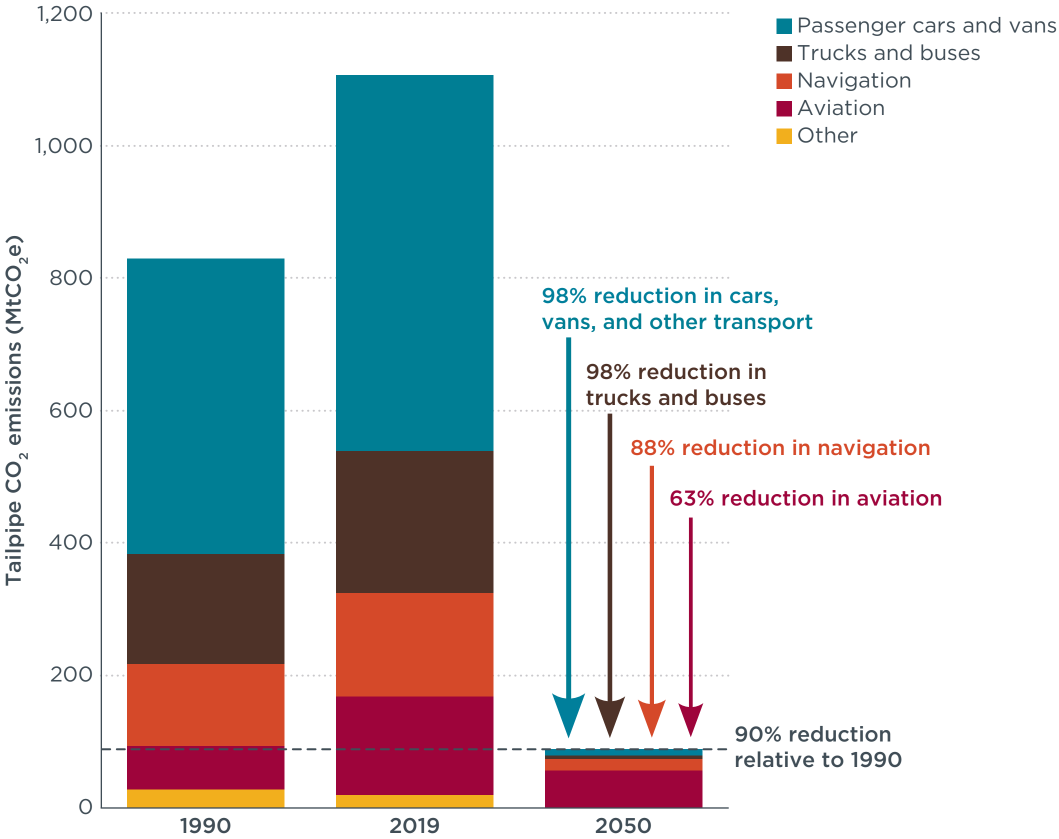

Figure 3. Sectoral emission pathways in million tonnes of CO_2 equivalent, compatible with a 90% reduction relative to 1990.

For the European Climate Law scenario, we model the ZEV adoption curves required for all trucks and buses in operation to achieve nearly full decarbonization by 2050, i.e., a 98% reduction in tailpipe emissions relative to the baseline. As the adoption curves for fast transition vehicles, i.e., buses, already achieve such an emission reduction in the Sustainable and Smart Mobility Strategy scenario, we apply the same ZEV adoption curve here. For medium and slow transition vehicles, we model the minimum ZEV adoption necessary to comply with a similar level of decarbonization across the entire fleet.

MODELING OVERVIEW

We evaluate the tailpipe CO_2 emissions from HDVs between 2020 and 2050 using the ICCT's Roadmap model (International Council on Clean Transportation, 2021). We segment the HDV market into 25 categories to align with the segmentation in the HDV CO_2 regulation and the precursory certification regulation (European Commission, 2017) (see Table 3 for a definition of each HDV segment). While not accounted for in this study, the Commission has recently proposed an amendment to the certification regulation that would extend the rule to medium trucks of vehicle category N2 with 5 t < Gross Vehicle Weight (GVW) < 7.4 t, N3 heavy trucks with GVW > 7.4 t, and heavy buses with GVW > 7.5 t (European Commission, 2021e). The proposed ammendment has been accepted, although has not yet formally implemented.

Table 3. HDV categories modeled in this analysis. Rows in dark blue denote the categories currently covered under the CO_2 regulation.

VECTO group	Axle configuration	Body type	GVW (t)	Sales share (2019)	First year mileage assumptions (km/year)	CO_2 reduction potential of combustion-powered HDVs in 2030 relative to 2020
Light and medium trucks	4x2	Rigid	>3.5–7.5	8.05%	40,000	25%
1	4x2	Rigid/tractor	7.5–10	1.33%	62,000	25%
2		Rigid/tractor	>10–12	3.41%	62,000	25%
3		Rigid/tractor	>12–16	3.45%	62,000	36%
4-UD	4x2	Rigid	>16	0.32%	60,000	38%
4-RD		Rigid	>16	6.40%	78,000	38%
4-LH		Rigid	>16	1.54%	98,000	31%
5-RD		Tractor	>16	0.54%	78,000	33%
5-LH		Tractor	>16	42.18%	116,000	31%
6	4x4	Rigid	7.5–16	0.99%	53,000	38%
7		Rigid	>16	0.83%	53,000	31%
8		Tractor	>16	0.69%	60,000	33%
9-RD	6x2	Rigid	all weights	4.94%	73,000	38%
9-LH		Rigid	all weights	6.32%	108,000	32%
10-RD		Tractor	all weights	0.02%	68,000	33%
10-LH		Tractor	all weights	2.32%	107,000	32%
11	6x4	Rigid	all weights	1.58%	75,000	16%
12		Tractor	all weights	0.47%	105,000	25%
13	6x6	Rigid	all weights	0.43%	60,000	38%
14		Tractor	all weights	0.02%	60,000	33%
15	8x2	Rigid	all weights	0.48%	51,250	38%
16	8x4	Rigid	all weights	3.15%	60,000	24%
17	8x6/8	Rigid	all weights	0.35%	60,000	38%
Buses	All	Bus	>3.5–16	9.73%	50,000	25%
Other	All others	Rigid/Tractor	All weights	0.45%	60,000	31%

Note: The CO_2 reduction potential of each vehicle class is determined through calculations conducted with the vehicle simulation model used in this analysis.

We modeled these categories with supporting country-level sales information dating from 2005–2020 (IHS Markit, 2021). This sales data series was used to calculate stock by vehicle vintage using survival curves, age profiles, and secondhand import assumptions, which we describe further in Appendix A. We obtained mileage data from the HDV CO_2 regulation's reference values, and we apply mileage degradation profiles derived from the European Commission funded TRACCS project (Emisia, 2013).

Tailpipe CO_2 emissions are calibrated through a scaling factor for each country to align baseline emissions with values reported to the UNFCCC (EEA, 2021a).

Activity levels of HDVs are aligned with the 2020 values of the PRIMES EU reference scenario, which sees an increase in truck activity (in tonne kilometers) of 51% between 2020 and 2050, and a 72% increase in bus activity (in passenger kilometers) over the same period (European Commission, 2021f).

We have not explored the potential reduction benefits of non-technology options, such as modal shift or improved freight logistics, to decrease overall on-road freight activity, which have been shown to be effective means to reduce overall emissions (International Energy Agency, 2017).

IMPROVEMENTS IN COMBUSTION-POWERED HDVS

To comply with the CO_2 standard, manufacturers use two main methods: improving the fuel efficiency of combustion-powered trucks, and increasing the sales of ZE-HDVs. The interplay between these two factors, driven by the costs and benefits of each, will impact the compliance pathways of manufacturers. In particular, vehicle efficiency improvements will be sufficient and cost-effective to comply with low levels of emission reductions. However, to achieve higher reduction targets in line with ambitous levels of decarbonization, deploying ZE-HDVs will eventually be required as the marginal efficiency improvement cost increases as ICE-powered vehicle efficiency approaches its limit.

A dedicated cost-benefit analysis could be applied to predict manufacturer compliance with the standards and will be addressed in an upcoming ICCT publication. For this analysis, we apply a simplified efficiency improvement assumption to each scenario. For the Adopted Policies scenario, the regulated HDV classes follow an efficiency improvement in line with the current HDV CO_2 regulation, achieving a 15% reduction by 2025 and a 30% reduction by 2030, relative to the baseline period. We calculate these CO_2 emission reductions using the methods followed in the HDV CO_2 regulation (European Commission, 2019), accounting for the Mileage Payload Weighting (MPW) factor and the ZLEV factor, described in more detail in Appendix B. Under the Adopted Policies scenario, the level of ZE-HDV adoption is low (see Figure 2) and has little impact on the final emission reduction, reducing the 2025 target from 15% to 14.76% and the 2030 target from 30% to 29.79%.[4] We assume that vehicles falling outside of the regulated classes have an efficiency improvement of 0.5% based on historic trends of fuel consumption for the best performing tractor-trailers (Dallmann and Jin, 2020).

For the other scenarios, we consider a wider range of more ambitious efficiency improvements undertaken by manufacturers. We impose an overall efficiency improvement of 3% per annum, in line with the requirements of the CO_2 regulation but applied to all HDV segments. This efficiency improvement continues until each HDV segment reaches its CO_2 reduction potential. We calculate this CO_2 reduction potential for each of the 25 HDV segments based on the CO_2 technology cost curves developed by the European Commission (Krause and Donati, 2018), which identified the upper limit of CO_2 reductions for the regulated vehicle groups (4, 5, 9, and 10). To assign a value to unregulated vehicles, we apply the same methodology. We estimate the fuel consumption of average 2016 unregulated trucks using the Vehicle Energy Consumption Calculation Tool (VECTO, 2017). We then apply the methodology to estimate the fuel consumption of a 2025 average diesel truck by considering technology improvements in the truck road load technologies, such as aerodynamics, rolling resistance, and chassis light-weighting, in addition to improvement in engine

4 ZEV adoption in unregulated HDVs contributes towards the ZLEV factor, however buses are not included in this calculation.

efficiency, implementing waste heat recovery technologies, and the use of more efficient auxiliaries (TNO, 2018). Moreover, we assume that not all trucks will benefit from the same technology improvements by 2025 and therefore assume different technology penetration rates for each truck class. Table 3 defines the resulting efficiency limitations.

The CO_2 limitations we identify for regulated classes show that the currently adopted CO_2 standard can be entirely achieved through efficiency improvements (Delgado, Rodríguez, & Muncrief, 2017). If the European Commission strengthens the standard significantly past the currently imposed 30% reduction required by 2030 relative to 2019/2020, then manufacturers will also need to increase the deployment of ZLEVs to achieve the targets.

ZEV UPTAKE

Beyond efficiency improvements, ZEV deployment is central to the strategies of manufacturers for the decarbonization of their fleet and compliance with current and future CO_2 standards. Therefore, we characterize our scenarios through a varied level of ZEV adoption, as presented in the Scenario Overview section (see Figure 2).

Several technologies can deliver zero tailpipe emissions, such as battery electric powertrains, hydrogen fuel cells, and electric HDVs powered by electric road systems, such as catenary lines or induction charging. These technologies have a variety of inherent characteristics, whereby certain technologies may be more applicable to some uses than others while delivering the same tailpipe emission reductions. Upcoming ICCT research explores the cost differential for some of these technologies, but in this paper we combine all zero-emission technologies under the nomenclature of ZE-HDV. The focus of this paper is on tailpipe emissions in line with the CO_2 regulation; we do not address upstream associated emissions from electricity production, hydrogen production, or fossil fuel refining.[5] Analysis from ITF (2021) has already shown the well-to-wheel life cycle emissions of electric trucks and buses in Europe to be significantly lower than their diesel counterpart in 2020, with a further reduction in emissions expected as renewable electricity capacity is increased.

We only consider ZEVs as those with no tailpipe emissions. ICE vehicles fueled by advanced biofuels and power-to-X (PtX)[6] fuels are not considered. The limited availability of feedstocks with zero well-to-tank emissions and their high production costs render them an economically unviable solution for the decarbonization of the transport sector (Searle, 2020). In comparison, a recent total cost of ownership analysis projected that battery-electric long-haul tractor-trailers in Europe will be cost-competitive with diesel in the next decade (Basma, Saboori, & Rodriguez, 2021).

5 Bieker (2021) studied life cycle emissions for passenger cars.

6 Power-to-X describes a process in which excess electricity is utilized to create hydrogen through electrolysis and is combined with CO_2 to produce liquid or gaseous fuel.

RESULTS

HDV EMISSION TRAJECTORIES

Figure 4 shows the tailpipe emissions trajectory of HDVs in the EU-27 from 1990 to 2019, derived from emissions reporting to the UNFCCC (EEA, 2021a) and modeled from 2019 to 2050 under our four scenarios. In the Adopted Policy scenario, efficiency improvements required to comply with the HDV CO_2 standards in 2025 and 2030 drive early emission reductions. However, increasing levels of freight activity require a greater stock of vehicles to cover increasing demands for trucks and buses, as assumed by the EU Reference Scenario. This assumption, alongside low levels of ZE-HDV adoption, offsets any efficiency improvements achieved by the current HDV CO_2 standards, driving up the overall level of emissions post-2030. By 2050, we estimate an emissions increase of 8% relative to 2019 levels under the Adopted Policy scenario. Deep decarbonization cuts rely heavily on the early and significant adoption of ZE-HDVs.

The Sustainable and Smart Mobility Strategy, which is intended to align the decarbonization efforts of the transport sector with the European Climate Law, is insufficient to engender the necessary reductions. Under this scenario, a considerable number of ICE HDVs will still be in circulation by 2050, and trucks will only achieve a near-complete ZEV sales share by 2050, indicating the need for an earlier phase-out of ICEs. We find that this scenario achieves a 78% reduction by 2050 relative to the baseline. Thus, without considerably increasing the reduction ambitions of the aviation and maritime sectors, the milestones in the Sustainable and Smart Mobility Strategy are incompatible with an 90% overall reduction in transport emissions as intended. Future policies will require greater ambition.

Notably, the milestone for buses established by the strategy aligns with the requirement of the European Climate Law. The bus milestone, which intends to phase out nearly all operational ICE buses by 2050, translates into a full phase-out of new sales of ICE buses by 2034 at the latest. Evidence from international regulators indicates that such a milestone is achievable and the potential exists for a stricter ambition. Increasing the ambition of buses could relax the effort required from trucks in the shift toward ZEVs, however we do not model a greater ambition in our analysis.

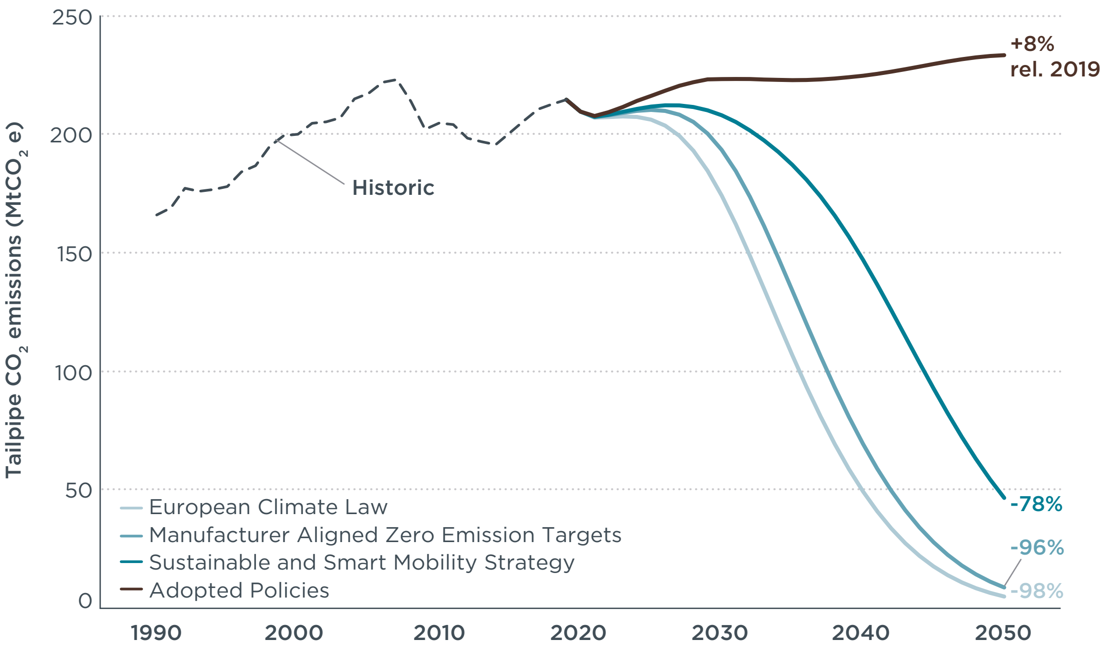

Figure 4. HDV emission trajectories from 2020–2050, with labels for reductions in 2050 relative to 2019. Historic HDV emissions derived from EEA (2021a).

Manufacturers' recent announcements outlining their ambitions to shift toward zero-emission and fossil-free trucks (see Table 2) if followed, would accelerate the technology transition by a decade compared to the milestones set by the Sustainable and Smart Mobility Strategy. Our optimistic interpretation of the ICE phase-out by 2040 accelerates the increase in overall emissions reduction, if achieved, to 96% by 2050 relative to 2019 levels, falling just short of the 98% reduction necessary to comply with the European Climate Law.

While almost compatible with the European Climate Law, these high levels of emission reductions depend heavily on the production of vehicles with zero tailpipe emissions. Thus, our analysis considers the upper bound of achievability based on these announcements, applying the optimistic interpretation that the commitment to fossil-free-only HDVs laid out by all major European HDV manufacturers for 2040 will translate to the sole production of zero-tailpipe emission vehicles fueled by renewable electricity and green hydrogen. Bieker (2021) identifies the incompatibilities of non-ZEV fossil-free vehicles with achieving deep decarbonization cost effectively and at scale. In particular, Bieker identifies supply-side issues with low-carbon biofuels and their inability to deliver net-zero life cycle emissions due to impacts related to indirect land use change. That analysis further identified high associated cost issues with PtX due to low production-side efficiencies, concluding that no realistic pathway exists for deep decarbonization which involves the combustion engine vehicle in road transport. This highlights the necessity for any future CO_2 standards only to consider zero-tailpipe emission vehicles, and not fuel crediting mechanisms, in future revisions.

To achieve the 98% reduction necessary to comply with the European Climate Law, ICE trucks must be phased out by 2038, two years earlier than the manufacturers' goal of 2040. However, in its current form, the regulatory framework of the CO_2 standard only sets new targets every 5 years, starting in 2025. Earlier targets will be crucial to phase out ICE trucks more quickly and achieve a ZEV share of 65% across all trucks by 2030 and 94% in 2035—higher than the respective 41% and 86% weighted average shares from the manufacturer announcements. This finding is compatible with those of a recent study by the World Economic Forum, which found that a 67% ZE-HDV share is necessary by 2030 for the European HDV market to keep global warming under 1.5 °C (World Economic Forum & Road Freight Zero, 2021). The vehicle-differentiated level of ZEV adoption required to achieve the European Climate Law target for 2050, alongside the decarbonization efforts of the other scenarios defined in this section, is explained in Figure 2.

The annual level of HDV emissions achieves a similar value between the Manufacturer Zero Emission Targets and European Climate Law scenarios by 2050. However, higher early ambitions under the European Climate Law scenario, achieved through increased ZEV adoption, avoids 418 $MtCO_2e$ more than the Manufacturer Aligned Zero Emission Target scenario, corresponding to an additional 14% of emissions savings. Such cumulative emissions savings are critical when considering the overall global warming potential of scenarios, as opposed to annual emission reductions.

The European Climate Law scenario also achieves a 19% emission reduction in 2030 relative to 2019, compared to a 10% reduction in the Manufacturer Aligned Zero Emission Target scenario (see Table 4). Europe has an economy-wide target to reduce overall emissions by 55% by 2030 relative to 1990 (European Commission, 2021a); increasing the ambition of the HDV CO_2 regulation can aid in achieving this target.

Table 4. Cumulative HDV emissions reductions and relative changes compared to 2019.

Scenario	New HDV CO_2 target (vs. 2019/2020) 2030	2035	2040	HDV CO_2e emissions savings (vs. 2019)[a] 2030	2050	Cumulative CO_2e reduction by 2050 compared to Adopted Policies
Adopted Policies	-30%	-30%	-30%	**+4%**	**+8%**	-
Sustainable and Smart Mobility Strategy	-40%	-51%	-77%	**-3%**	**-78%**	1,897
Manufacturer Aligned Zero Emission Targets	-60%	-90%	-100%	**-10%**	**-96%**	3,080
European Climate Law	-82%	-95%	-100%	**-19%**	**-98%**	3,498

[a]The economy-wide target for 2030 is at least -55%. The HDV contribution required by 2050 is -98%.

REVISION OF THE HDV CO_2 STANDARDS TO MEET SCENARIOS

The European Commission in 2022 will review the HDV CO_2 regulation, revise the current standards for 2030, consider the introduction of targets for 2035 and 2040, and possibly extend the compliance flexibility provisions under the credit/debt system (see Appendix C). Here, we propose targets for 2030–2040 that would align the HDV sector with each of the scenarios defined above. We assume that the 2025 target will remain unchanged at 15% below the baseline.

The actual determination of manufacturers' fleet average CO_2 emissions in the currently adopted standards—i.e., the metric used to evaluate compliance—is complex. The metric is a weighted sum of the CO_2 performance of the manufacturer across individual vehicle groups, weighted with a MPW factor and a ZLEV factor.[7]

For the Adopted Policies Scenario, we apply both the MPW and ZLEV factors to the determination of CO_2 emissions as established by the standard. For all other scenarios, we phase out the ZLEV factor from 2030 onward and continue to account for the MPW. The ZLEV factor has been found to reduce the real emission reduction potential of the regulation, as highlighted in Buysse et al. (2021), and should thus be phased out, as has been proposed for the CO_2 standards of cars and vans (Dornoff et al., 2021).

The CO_2 standard currently applies to four VECTO truck groups, which cover approximately 65% of total HDV sales. Ragon and Rodríguez (2021b) show the necessity of including the currently unregulated classes to achieve deep cuts in emissions in the HDV sector. Thus, we assume that buses and the currently unregulated truck groups will be included in the standard, ignoring the potential standalone standard for trailers.

We first calculate the new HDV fleet average emissions (called manufacturer's average specific CO_2 emissions, in the regulatory context) using the following formula, where SG denotes the vehicle's sub-group as defined in Table 1:

New HDV Fleet Average Emission (gCO_2/tkm)

$$= \textit{ZLEV Factor} \times \sum_{SG} \textit{Fleet } gCO_2/tkm_{SG} \times \textit{Sales Share}_{SG} \times MPW_{SG}$$

Figure 5 presents the resulting CO_2 emissions relative to 2020. These curves represent the emission targets that would be required if they were defined on an annual basis. However, based on the current regulatory design, the CO_2 standard is likely to establish 5-year time steps. Recent market data from the European LDV sector have shown that manufacturers tend to achieve marginal emission improvements until close to the year a target comes into effect, and then rapidly increase decarbonization ambitions (Miller

7 The MPW is calculated as the product of the vehicle's mileage and payload relative to the equivalent for class 5-LH. The ZLEV factor is calculated in two phases, which are described in Appendix B.

and Sen, 2021). Introducing additional interim targets, as opposed to setting targets over 5-year periods, would help enable a consistent decarbonization trend rather than encourage the last-minute approach evident from the LDV market.

We define both the 5-year step and annual reductions necessary to comply with the scenarios we have outlined in Figure 5. We define the 5-year targets consistent with the compliance flexibilities in the HDV standard, whereby manufacturers can earn credits through early emission reductions and can accumulate debts from non-compliance over each 5-year period. We describe the credit/debt system in greater detail in Appendix C. We define the 5-year targets to be the level necessary for credits and debts to net zero over each 5-year period, based on the annual emissions reductions. We assume that the target for 2025 will remain unchanged at its current reduction value of 15% over the baseline.[8] Setting an earlier interim target within the 2025–2030 timeframe would help in achieving a more stringent 2030 target. While we do not explicitly explore this action in this analysis, the results shown in Figure 5 inform the required stringency for any potential interim target.

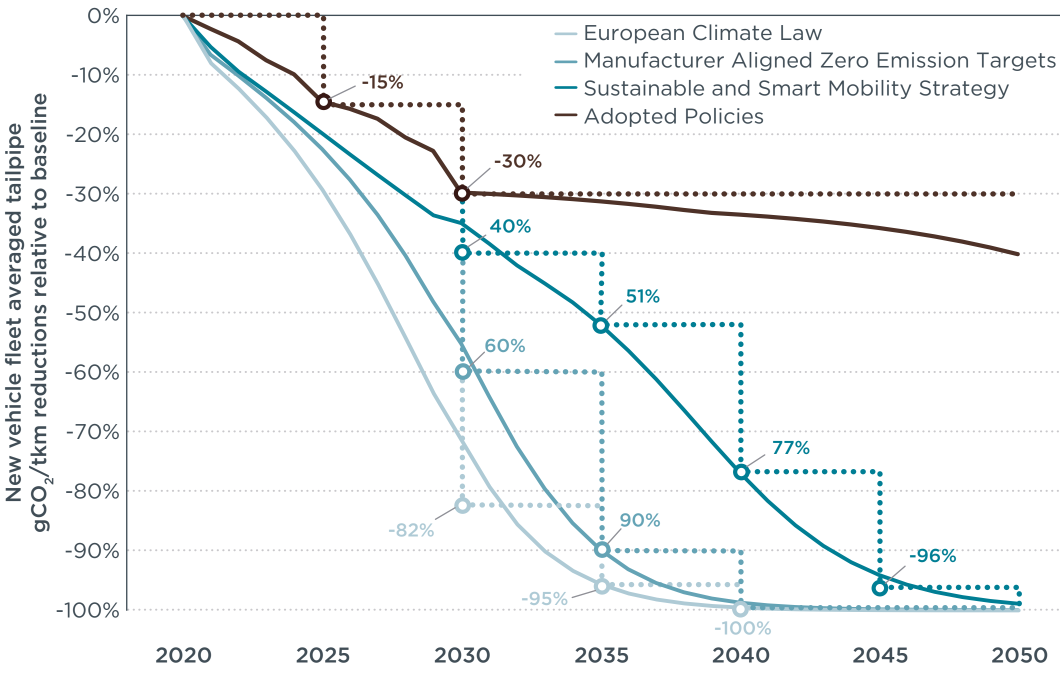

Figure 5. New vehicle fleet averaged annual emissions reduction relative to 2020 and corresponding 5-year targets by scenario.

The 5-year targets established for the Sustainable and Smart Mobility Strategy show the necessary efforts required to align the HDV CO_2 standard with the milestones set out by this strategy. While the milestones are intended to align the transport sector with the European Climate Law, we have shown above that the necessary commitments of the HDV sector fall short of the 98% reduction that is required (see Figure 4).

The current targets announced by major HDV manufacturers across the EU exceed the ambitions of the Sustainable and Smart Mobility Strategy. Major HDV manufacturers have already sent a signal that they are willing to commit to a high level of technology transition. While some uncertainty remains over the resulting share of ZE-HDVs intended under the manufacturer joint pledge for 2040 (ACEA and PIK, 2020), all targets announced for 2025 and 2030 to date have exclusively applied to ZEVs (see Table 2). Increasing the 2030 target to a 60% reduction would enshrine these

8 The standard will be reviewed in the fourth quarter of 2022 and an amendment is unlikely to take place prior to 2023. Thus, we consider updating the 2025 target under this time frame to be unlikely.

manufacture pledges in regulation. In addition, introducing a target for full ICE phase-out in 2040 would ensure that manufacturers invest only in ZEVs, and not in fossil-free vehicles fueled by advanced biofuels or PtX, which raise techno-economic and sustainability concerns. Figure 2 shows the level of ZE-HDV uptake required to comply with these proposed standards.

Aligning the HDV CO_2 standards with the European Climate Law to contribute toward the EU-27's overall goal of net-zero emissions by 2050 would require a drastic increase in the stringency of the standard. Based on the mechanisms for CO_2 calculations in the regulation, the target for 2030 would need to increase from the current 30% to 82%. Targets for 2035 and 2040, which the European Commission will address in its review of the standard in 2022, would need to be 95% and 100%, respectively, to ensure a phase-out of the ICE HDVs compatible with the deep decarbonization necessary to comply with the European Climate Law.

Table 4 presents the 5-year targets necessary to comply with each scenario and the corresponding overall emissions reductions. Interim targets would ensure consistent decarbonization efforts. Lessons learned from the LDV sector show manufacturers tend to delay decarbonization efforts and make significant changes to their fleet portfolio just in advance of the CO_2 standard coming into force (Wappelhorst et al., 2021). We expect a similar response from the HDV manufacturers and recommend setting annual or bi-annual interim targets, as defined by the solid lines in Figure 5, to ensure consistent emission reductions.

CONCLUSIONS AND POLICY RECOMMENDATIONS

The existing HDV CO_2 standard for the EU-27 is incompatible with climate neutrality. The review of the standard in 2022 presents an opportunity for the European Commission to align the reduction ambitions of the HDV sector with the European Climate Law by increasing the stringency of the 2030 target and introducing targets for 2035 and 2040.

This paper analyzes the stringency required by the standard to align the HDV market in the EU-27 with climate neutrality. Based on our analysis, we propose that the European Commission implements the following key changes during the HDV CO_2 regulation review to reduce the sector's CO_2e emissions in 2050 by 96% relative to 2019:

» **Extend the scope of the regulation to include all sales of HDVs, to the extent feasible;**

» **Revise the CO_2 reduction target for 2030 from 30% to at least 60%;**

» **Introduce CO_2 reduction targets of at least 90% for 2035 and 100% for 2040; and**

» **Phase out the fleet-wide multipliers for zero- and low-emission vehicles from 2030.**

Below, we elaborate on these policy recommendations.

The stringency of the HDV CO_2 standards should be tightened and extended to all HDVs to comply with the European Climate Law. Under the currently adopted policies, without further policy intervention, total emission reduction over the 2019–2050 timeframe is limited to 10%. However, to comply with the European Climate Law, HDVs require a near total emission reduction by 2050, which highlights the need to tighten the stringency of this standard. Further inhibiting reduction potential is the scope of the standard, which is limited to just 65% of HDV sales. To achieve deep decarbonization cuts within the sector, the HDV standard should be extended to all HDV classes in the upcoming review, as discussed in greater detail by a recent ICCT study (Ragon and Rodríguez, 2021b).

The guiding milestones set in the Sustainable and Smart Mobility Strategy are incompatible with the European Climate Law. The Sustainable and Smart Mobility Strategy outlines milestones which are intended to align the European transport sector with the long-term climate ambitions of the EU-27. Our analysis has shown that the milestones of this strategy contribute to an 82% reduction in emissions by 2050 relative to 2019—significantly short of the emissions reduction necessary to align with the European Climate Law.

Manufacturer goals for ZE-HDV adoption could put the HDV sector on a pathway close to compliance with the European Climate Law, but a stricter standard is essential to enshrine these commitments. At a minimum, the commitments of HDV manufacturers should be enshrined by the HDV CO_2 regulation. Manufacturers have signaled that they are willing to commit to a technology transition, pledging for sales of ZE-HDVs in 2030 ranging from 35%–60% and committing to only selling fossil-free vehicles by 2040. By accounting for potential efficiency improvements of ICE vehicles and increasing the CO_2 regulation's reduction target from 30% to 60%, the standard could encourage manufacturers to stick to these commitments. Introducing an emissions reduction target of 100% for new HDVs in 2040 would also commit manufacturers to focus on ZEVs as opposed to ICEs powered through PtX and advanced biofuels. Establishing CO_2 standards based on manufacturer announcements would enable a emission reductions of roughly 96% in 2050 relative to 2019, achievable only if manufacturers solely develop ZE-HDVs in the long term.

Full compliance with the European Climate Law requires strong, early action. Compliance with the European Climate Law will require a 98% reduction in overall

HDV CO_2 emissions by 2050 relative to 2019. This reduction can be achieved through significant early action, which the European Commission can encourage by increasing the CO_2 standard from 30% in 2030 to 82% and introducing targets for 2035 and 2040 corresponding to 95% and 100%, respectively. A full phase-out of ICE vehicles would technically be required by 2038 to comply with these standards, but the targets in the current standard are set in 5-year intervals. Introducing annual or biannual targets would allow for an earlier phase-out. While achieving a similar level of annual emissions by 2050 as our Manufacturer Aligned Zero Emission Targets scenario, the European Climate Law scenario achieves an additional 13.6% reduction in cumulative emissions over the manufacturer scenario, which is a vital indicator of reducing global warming potential. Any significant update to the CO_2 standard encouraging ZE-HDV uptake must incorporate a corresponding infrastructural investment to enable sufficient access to charging.

Aligning with the European Climate Law will require increasing the 2030 target from the current 30% reduction requirement to 82%. Manufacturers would meet this target through ICE efficiency improvements and an increase in the ZE-HDV sales share to 65%. At present, manufacturers have announced an average ZE-HDV sales share of 43% for 2030, which would correspond with increasing the CO_2 standard from 30% to 60%. Based on manufacturers' announced willingness to produce ZE-HDVs, increasing the 2030 target to 60% should represent the absolute minimum increase in stringency over the 2022 review of the HDV CO_2 standard.

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APPENDIX A: FLEET MODELING

The age profile of heavy-duty vehicles (HDVs) varies significantly across the EU27. For example, Austria has the youngest HDV fleet, with an average age of trucks and buses at 6.4 years and 4.4 years, respectively, in 2019. Greece has the oldest HDV fleet, with trucks and buses at respective average ages of 21.2 and 19.9 years (ACEA, 2021). The wide range of HDV age profiles requires any model of the future evolution of the EY27 HDV fleet to to represent an accurate depiction of the fleets' survival.

Age disaggregated stock in a specific year can be calculated by applying a survival profile, which quantifies the probability that a vehicle of a certain age will either be scrapped or exported, to historic sales, and appending the result to the level of secondhand imports disaggregated by age, as shown in Equation 1, where Y is the year, v is the vintage of the vehicle, and SHI is the stock of secondhand imports.

$$Stock_{Y,v} = SHI_v + (Sales_{Y-v} \times Survival_v)$$

Thus, for countries with a low level of secondhand imports, HDV stock disaggregated by age can be determined with the historic sales and survival profiles alone.[9] To this end, we modeled survival profiles in this analysis by drawing upon Member State-specific sales data from 1988 to 2018 (IHS Markit 2021),[10] and fitting a survival curve capable of representing national stock values in 2018 through Equation 2:

$$Stock_Y = \sum_{n=0}^{30} Sales_{Y-n} \times Survival_n$$

Where Y is the year, and the survival is approximated by the following function:

$$Survival_n = \frac{1}{1 + e^{\alpha(n-\beta)}}$$

Where α represents a function parameter defining the slope of the survival profile, and β represents the year at which the probability of survival is 0.5.

To calculate these function parameters, this analysis applies an optimization solver to apply values to these survival function parameters for each country and applies the resulting survival curves to the historic sales values to replicate the 2018 stock values and average age presented in ACEA (2021) as close as possible. To conduct this optimization, we applied the Python function scipy optimize.minimize and applied the Powell method to select values of α and β, applying bounds for α to fall between 0 and 1, and bounds for β to fall between 0 and 30. These constraints were chosen for α as values above 1 presented unnaturally high scrappage rates and below 0 presented inverted scrappage rates. We chose constraints for β based on market data; this factor represents the year by which the probability of survival reaches 50%, and we deemed it unlikely that this point is reached beyond 30 years of vintage.

We conducted this optimization to fit a survival profile to countries with a young average fleet age, such as Austria, which are expected to have a low level of secondhand HDV imports, allowing for the total stock to be determined by applying a survival profile to the historic sales alone. For these countries, this optimization method is able to replicate closely the 2018 stock values and average age presented in ACEA (2021) from the historic sales. For countries with a high level of secondhand imports, we could not apply this approach, as no preexisting information was available on these

9 These survival profiles represent both the retirement of the fleet, whereby the vehicle is scrapped and decommissioned from use, and the export of the vehicle for a secondary life outside of the Member State.

10 Data from 2005-2018 are based on content supplied by IHS Markit (2021). Data prior to 2005 were back-casted following the trend of overall sales data from the IEA's Mobility Model.

imports. Thus, we first applied the survival functions determined for countries with low levels of secondhand imports to countries with high levels of these imports, making some adjustments to account for regional differences.

We observed little variance in the α factor across those countries in the optimization. For this reason, we assumed a constant α factor across all countries. Evidence from the optimization exercise showed that the β factor increased as GDP per capita decreased, signifying that countries with lower income delay the retirement of vehicles compared to higher income countries. We then applied a regression of GDP per capita to the calculated β factors from these countries and extended it to countries with a high level of secondhand imports. The resulting survival curves are shown in Figure A1.

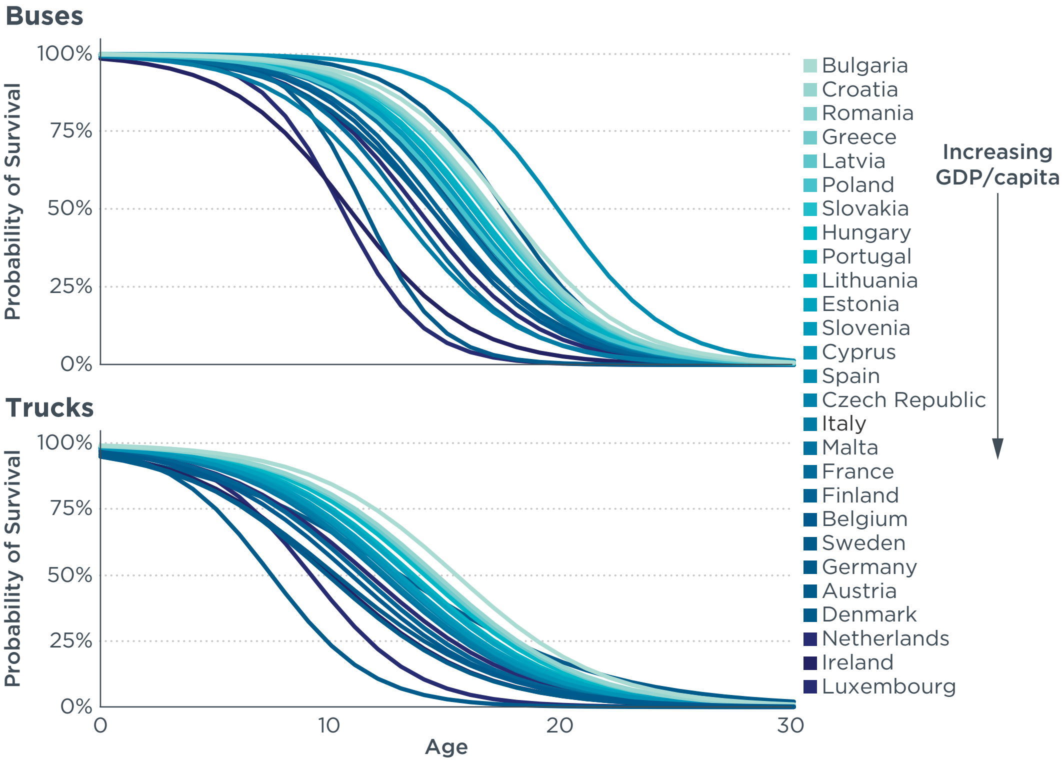

Figure A1. Survival profiles applied in this analysis.

Finally, we applied the survival profiles to the historic sales of countries with a high proportion of secondhand imported vehicles to calculate the portion of stock in the base year which is from firsthand vehicles. We then calculated the difference between these stock values and the total stock from ACEA. The difference was determined to be the proportion of vehicle stock which were secondhand imports. Finally, we applied an age distribution to the secondhand imports to align the average age of the total stock with that of ACEA. Figure A2 describes this process.

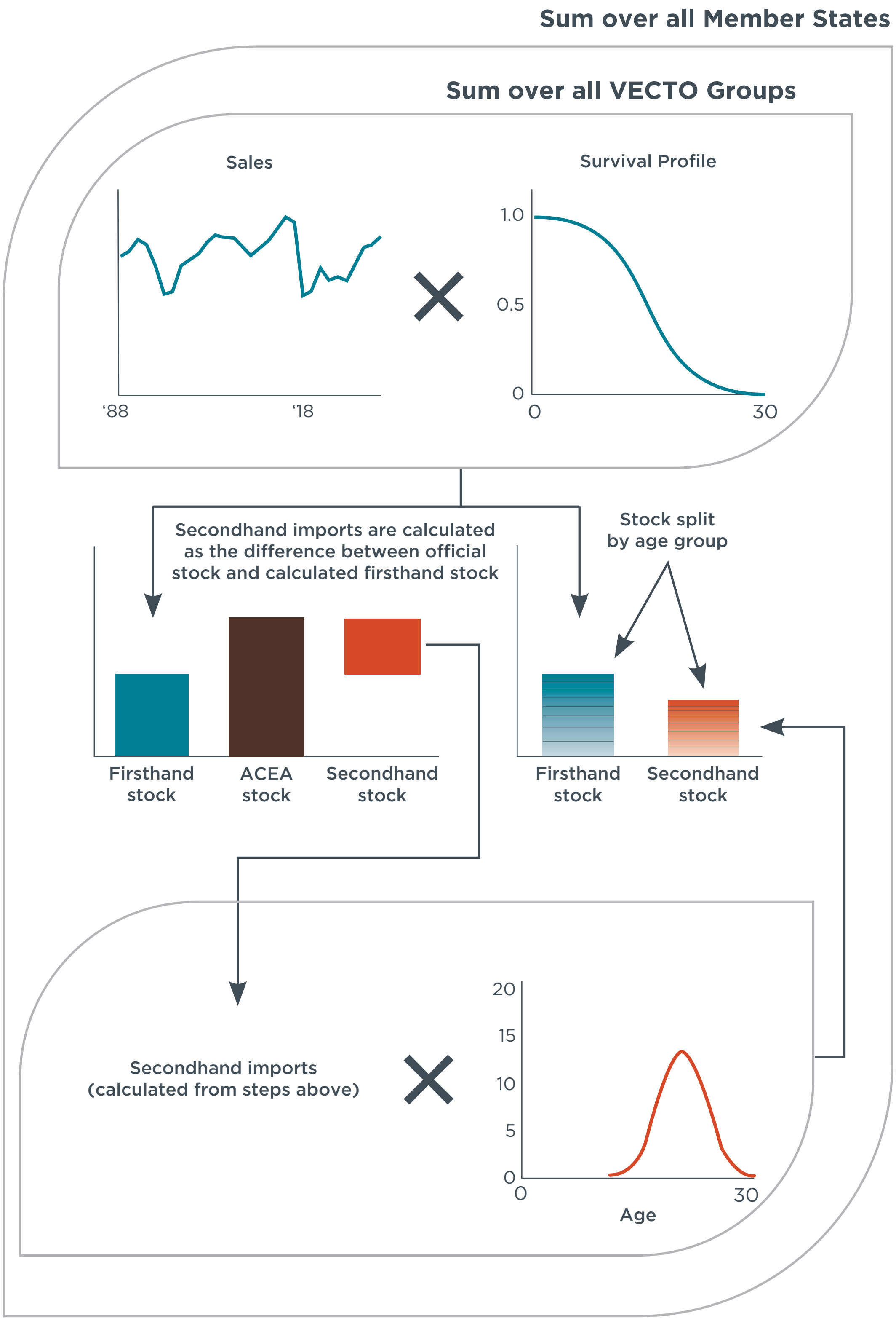

Figure A2. Calculation of HDV stock by age profile and VECTO grouping.

APPENDIX B: ZLEV FACTOR

The HDV CO_2 regulation aims to reduce the specific average tank-to-wheel CO_2 emissions from new HDVs by 15% in 2025 and by 30% in 2030 relative to a 2019 baseline. These targets apply to the fleet averaged gCO_2/tonne-kilometer (t-km) for each manufacturer.

Increasing the sales share of zero- and low-emission vehicles (ZLEVs) enables manufacturers to contribute toward these targets in two phases: the super-credits phase, which runs to 2025, and the benchmark phase, which runs to 2030.

During the super-credits phase, vehicles with zero emissions are double-counted toward the target. Low-emission vehicles, which have average emissions of under 50% of the subgroup's baseline, have a linearly increasing contribution starting at a single counting at 50% and increasing to double counting at 100%. A ZLEV factor is also applied which, during the super-credits phase, is calculated through the following formula, where V is the total number of regulated HDVs, V_{conv} is the total number of regulated HDVs with conventional powertrains, $ZLEV_{in}$ is the resulting number of ZLEV vehicles within the regulated groups after accounting for super-credits, and ZEV_{out} is the number of ZEV vehicles outside of the regulated groups multiplied by 2.

$$ZLEV\ Factor = \frac{V}{V_{conv} + ZLEV_{in} + ZLEV_{out}}$$

During the benchmark phase that runs from 2025 onward, manufacturers with a ZLEV share of 2% or more are rewarded through a different ZLEV factor, which is calculated by the following formula:

$$ZLEV\ Factor = \begin{cases} 1, & \text{if } ZLEV_{sales\ share} \leq 2\% \\ 1 - (ZLEV_{saleshare} - 2\%), & \text{if } ZLEV_{sales\ share} > 2\% \text{ and } \leq 5\% \\ 0.97, & \text{if } ZLEV_{sales\ share} \geq 5\% \end{cases}$$

As shown in the equation above, the ZLEV factor is capped at a minimum of 0.97, meaning at ZLEV shares (including regulated and unregulated classes) greater than 5%, the CO_2 targets are only relaxed by a maximum of 3%. Low-emission vehicles (LEV) are counted between 0 and 1, depending on their CO_2 emissions. For example, a LEV with CO_2 emissions 75% lower than the subgroup's baseline would count as 0.5 in the ZLEV sales share calculation.

APPENDIX C: COMPLIANCE FLEXIBILITIES

The HDV CO_2 regulation includes flexibilities for compliance with the standard. Manufacturers may accumulate credits over the regulation period by surpassing the standard's requirements. For the interim years surrounded by the regulatory period, overcompliance is calculated based on the reduction trajectory, which is a linear reduction from 0% to 15% of the baseline emissions over the period 2019–2025, and a linear reduction from 15% to 30% of the baseline emissions over the period 2025–2030.

In the first interim period, manufacturers can only use the credits they accumulate between 2019 and 2024 for compliance in 2025; the credits are not valid thereafter. Similarly, in the second interim period, credits that manufacturers accumulate between 2025 and 2030 can be used for compliance in 2030, while manufacturers accrue debts if their fleet emissions surpass 15% of the baseline emissions during this period. All debts must be cleared by 2029, and manufacturers cannot carry over accumulated credits or debts to 2030. These restrictions are depicted in Figure C1.

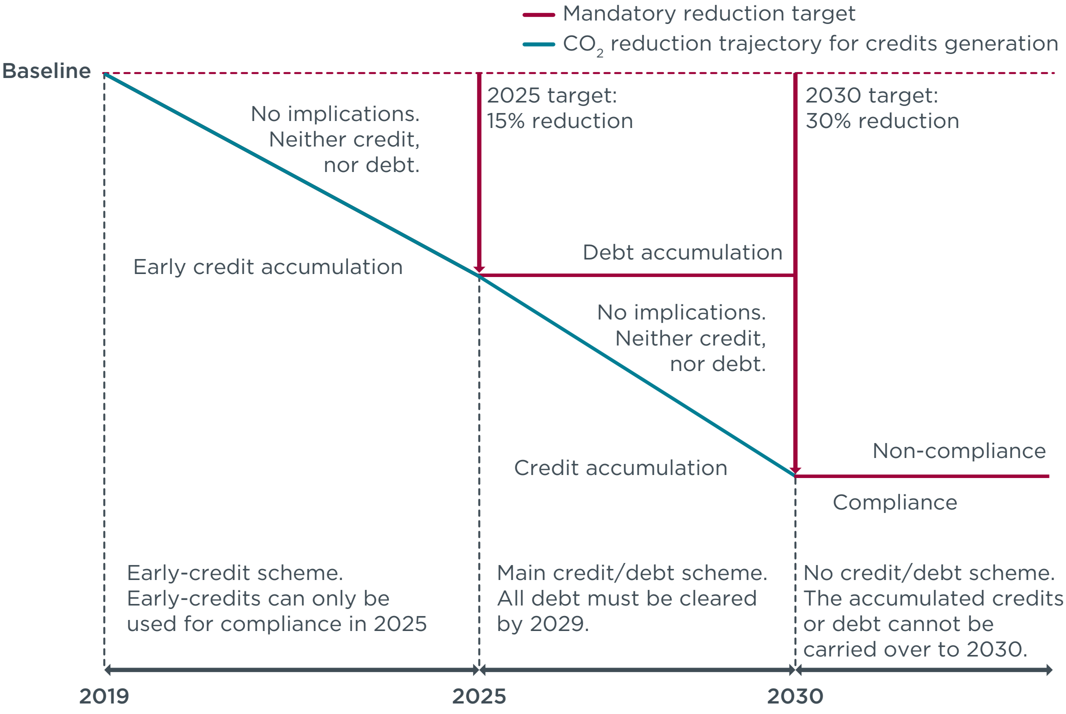

Figure C1. Illustration of the credit/debt system for compliance flexibility. Source: Rodríguez (2019).

Under the current standard, between 2025 to 2029, if the total debt is higher than 5% of the product between a manufacturer's target and the number of vehicles, the manufacturer is required to pay a penalty of €4,250 per vehicle for each gCO_2/t-km of excess emissions. From 2030 onward, CO_2 emissions above the target will result in immediate financial penalties of €6,800 per vehicle for each gCO_2/t-km of excess emissions.

APPENDIX D: ZE-HDV SALES SHARES

Table D1. Share of ZE-HDV sales in 5-year increments for each technology transition class and scenario in this analysis.

	Technology Transition Speed	2019	2025	2030	2035	2040	2045	2050
Adopted Policies	Fast	4%	7%	12%	18%	27%	38%	50%
	Medium	1%	1%	2%	4%	7%	12%	20%
	Slow	0%	0%	0%	1%	2%	4%	10%
Sustainable and Smart Mobility Strategy	Fast	4%	40%	87%	98%	100%	100%	100%
	Medium	1%	1%	8%	32%	73%	94%	99%
	Slow	0%	1%	5%	21%	61%	90%	98%
Manufacturer Aligned Zero Emission Targets	Fast	4%	24%	63%	90%	98%	100%	100%
	Medium	1%	10%	52%	91%	99%	100%	100%
	Slow	0%	5%	35%	84%	98%	100%	100%
European Climate Law	Fast	4%	40%	87%	98%	100%	100%	100%
	Medium	1%	21%	73%	96%	100%	100%	100%
	Slow	0%	12%	57%	93%	99%	100%	100%