Energy Policy 159 (2021) 112640

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

CO_2 fleet regulation and the future market diffusion of zero-emission trucks in Europe

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ARTICLE INFO

Keywords:
Electric truck
Zero emission vehicle
CO_2 fleet regulation
Climate policy

ABSTRACT

Fuel economy regulation is a powerful instrument to reduce CO_2 emissions of vehicles and has recently been extended to heavy-duty vehicles. In Europe, truck manufacturers are required to reduce the CO_2 emissions of newly sold vehicles by 30% until 2030 compared to 2019/2020. Accordingly, several manufacturers have announced the introduction of zero emission vehicles (ZEVs) such as battery electric or fuel cell trucks. However, the sales shares of zero emission trucks to meet the targets have not been analyzed in the literature yet. Here, we derive sales share scenarios for zero emission trucks in Europe based on emissions reduction options and their associated costs. We find that manufacturers will require at least 4–22% of their newly sold heavy-duty vehicles to be zero emission in 2030, depending on their strategy to improve their diesel trucks. This implies a stock share of 2–11% for ZEV trucks in Europe in 2030. Yet, high sales shares for ZEVs and the super credits granted by the regulation allow manufacturers to meet their target with little CO_2 reduction in the conventional fleet leading to low actual emission reduction.

1. Introduction

The European Union (EU) aims for climate neutrality by 2050 (European Commission, 2018). Today, about one quarter of the energy-related greenhouse gas (GHG) emissions in Europe stems from transport (European Commission, 2016) and heavy-duty vehicles (HDV) above 3.5 tons gross vehicle weight (GVW) are responsible for 6% of total energy-related GHG emissions in the EU (European Commission, 2019). Accordingly, the transport sector must reduce GHG emissions significantly. Yet, the fuel efficiency of HDV has remained almost constant for more than a decade (Muncrief and Sharpe, 2015). Therefore, the EU has set percentage-based CO_2 reduction goals of 15% and 30% for the years 2025 and 2030 compared to 2019/2020 emissions levels for HDVs in Regulation (EU) 2019/1242.

The aim of the present paper is to determine the impact of the CO_2 reduction targets on the market penetration of zero emission vehicles (ZEV) in the EU truck market. Today, the HDV fleet consists almost entirely of diesel vehicles. We compare future CO_2 emission reduction potentials of internal combustion engine vehicles (ICEV) for 2025 and 2030 to the emission targets as defined by Regulation (EU) 2019/1242. The gap, if existing, needs to be closed by ZEVs to avoid penalties.

The outline of the paper is as follows. Section 2 sums up the policy background and the existing literature. Section 3 describes the vehicle sales data and the calculations. Section 4 contains the results. A discussion of our findings is provided in section 5 and we conclude the paper with a summary and conclusions in section 6.

2. Policy background and existing literature

2.1. Policy background

In line with the EU's goals to reduce CO_2 emissions in the transport sector, Regulation (EU) 2019/1242 introduces CO_2 emissions requirements in the heavy-duty market segment for the first time in Europe. Regulation (EU) 2019/1242 sets a CO_2 limit for the newly sold vehicles of each manufacturer. The actual values that need to be achieved are a 15% reduction compared to baseline from 2025 onwards, and a 30% reduction from 2030 onwards (European Commission, 2019). The baseline CO_2 emissions level are calculated for the newly sold vehicles during the reference period 1 July 2019–30 June 2020. The Commission expects to publish this data by April 30, 2021 (European Commission, 2019).

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https://doi.org/10.1016/j.enpol.2021.112640
Received 21 December 2020; Received in revised form 31 August 2021; Accepted 27 September 2021

The regulation affects HDV classes in four categories: rigid lorries with a 4 x 2 axle configuration and GVW of over 16 tons, tractors with a 4 x 2 axle configuration and GVW of over 16 tons, and all rigid lorries and all tractors with a 6 x 2 axle configuration. These four groups are classified by the EU's Vehicle Energy Consumption calculation Tool (VECTO) as group 4, 5, 9, and 10, respectively. These HDVs account for approx. two third of all HDV CO_2 emissions (European Commission, 2019). The average specific CO_2 emissions are then calculated for each manufacturer based on reported CO_2 values, expected mission profile weights (i.e. type of driving condition), number of vehicles in a subgroup sold, and expected average payload. The resulting average specific CO_2 emissions are used to determine if the manufacturer satisfies the respective targets of 15% and 30% reductions for 2025 and 2030. Manufacturers that do not meet their targets face fines of 4,250 € for every g CO_2/tkm from 2025 and 6,800 € for every gCO_2/tkm from 2030 onwards (European Commission, 2019).

A zero- or low-emissions vehicle (ZLEV) is defined as having zero or less than half of the reference tank-to-wheel CO_2 emissions. Manufacturers that sold ZLEV receive a discount on their average specific CO_2 emissions. Two ZLEV credit systems can reduce a manufacturer's average specific CO_2 emissions. Until 2025, a super crediting system will be used. A ZEV counts as two vehicles and a LEV will count between 1 and 2, depending on its specific emissions in relation to the average emissions in its subgroup (European Commission, 2019). The ZLEV super credits system will be replaced by a benchmark-based crediting system with a 2% benchmark from 2025 onwards. If a manufacturer's ZEV fleet share is higher than this, the manufacturer receives a 1% discount to their average specific CO_2 emissions for every percentage point over the benchmark (yet at least three quarters of the ZLEV fleet used for the calculation must be subject to the emissions standards (European Commission, 2019)). The maximum ZLEV discount allowed under both systems is 3% (1.5% from non-subjected vehicles is included in this number). Additionally, manufacturers can collect credit points in credit-debt-system between 2025 and 2029 (cf. Regulation (EU) 2019/1242 for details).

To summarize, the EU's fleet targets for HDVs in four categories include a 15% reduction by 2025 and a 30% reduction by 2030 compared to 2019/2020. Manufacturers may receive some discount through ZLEV in their fleets, including in the years leading up to 2025.

2.2. *Existing literature*

We perform a literature overview of emission reduction potential and associated costs for various technologies (CE Delft et al., 2018; Delgado et al., 2017; Delgado and Lutsey, 2015; Dünnebeil et al., 2015; Heidt et al., 2019; Kluschke et al., 2019; Krause and Donati, 2018; Meszler et al., 2015; Moultak et al., 2017; Norris and Escher, 2017). There are different technology solutions to improve fuel economy of diesel HDV with individual CO2 reduction potentials that can be combined into "packages" or combinations of certain technologies. Multiple technology packages are then applied to a simulated vehicle in the EU's VECTO. There are eight main categories of reduction technologies: aerodynamics, tires, mass reductions, transmission improvements, Advanced Driver Assistant Systems (ADAS), engine improvements, and alternative powertrains. An overview of the reduction potentials and associated costs cited in the literature is provided in Section 3 below.

There is a limited number of studies on the future market penetration of electric or fuel cell HDVs. Kluschke et al., 2019 and Plötz et al., 2019 provide an overview of existing studies on the market diffusion of alternative fuel HDV. About half the studies use simulation models, and many have normative goals (with future targets defined and then backtracked to present normative scenarios). Prior to 2013, studies focused more heavily on alternative liquid fuels – such as LNG and biofuels – as a viable option, but after 2013 alternative powertrains have become more appealing, and alternative liquid fuels alone were no longer deemed sufficient (Kluschke et al., 2019; Cong et al., 2017; Ewing, 2019; Rodríguez, 2020b). The existing literature does not see one best technological solution. Long-haul applications may benefit more from fuel cell electric vehicles (FCEV), for example, while regional delivery may benefit more from battery electric vehicles (BEV) due to infrastructure costs. Kluschke et al. (2019) depicted the market diffusion calculated by each study in a reference and climate protection scenario. The authors note the limitations of over-optimism, as almost 100% of HDVs are currently diesel.

Siskos and Moysoglou (2019) studied different policy scenarios and their ramifications, and found that ZEV take-up starts at the 30% CO_2 emissions reduction level. They used a multi-agent choice model with constraints that simulate the equilibrium of the transport market. They observed that most companies would benefit from implementing the fuel reductions technologies, before considering ZEV, which would be a major pay-back in terms of fuel savings overall. In another study, Brauer (2011) predicted a 40–50% market penetration of hybrid HDVs in 2030 using an innovation diffusion model with three market scenarios of no, some and large incentives supporting hybridization. In Mathieu et al. (2020), the authors introduced three different scenarios with future ZEV sales shares. The authors defined their scenarios based on given expert opinions of ZEV shares in the future (Industry-Baseline), some automaker's announcements for electrification goals (EV-Leaders), and a calculated amount of ZEV required to achieve climate neutrality by 2050 (Road-2-Zero). Their primary research goal was to determine where prioritizing charging infrastructure will help the uptake of ZEV HDVs, and was thus more top-down with their assumptions of ZEV share in the three scenarios to meet this research goal. The expected ZEV shares in 2025 and 2030 proposed by Mathieu et al. (2020) are between 1.3% and 10% ZEV sales in 2025 and between 15% and 30% ZEV sales in 2030.

In summary, the existing literature does not agree on the future market diffusion of ZEV and no dominating alternative fuel technology is identified. There is a significant spread between the forecasted market shares in the studies. The impact of individual policies (such as Regulation (EU) 2019/1242) on ZEV market diffusion within the HDV sector also needs further work.

2.3. *Our contribution*

The present paper aims to analyze the effect of the existing fuel economy standards in the EU on ZEV HDV market uptake. As described in section 2.1, we consider vehicles from group 4, 5, 9 and 10, which are used in VECTO to calculate the CO_2 fleet targets. We determine the ZEV share that is required when making strategic investments in certain technologies such as Diesel HDV improvement or ZEV HDVs. ZEV mandates such as in California clearly lead to a direct increase in ZEV sales. However, the actual impact of ambitious CO_2 fleet targets on ZEV sales has to the best of the authors knowledge not been analyzed for HDVs in Europe before. Fritz et al. (2019) analyzed the impact of the European fleet regulation on ZEV sales for passenger cars, but did not consider HDVs.

Our work thus differs from previous work in several aspects. First, we study the fleet regulation effect on ZEV HDV sales in Europe. Second, our methodology is highly transparent by extrapolating existing fuel economy combined with emission reduction targets.

3. Data and methods

3.1. *HDV emissions reduction potential*

CO_2 emission reduction technologies for conventional HDV and their associated costs have been taken from a survey of the existing literature. The various reduction technologies can be implemented in different combinations or so-called "packages". To determine the most cost-effective technologies – i.e. those that achieve a high CO_2 reduction for less additional investment – the expected costs of each technology are also examined. Table 1 provides an overview of these packages and

Table 1
Diesel motor fuel savings potential and associated costs for technology packages for group 5 vehicles.

Package	Technologies Included	Total Fuel Reduction Potential	Total Costs [2015€]
Aero package “moderate,” modified	Roof spoiler plus side flaps, Side and underbody panels at truck chassis, Aerodynamic mud flaps	−8.1%	2,674€
Engine, modified	Improved turbocharging and EGR, reduce friction + improve water/oil Pumps, Improved lubricants, Down speeding with optimized map	−7.1%	2,632€
Hybrid Electric Vehicle (HEV)	Full Hybrid best vehicle (current legislation) 80 kW electric motor continuous power/6 kWh Battery capacity nominal, no plug-in vehicle	−4.2%	14,512€
Aero package “advanced” modified	Rear view cameras instead of mirrors, Redesign, longer, rounded vehicle front	−3.9%	3,180€
ADAS	PCC (w/Eco-roll, w/ESS)	−2.3%	1,930€
Auxiliaries, modified	Electric hydraulic power steering, Air compressor, Engine Cooling fan	−2.0%	675€
WHR	Waste Heat Recovery	−2.1%	5,000€
Transmission	Reduced drivetrain losses	−1.5%	250€
Speed limiter 80 km/h	Speed limiter 80 km/h	−2.7%	0€
Low Rolling Resistance RR truck + trailer “moderate"	Low rolling resistance tires on truck/tractor + trailer	−12.6%	420€
Aero package “trailer"	Side and underbody panels at trailer chassis, Boat tail trailer (50 cm)	−6.2%	2,750€
Light weighting truck + trailer	Light weighting strong reduction truck/tractor including trailer	−3.6%	4,234€
Low RR truck + trailer “advanced"	ATIS on truck and trailer, Wide-base single tires	−1%	1,315€
*Low RR “moderate” **	*Low rolling resistance tires on truck/tractor*	*−6.2%*	*210€*
*Light weighting **	*Light weighting strong reduction truck/tractor*	*−1.4%*	*3,112€*
*Low RR “advanced” **	*ATIS on truck Wide-base single tires*	*−0.7%*	*1,045€*
Total with trailer optimization measures		**44.8%**	**39,572 €**
Total without trailer optimization measures		35.2%	35,220 €

Adapted from: CE Delft et al. (2018). Notes: Packages modified from those proposed by CE Delft et al. (2018). Reduction Potential is with reference to the weighted potential across four different cycles and loadings and with reference to a baseline vehicle. Euro amounts expressed in 2015€. *Last three packages are for truck/tractor only, and do not include trailer measures.

costs for a group 5 vehicle with and without a trailer (CE Delft et al., 2018). Please note that the reductions are compared to a baseline vehicle, defined as having none of the mentioned reduction technologies. Further scenarios and literature values for reduction potentials and associated costs both for diesel and non-diesel HDVs are given in Table 3 and Table 4 in the Appendix and further details are given in Breed (2020).

The list of technical CO_2 reduction options show that it is generally possible for manufacturers to achieve the 2025 emission goal of a 15% reduction solely by using improvement technologies with diesel engines. This is also likely to be more cost-efficient than exploring alternative powertrain options in the short-term. However, the goal for 2030 of a 30% emission reduction is more difficult. In Norris and Escher (2017), tractor-trailer combinations were found to have a potential reduction of 33%, compared to an average 2015 vehicle. Likewise, the total reduction potential in Table 1 amounts to 35% compared to the baseline vehicle without the trailer and almost 45% with the trailer. However, this is achieved only if all available technologies are implemented in 100% of the fleet. As the manufactures need time to add new technologies to all their makes and models and model variants, a 100% integration of a new technology in the fleet takes many years (see e.g. Mock and Meyer (2019) and Bieker et al. (2019) for new technologies in cars). The list also includes efficiency improvements to trailers, as well as some technologies that are not yet considered by VECTO, such as Tire Pressure Monitoring Systems. Furthermore, the adoption of some of the technologies in the fleet are difficult to steer by the manufacturers such as, e.g., low rolling resistance tires or speed limiters. Accordingly, it is very unlikely that manufacturers can achieve 30% reduction without LEV or ZEV.

The estimated costs for achieving this reduction for both tractor trucks and rigid trucks are in Table 2.

The data shown here refer to group 5 vehicles, which are by far the most important for the fleet targets. An overview of vehicle classes 4, 5, 9 and 10 and the assumed possible penetration of the technology packages can be found in Table 5 in the appendix.

To summarize, a 15% reduction of CO_2 emissions should be possible with the diesel improvement technologies mentioned in the literature. A 30% reduction may also be theoretically possible, and the per-vehicle additional capital costs to achieve this are still cheaper than the additional costs of a zero emission vehicle, at least without additional funding.

3.2. EU HDV sales data

Unlike in the passenger car segment, there is no official heavy-duty market emissions data. There have been, however, research studies conducted on the various sales mixes of manufacturers in the heavy-duty market, as well as new vehicle registration figures and a preliminary report on average emissions provided by the European Automobile Manufacturer’s Association (*Association des Constructeurs Européens d’Automobiles* – ACEA). The data available in these studies does not include vehicle registrations sorted by manufacturer *and* by vehicle group for the reference period. For our analysis, we use percentages of each vehicle category (groups 4, 5, 9, and 10 defined in VECTO) sold by each manufacturer -their sales mixes-from a report from the International Council of Clean Transportation (ICCT), and assumed them to remain constant for 2019 (Bieker et al., 2019; Piere-Louis and Rodriguez, 2020). Additionally, the ACEA publishes data on new registrations

Table 2
Additional capital costs per vehicle to achieve −30% reduction in 2020 euros.

Truck Type	Costs for Diesel Improvement Technologies	Costs for Zero-Emission Truck
Tractor Truck	26,000 € - 45,000 €	41,700 € - 60,500 €*
Rigid Truck	**16,200 € - N.A.****	**69,000 € - 73,500 €***

Sources: CE Delft et al., 2018; Dünnebeil et al., 2015; Hall, 2018; Hall and Lutsey, 2019; Heidt et al., 2019; Meszler et al., 2015; Moultak et al., 2017; Norris and Escher, 2017. From the literature, an estimate of additional capital costs on a per vehicle basis to achieve a 30% reduction in emissions in diesel trucks, compared to the estimated costs required to manufacture a ZEV. For full technology package details and costs, see Tables 3 and 4. *BEV represent the lower end of the price range, FCEV the upper end. **Cost information was not available in many studies for a −30% reduction in rigid trucks. At least a −15% reduction was however reported in many studies, with costs ranging from 14, 200–53,900 € in 2020 €.

from all vehicle markets in the EU and the European Free Trade Association EFTA monthly. The new registrations are provided by country and by manufacturer, but beyond a differentiation of light-, medium-, and heavy-duty, there is no further subdivision into vehicle category such as those defined by VECTO. The ACEA also published a report on preliminary values of CO_2 emissions for the first half of the regulatory reference period (the third and fourth quarters of 2019) ((ACEA - European Automobile Manufacturers' Association, 2020a). These data are averages across each subgroup. The subgroups defined by VECTO are simply the vehicle groups divided further by use case, such as 4-RD (group 4 regional delivery) or 5-LH (group 5 long-haul).

Using the total registrations per manufacturer from the ACEA and the sales mixes per vehicle group provided by the ICCT, we estimate the number of vehicles in each VECTO subgroup sold by each manufacturer. These figures correspond to the share per subgroup – i.e. variable $share_{,sg}$ – used in the calculation for emission targets according to Regulation (EU) 2019/1242 (see below). Due to insufficient data that would ensure anonymity of manufacturers (at least five selling in that category), the ACEA decided not to provide emissions data for 4-UD. Since this subgroup amounted to only 0.4% of sales, we neglected this subgroup. We provide the number of vehicles by subgroup in Table 6 in the Appendix.

Finally, we used Eurostat data to find the percentage of vehicle stock under five years old in 2018 (Eurostat, 2020). This was used to model stock evolution, i.e. to estimate how many ICEVs and ZEVs will be in operation in 2030.

3.3. *ZEV diffusion model*

The general modelling approach of the present study is as follows: (1) calculate the targets that each manufacturer needs to meet, (2) calculate what their expected emissions might be, and (3) supplement the diesel fleet with enough ZEV to account for this gap, if it exists, accounting for the ZLEV discount. This methodology is roughly similar to the one presented in Fritz et al. (2019).

For step (1), to calculate the CO_2 targets, average emissions by subgroup from the ACEA and the calculated shares of vehicles per manufacturer per subgroup were extrapolated to determine a manufacturer's overall fleet target. To calculate the expected emissions in step (2), the diesel improvement technologies and their costs are examined. Using different groupings of technology packages, several strategic scenarios that a manufacturer might follow are developed, which dictate when a manufacturer's decision to start to produce ZEVs occurs (see below for the scenarios). To confirm how realistic these scenarios might be, several interviews were conducted with three of the main HDV manufacturers in the market. These reduction potential scenarios then imply a reduction of fuel consumption in the diesel fleet, leading to different values of expected emissions depending on what strategy a manufacturer follows. Fig. 1 illustrates the ZEV diffusion model. The formulas are from Regulation (EU) 2019/1242 and are how the EU will calculate both targets and emissions. The Figure shows the model with the data sources and the interconnection between the calculation steps.

The uppermost part of the model diagram in Fig. 1 displays the CO_2 targets per subgroup. The leftmost part details the information that resulted in the reduction potential scenarios. The middle section details the fleet shares per subgroup calculation discussed in the previous section. Finally, the expected emissions (CO_2) and targets (T) per manufacturer are determined, using a weighting factor defined by the regulation that weights all subgroups by the group 5 long haul. The gap between these two numbers – and accounting for the ZLEV benchmarking discount provided by Regulation (EU) 2019/1242 – is the percentage of ZEV that a manufacturer will need to avoid paying fines. The steps involved in the calculation are as follows:

1. Check if $CO_2 > T$.
   a. If $CO_2 < T$, there is no need of additional ZEV in the fleet.
   b. If $CO_2 > T$, calculate the percentage of fleet to be replaced by ZEV such that $CO_2 = T$.
2. Check if percentage of ZEV share >2% (the benchmark credit).
   a. If ZEV share ≤2%, the manufacturer receives no ZLEV discount, and the ZEV share from step1, is the ZEV share needed to reach the target.
   b. If ZEV shares >2%, the manufacturer receives a discount of maximal 3% off their CO_2 value.
3. Calculate discounted CO_2 value. Repeat step 1. The calculated ZEV share is what is needed to reach the target.

This procedure results in the ZEV sales shares per manufacturer in a given technology scenario.

Please note that vehicle load is an average value per vehicle category given from the EU's official calculation procedure. No additional assumptions concerning load factors have been made, as the focus here is not so much on real world energy consumption but energy consumption

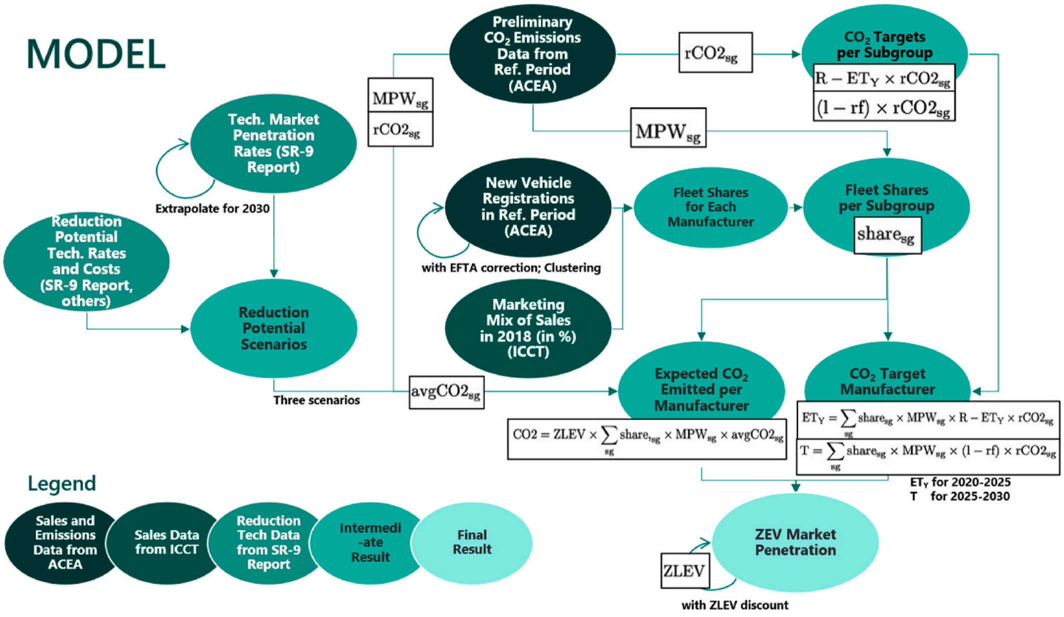

Fig. 1. Illustration of model breakdown.

according to EU official calculations, as the OEMs need to meet the official criteria in order to avoid penalties.

We obtain the ZEV stock from the following simplified stock model. Following Eurostat's database on lorries and commercial vehicles by age (Eurostat, 2020) reveals that of all commercial vehicles in the EU under 3.5 tons gross vehicle weight in 2018, only 9% were under five years old and for tractors that number was 41% (Eurostat, 2020). Hence, we assume that 41% of the stock of HDVs sold before 2025 will no longer be in service in 2030 and that any vehicle sold prior to 2020 will no longer be in service in 2030. For simplicity, all vehicles sold from 2025 to 2030 are assumed to be in operation in 2030. The overall market growth expected in HDV-related transport from 2010 to 2030 is an increase of 39% (BMVI, 2016). We employ a linear extrapolation of a 19% market growth from 2020 to 2030 to calculate total expected vehicle sales. The combination of absolute ZEV sales and the simplified stock calculation results in the ZEV stock in 2030.

3.4. Reduction potential scenarios for diesel HDVs

As mentioned above, part of the literature deems a 30% reduction in fuel consumption feasible only using diesel improvement technologies, if 100% of the emission reduction technologies were implemented in 100% of the newly sold fleet. It is highly unlikely that the entire fleet would have all technologies, and this also includes trailer improvement measures (CE Delft et al., 2018). Thus, manufacturers have a strategic decision to make in terms of continual investment in diesel HDVs or switching to some ZEV. As this is a strategic manufacturer decision, we use three scenarios to capture this.

First, the ICEV-Focused scenario chooses the most per-capital cost-effective route on a short-term basis and invests in all possible ICEV technologies at the expected penetration rates for the next decade. This does not mean the company does not invest at all in ZEV but merely that a manufacturer focuses on ICEV for cost reasons and delays larger investing in ZEV. Second, another strategy evaluates the technology packages by how cost-effective they are in terms of expense and reducing fuel consumption. Hybridization, for example, does reduce fuel consumption by 4.2%, but also costs around 15,000 € for a group 5 vehicle. To determine what the cost per fuel saving potential might be for deciding to implement a specific technology package, the cost-fuel reduction potential curve for Group 5 vehicles can be seen in Fig. 2. Each package is examined by its additional vehicle capital cost per a 1% reduction in fuel consumption. The x-axis represents the CO_2 savings compounded over the packages. There are two major spikes in the graph that can be used as cut-off points for strategic decisions. The first larger jump in the cost-fuel consumption curve appears with engine modifications costing about 370€ per 1% reduction and the advanced aerodynamics package costing about 815€ per 1% reduction. The Low-Hanging Fruits Strategy defines this jump as the cost cut-off point and thus implements only technology packages that require an additional investment of less than 500€ per a 1% reduction.

The third strategic scenario is the ZEV-Focused scenario. This strategy recognizes that while the initial capital costs are higher for a ZEV, the long-term benefits of investing earlier will pay off in 2030 and beyond. This scenario takes only those packages identified in the Low-Hanging Fruits Scenario that do not directly deal with the diesel powertrain. By investing money only in those packages that are not powertrain-specific, a manufacturer will be able to enjoy some short-term benefits from reduced fuel consumption in the diesel fleet and long-term benefits of having a high-efficiency heavily electrified fleet. Below are the technology packages in each of the three strategic scenarios.

- **ICEV-Focused Strategy** contains all improvement technology packages. Approximate additional costs per group 5 vehicle: 35,220 €.
- **Low-Hanging Fruits Strategy** only contains the packages Aerodynamics "moderate," Engine Auxiliaries, Transmission, and Low Rolling Resistance (RR) "moderate." Approximate additional costs per group 5 vehicle: 6,500 €.
- **ZEV-Focused Strategy** only contains non-diesel packages, namely Aerodynamics package "moderate," Auxiliaries, and Low RR "moderate." Approximate additional costs per group 5 vehicle: 3,600 €

These three scenarios were used to calculate the expected fuel consumption of ICEVs assuming all manufacturers choose the same scenario. This provided a range of values for expected ZEV penetration; the true market penetration should lie in between. Please note that the additional costs are for describing the packages and have no influence on the scenario results. The aim is to compare possible strategies of manufacturers against the background of current legislation until 2030 and to derive the market penetration of ZEV. Since the decision for or against a strategy is not exclusively driven by the medium-term costs until 2030, there is no cost optimization of efficiency increases versus ZEV.

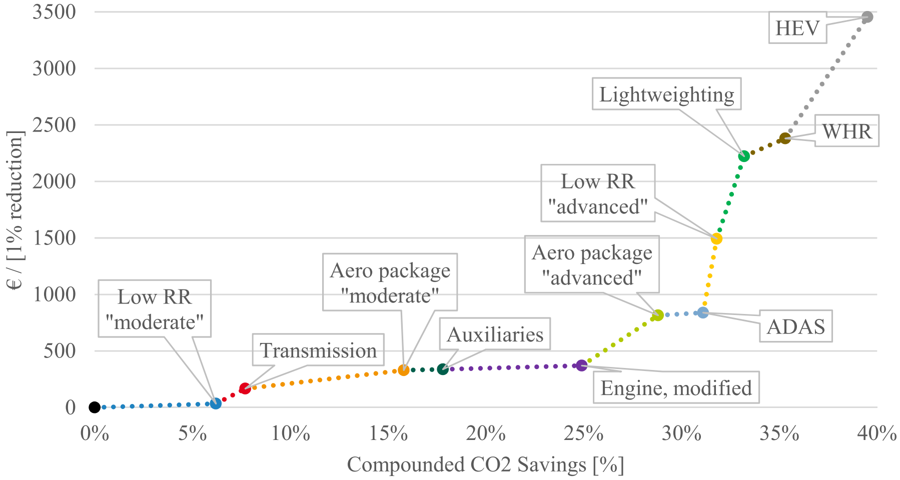

Fig. 2. Cost-Fuel Reduction Potential Curve for Group 5 Vehicles. Notes: HEV is Hybrid Electric Vehicle, WHR is Waste Heat Recovery, ADAS is Advanced Driver Assistant Systems, and RR is Rolling Resistance.

Fig. 3. Fuel consumption of average ICEVs in each strategy in 2025 and 2030.

4. Results

4.1. Market uptake of ZEV HDVs

The strategic scenarios result in different levels of fuel consumption reductions. Fig. 3 shows the fuel consumption of the average ICEV in each vehicle group under each scenario in 2025 and 2030, respectively. The three scenarios show the fuel consumption reduction under different manufacturer strategies on how much to invest in ICEV improvements or in ZEVs. The comparison is to the average vehicle in 2016 calculated by CE Delft et al. (2018).

At reductions ranging from 18 to 23% less fuel consumption in the ICEV-Focused scenario, manufacturers should be able to achieve the 2025 goal without any ZEV HDVs in their fleets. However, no vehicle group can attain a 30% reduction of Diesel HDVs by 2030 in any strategy. Even in the case where all known improvement measures are implemented to the fullest extent possible, manufacturers will need to sell some ZEVs to achieve their targets.

We calculated the CO_2 targets for 2025 and 2030 for each subgroup based on the average emissions reported for each subgroup in ACEA's preliminary report (ACEA - European Automobile Manufacturers' Association, 2020a)(. Fig. 4 shows the CO2 targets for each subgroup. The dotted lines represent the emission reduction trajectory that Regulation (EU) 2019/1242 uses to determine debts and credits prior to 2025. From 2025 onwards, the targets are legally binding.

Based on the gap between the required total CO_2 reduction and the reduction of Diesel HDVs within the three scenarios, market uptake curves of ZEV HDVs to comply Regulation (EU) 2019/1242 are obtained (see methods section) and are shown in Fig. 5. The resulting ZEV sales shares to meet the Regulation requirements are 0–7% in 2025 and

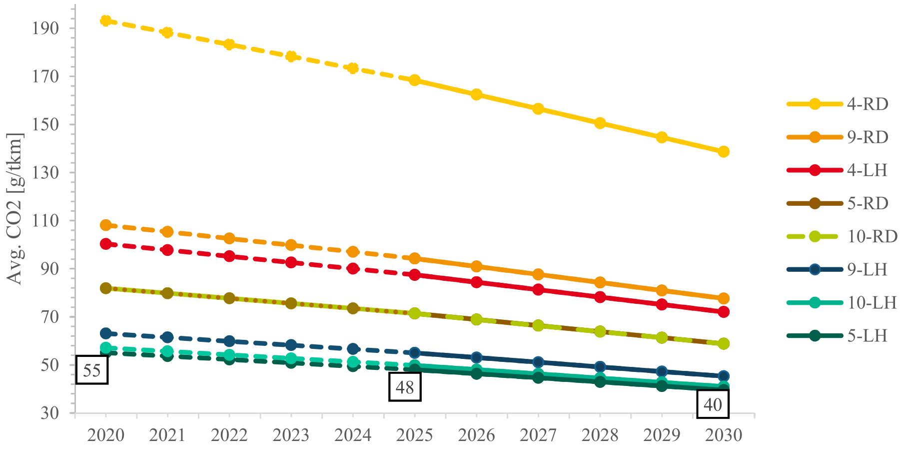

Fig. 4. CO_2 Targets per subgroup in g/tkm. Subgroup 5-long haul is highlighted, as it is the most important group in terms of sales and CO_2 emissions.

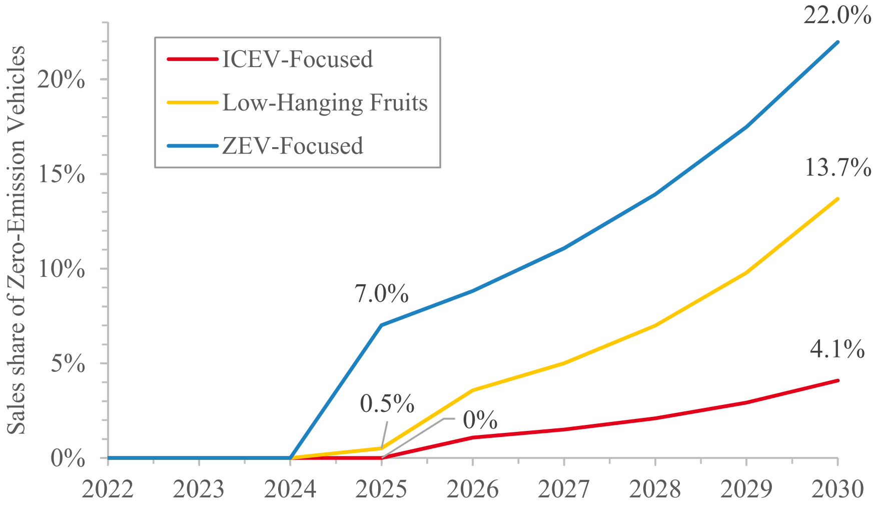

Fig. 5. Percentage of ZEV sales required to meet the emission regulation in the technology strategy scenarios.

4–22% in 2030. The large range of values stems from the different strategies manufacturers can follow to achieve their 2030 targets.

The ICEV-Focused strategy needs the least ZEV to fulfill the emission targets, and logically the strategy to focus on ZEV results in the highest penetration rate (22% of model year 2030 vehicles). While in both the ICEV-Focused and Low-Hanging Fruits strategies a manufacturer would need very little ZEV in 2025, the ZEV-Focused case already requires 7% of the newly sold fleet to be electrified to meet the target. Quite likely, a manufacturer following this strategy would need 2–3% ZEV in 2023 or 2024 to ramp up to this level. It is worth noting that the model assumes all manufacturers follow the same strategy in each of the three cases, so the values should act as a range of expected ZEV penetration. It is likely that different manufacturers will choose different strategies with some more and others less ambitious with respect to ZEVs such that the most likely future market evolution is a mixture of these scenarios with ZEV sales shares of 10–15% in 2030 to meet the regulation.

4.2. Total CO_2 emissions in regulated heavy-duty sector

With each year starting from 2025, the European fleet of HDVs will be partially electrified. Accordingly, the total ZEV HDV fleet percentage can be calculated for 2030. As 41% of tractors in stock are under five years old (Eurostat, 2020), we assume that 41% of the stock of HDVs sold before 2025 will no longer be in service in 2030 and that any vehicle sold prior to 2020 will no longer be in service in 2030 (cf. section 3.3.). Together with the overall market growth expected in HDV-until 2030 (BMVI, 2016), we obtain the total truck stock and ZEV stock in 2030. The calculated ZEV fleet percentages in the entire EU stock in 2030 is 1.4% in the ICEV-Focused Scenario, 4.9% in the Low-Hanging Fruits Scenario, and 10.8% in the ZEV-Focused Scenario.

The number of ZEV HDVs in operation in 2030 (in the regulated vehicle categories) allows us to calculate the total direct CO_2 emissions from the ICEV fleet. Fig. 6 shows the CO_2 emissions of newly registered Diesel HDV in million tons (Mtons) in the three scenarios. Depending on the strategy, different fuel consumptions are assumed in 2020. Therefore, the CO_2 emissions diverge, too. The scenarios assume that all manufacturers follow the same strategy. Depending on the individual decision of the manufacturers, the real emissions therefore are between those scenarios. Please note that the three scenarios meet in 2030 for two reasons: First, we assume no further ZLEV factors in 2030. Second, the overall reduction is fixed by the current legislation for newly sold vehicles, such as all strategies should lead to the same total emissions in the new fleet in 2030. Currently, it is not clear whether further ZLEV factors will be active in 2030 or beyond as the 2030 benchmark level will be set in the context of the 2022 fleet target review. For the sake of simplicity, we used the simplest assumption of no ZLEV factor in 2030.

As mentioned in the previous section, 41% of tractors are less than five years old in the EU market (Eurostat, 2020); thus 59% of a fleet

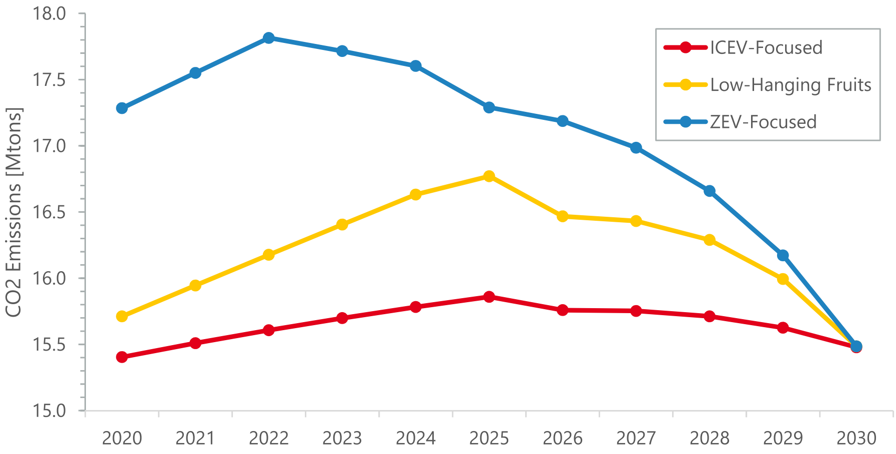

Fig. 6. Yearly CO_2 emissions of all newly registered Diesel HDV in Groups 4, 5, 9, and 10 in each scenario. Please note the shortened y-Axis.

comprised of vehicles between five and ten years old are assumed to be retained. For the ZEV calculation, this implies that all vehicles registered before 2020 were not included, 59% of those from 2020 to 2025 were, and all vehicles introduced from 2025 to 2030 were included. Using this method, the total expected emissions of HDVs in the four regulated groups could be calculated for 2030. The vehicle fleet from group 4, 5, 9, and 10 will emit 140 Mtons CO_2 in the ICEV-Focused Scenario, 145 Mtons CO_2 in the Low-Hanging Fruits Scenario and 152 Mtons in the ZEV-Focused Scenario in 2030. It is important to note that emissions are worse in the ZEV-Focused Scenario. As less investment is present for diesel motors, the reduction in fuel consumption of diesel vehicles is the lowest in the ZEV-Focused scenario, thus leading to higher emissions until a certain threshold of ZEV will be surpassed. Assuming a linear trend based on the values from 2027 to 2030 as a first approximation, the annual emissions in the three scenarios would be equal in 2034, reaching 138 Mtons.

The obtained order of magnitude of emissions is consistent with current $CO_{2\text{-eq}}$ emissions from all HDV and buses in 2017 that were 235.2 million tons (Publications Office of the European Union, 2019). As about two third of the emissions or about 157 million tons fall under Regulation (EU) 2019/1242, the calculated emissions from the future Diesel HDV fleet are in line with current values.

In summary, CO_2 emissions of newly sold Diesel HDV will be reduced until 2030 but additional ZEV sales are needed for the manufacturers to meet the requirements of the CO_2 HDV fleet regulation in Europe. Depending on the manufacturer's strategy how much to further invest in Diesel HDV improvement, the manufacturer will require between 4% and 22% of their newly sold fleet to be ZEV in 2030. However, high ZEV shares allow the sales of less efficient Diesel HDVs in noteworthy shares even in 2030 leading to higher total tail-pipe emissions of the HDV fleet under the regulation in a ZEV focused scenario than in a scenario with more Diesel HDV improvements.

5. Discussion

Our results show that some ZEV sales are required by all manufacturers to meet the 30% CO_2 reduction in the EU HDV fleet regulation. In the present section, we discuss existing limitations in our findings and compare it to other sources.

First, the calculations in this paper come with some general limitations. All considerations are based on the current state of legislation. As part of the 2022 revision, targets can be even more rigorous or additional vehicle classes can be included. Additionally, data on fleet structure and vehicle efficiency is more difficult to obtain compared to passenger cars. Manufacturers could lower the targets by over-reporting their emissions in the reference period (Rodríguez, 2020a). This effect, known as "Baseline Bubble," may influence the data in this paper as well as future official data. Furthermore, two special effects influence the data in the reference period: The obligatory introduction of next generation tachographs slightly reduced new vehicle registrations compared to 2018 (Piazza, 2019). This effect will be further influenced by the COVID-19 pandemic in the second part of the reference period. As only the first half of the reference period data is available so far, they are assumed representative of pre-COVID-19 market conditions (cf. Piere-Louis and Rodriguez, 2020). The effect of COVID-19 on the emissions levels of HDV is beyond the scope of this analysis.

Second, the methodological approach contains some simplifications. While the model differentiates vehicle sales by manufacturer and by subgroup, it assumes equal energy consumption and reduction potentials for all manufacturers. Due to different applications and associated different reduction potentials, selection effects can occur between manufacturers. As soon as manufacturer-specific data is available, further differentiations can improve the quality of the results at manufacturer level. However, the introduction of scenarios reduces this uncertainty in the manufacturer-independent analysis. Furthermore, low emission vehicles (LEV) are not considered in our analysis. To the best of the authors' knowledge, Scania is so far the only manufacturer that has announced a plug-in hybrid that can comply with the relevant regulation. In addition, ZEV super credits before 2025 and ZEV busses, which provide credits too, are excluded for simplification. Due to a limitation of the maximum allowed reduction from those vehicles, their influence on the total result is relatively small. Finally, the model assumes that ZEV close the gap between the calculated emissions and the target value. Alternatively, the manufacturer can pay fines, which was not taken into account here.

Third, due to the large influence of the percentage change in fuel consumption over time (Fig. 3), we applied a variation of ± 20% as a robustness check. The largest effect happens in the ICEV-Focused Strategy, where the variation leads to a consumption reduction between 20.5% (−20%) and 30.7% (+20%) instead of 25.6% for a group 5 vehicle in 2030. In case of an efficiency reduction, the share of ZEVs in new registrations increases from 4.1% to 10.0% in 2030. In case of an increase in efficiency, no ZEVs are necessary in the ICEV-Focused Strategy. The effect in the ZEV-Focused Strategy is much smaller, since efficiency improvements are only assumed to a small extent in any case. The share of ZEVs in new registrations varied between 20.7% and 23.2% in 2030, deviating only slightly from the previous result of 22.0%. In the Low-Hanging Fruits Strategy, the share of ZEVs in new registrations in 2030 is between 10.2% and 16.9%. Overall, the solution space remains almost identical, the maximum share of necessary ZEV in registrations in 2030 increases from 22% to 23.2%. To meet the 2030 fleet target with diesel vehicles only, efficiency options would have to be identified that do not seem conceivable today.

Fourth, interviews conducted with representatives from three manufacturers confirmed that the presented scenarios seem realistic, as the interviewees noted that switching "overnight" from diesel to ZEV is not feasible. Electrification is a main priority, however, and none of the three major manufacturers plans to direct their focus on diesel vehicles by the end of the decade. They noted that the targets would not be attainable using only diesel vehicles. As stated by the interviewees, the share of ZEV in 2030 could be even higher, since they expect higher targets in the long term. Two manufacturers agreed the ZEV sales percentage could reach 5% by 2025, and their guesses for 2030 ranged between 20 and 30%. Spillover effects from other markets with stricter regulations, such as California, could also further accelerate development. Using a somewhat similar method, Göckeler et al. (2020) assume a 22% share of ZEV registrations in 2030, which corresponds to the ZEV-Focused scenario presented here. The interviews also showed that the choice of strategy depends in particular on the available infrastructure and the cost-competitiveness of ZEV compared to diesel vehicles. Depending on the political framework conditions, the experts expected some types of ZEVs to be economically attractive for a large proportion of customers around 2030.

In summary, despite the uncertainty in technology assumptions concerning cost and emission reduction potential, our main finding is robust: depending on remaining improvements to diesel vehicles, the 2030 fleet target leads to a ZEV (BEV + FCEV) registration share of 4–22%. Further differentiation between various manufacturers and varying strategies will be possible based on future data. Today, the ZEV-scenario seems to be the most likely one, due to expected tightening of the targets and manufacturer statements.

6. Conclusions and policy implications

Our results show that ambitious CO_2 reduction targets will require significant ZEV HDV sales share. The required industry average ZEV HDV fleet penetration to meet the CO_2 reductions targets according to Regulation is 0–7% in 2025 and 4–22% in 2030. It is possible to attain the EU's goals for 2025 without any ZEV being introduced. However, even manufacturers following the ICEV-Focused strategy will need to have 4% of ZEV by 2030 to meet the 30% reduction target. These results are also in line with the interviewed experts' estimates of 0–5% ZEV in

2025 and 20–30% ZEV in 2030. By 2030, the estimated ZEV stock share in Europe will be 2–11% depending on the scenario manufacturers follow.

Our results have a number of policy implications. First, there will be a noteworthy fleet of ZEV HDVs on European roads in 2030. The successful market introduction and operation of these vehicles requires additional charging or refueling infrastructure along the roads and in depots. The revision of the European Alternative Fuels infrastructure Directive in 2021 needs to start a coordinated roll out of the required recharging or refueling infrastructure for HDV. Second, the 2022 revision for the current Regulation (EU) 2019/1242 needs to carefully evaluate the baseline data to avoid any baseline bubble effect, in particular as (1) little historical CO_2 emission sales data is available on detailed level for HDV and (2) the baseline years 2019/2020 were partially impacted by the COVID-19 pandemic. Third, our analysis of total CO_2 emissions of newly sold HDV in the three scenarios shows that large ZEV sales shares can lead to higher CO_2 emissions as less improvement in the dominating Diesel technologies are required to meet the CO_2 target. Accordingly, the 2022 revision of the current regulation should carefully examine lower or no ZEV credits for the manufacturers. An alternative approach to tackle diesel HDV emissions and stimulate ZEV HDV growth is the introduction of ZEV HDV quotas in Europe similar to California. Both policies would need to be carefully balanced but would guarantee a coordinated emission reduction from conventional HDV and high future ZEV sales shares to transition to low carbon heavy-duty road transport. Lastly, the noteworthy CO_2 emissions in the new HDV fleet despite the introduction of ZEV HDVs highlights the need to strengthen the existing 30% reduction target if HDV are to deliver their share to the 55% reduction of Europe's CO_2 emissions by 2030 compared to 1990 level (European Commission, 2020).

CRediT authorship contribution statement

Annelis K. Breed: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. **Daniel Speth:** Conceptualization, Methodology, Validation, Writing – original draft, Project administration. **Patrick Plötz:** Conceptualization, Methodology, Validation, Writing – original draft, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was prepared as part of the projects eWayBW (grant number 16EM3167-1) and BOLD (grant number 16EM4011-1), funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. Patrick Plötz further acknowledges funding by the EC H2020 funded PARIS REINFORCE project (grant number 820846). Daniel Speth and Patrick Plötz performed this work within the framework of the Profilregion Mobilitätssysteme Karlsruhe, which is funded by the Ministry of Economic Affairs, Labour and Housing in Baden-Württemberg and as a national High Performance Center by the Fraunhofer-Gesellschaft.

A.1 Appendix 1. Reduction Potential Packages

These tables provide a traditional literature review of both diesel improvement technologies (Table 3) as well as those from alternative powertrains (Table 4). The costs displayed are vehicle capital costs.

Table 3

Overview of Reduction Potential Packages and Related Costs from the Literature (Diesel Improvement Technologies)

Source	Vehicle and Profile	Vehicle Package	Reference Vehicle	Potential Year	Fuel Consumption [l/100 km]	Reduction Potential [%]	Added Costs [€][1]
Dünnebeil et al. (2015)	Tractor-trailer, long-haul	Diesel B	EURO VI[2]	2020	27.3 l/100 km	−21%	+26,670€ [2010 €]
Dünnebeil et al. (2015)	Tractor-trailer, long-haul	Hybrid A	EURO VI	2020	29.0 l/100 km	−16%	+66,700€ [2010 €]
Dünnebeil et al. (2015)	Tractor-trailer, long-haul	Hybrid B	EURO VI	2020	26.2 l/100 km	−24%	+75,670€ [2010 €]
Dünnebeil et al. (2015)	Rigid truck, urban cycle	Diesel B	EURO VI	2020	17.3 l/100 km	−17%	+12,485€ [2010 €]
Dünnebeil et al. (2015)	Rigid truck, urban cycle	Hybrid A	EURO VI	2020	17.8 l/100 km	−15%	+41,030€ [2010 €]
Dünnebeil et al. (2015)	Rigid truck, urban cycle	Hybrid B	EURO VI	2020	15.7 l/100 km	−25%	+47,485€ [2010 €]
Delgado et al. (2017); Meszler et al. (2018)	Tractor-trailer, long-haul	Moderate	2015 Vehicle	2020–2030[1]	25 l/100 km	−23%	+7,157€ [2016 €]
Delgado et al. (2017); Meszler et al. (2018)	Tractor-trailer, long-haul	Advanced	2015 Vehicle	2020–2030	24 l/100 km	−29%	+15,273€ [2016 €]
Delgado et al. (2017); Meszler et al. (2018)	Tractor-trailer, long-haul	Long-term (includes hybrid)	2015 Vehicle	2020–2030	19 l/100 km	−43%	+41,868€ [2016 €]
Delgado et al. (2017); Meszler et al. (2018)	Rigid truck, Urban Delivery	Mid-term	2015 Vehicle	2020–2030	16 l/100 km	−23%	–
Delgado et al. (2017); Meszler et al. (2018)	Rigid truck, Urban Delivery	Long-term (includes hybrid)	2015 Vehicle	2020–2030	12 l/100 km	−43%	–
Delgado et al. (2017); Meszler et al. (2018)	Rigid truck, Regional Delivery	Long-term (includes hybrid)	2015 Vehicle	2020–2030	13 l/100 km	−36%	–
Delgado et al. (2017); Meszler et al. (2018)	Rigid truck, long-haul	Long-term (includes hybrid)	2015 Vehicle	2020–2030	16 l/100 km	−34%	–
Norris and Escher (2017)	Tractor-trailer, long-haul	All tech	2015 Vehicle	2030	24 l/100 km	−33%	+24,596€ [2015 €]
Norris and Escher (2017)		All tech	2015 Vehicle	2030	17 l/100 km	−32%	

(continued on next page)

Table 3 (*continued*)

Source	Vehicle and Profile	Vehicle Package	Reference Vehicle	Potential Year	Fuel Consumption [l/100 km]	Reduction Potential [%]	Added Costs [€][1]
	Rigid truck, Regional Delivery						+15,350€ [2015 €]
CE Delft et al. (2018)	Tractor-trailer, long-haul	All tech including hybrid except speed limiter	2016 typical[4]	2025	18.6 l/100 km	−40%	–
CE Delft et al. (2018)	Rigid truck, long-haul	All tech including hybrid except speed limiter	2016 typical	2025	15.3 l/100 km	−34%	–
(CE Delft et al., 2018)[5]	Tractor-trailer, long-haul	Moderate	2016 baseline vehicle	2025	–	−36.4%	+15,565€ [2015 €]
(CE Delft et al., 2018)[5]	Tractor-trailer, long-haul	Advanced + WHR + speed limiter	2016 baseline vehicle	2025	–	−42.4%	+25,060€ [2015 €]
(CE Delft et al., 2018)[5]	Tractor-trailer, long-haul	Advanced + hybrid	2016 baseline vehicle	2025	–	−44.8%	+39,572€ [2015 €]

1 All costs displayed are additional costs to a standard vehicle, unless *not* denoted with a "+."

2 The EURO VI reference vehicle consumed 34.5 l/100 km for a long-haul cycle for tractor-trailers, and 20.9 l/100 km for rigids in urban cycle, according to (Dünnebeil et al. (2015)).

3 The costs here are for 2020. (Delgado et al., 2017; Meszler et al., 2018).

4 A typical vehicle from 2016 included some of the technologies mentioned in the SR9 Report. These reduction numbers are thus more accurate than those calculated in reference to the baseline vehicle, which had none of these technologies. The costs for these were, however, unavailable.

5 Adapted from (CE Delft et al., 2018).

Table 4
Overview of Reduction Potential Packages and Related Costs from the Literature (Zero Emission Vehicle Technologies)

Source	Vehicle and Profile	Vehicle Package	Reference Vehicle	Potential Year	Fuel Consumption [l/100 km]	Reduction Potential [%]	Added Costs [€][1]
Hall and Lutsey (2019)	Tractor-trailer, long-haul	BEV	–	–	–	−100%	+$49,000 [2020 $]
Hall and Lutsey (2019)	Tractor-trailer, drayage	BEV	–	–	–	−100%	+$35,000 [2020 $]
Hall and Lutsey (2019)	Tractor-trailer, long-haul	FCEV (hydrogen)	–	–	–	−100%	+$80,000 [2020 $]
Hall and Lutsey (2019)	Tractor-trailer, drayage	FCEV (hydrogen)	–	–	–	−100%	+$65,000 [2020 $]
Moultak et al. (2017)	Tractor-trailer	Hybrid Electric	2017 diesel[2]		–	–	+$6,000 [2015 $]
Moultak et al. (2017)	Tractor-trailer	Hydrogen Fuel Cell (FCEV)	2017 diesel		0	−100%	+$61,000 [2015 $][3]
Moultak et al. (2017)	Tractor-trailer	O-BEV	2017 diesel		0	−100%	+$42,000 [2015 $]
Moultak et al. (2017)	Tractor-trailer	DI-BEV	2017 diesel		0	−100%	+$5,000 [2015 $]
Dünnebeil et al. (2015)	Rigid truck, urban cycle	BEV A	EURO VI	2020	9 l/100 km[4]	−57%	+135,090 [2010 €]
Dünnebeil et al. (2015)	Rigid truck, urban cycle	BEV B	EURO VI	2020	7.9 l/100 km	−62%	+141,240 [2010 €]
Jöhrens et al. (2020)	Rigid truck, long-haul	O-HEV: 420 kW motor, 15 kWh battery	2020 (diesel) Vehicle	2020	27.8 l/100 km	−11.4% (hybrid) −100% (cat.)	+70,690€ [2017 €][5]
Jöhrens et al. (2020)	Rigid truck, long-haul	O-BEV: 420 kW motor, 100 kWh battery	2020 (diesel) Vehicle	2020	0	−100%	176,540€ [2017 €]
Jöhrens et al. (2020)	Rigid truck, long-haul	O-BEV: 420 kW motor, 500 kWh battery	2020 (diesel) Vehicle	2020	0	−100%	300,540€ [2017 €]

1 All costs displayed are additional costs to a standard vehicle, unless not denoted with a "+."

2 The cost of a base diesel tractor-trailer is assumed to be $220,000 US dollars, in 2015 USD, during 2020 (Moultak et al., 2017).

3 Costs presented for both catenary forms (O-BEV and DI-BEV) as well as FCEVs do not include infrastructure costs(Moultak et al., 2017).

4 The BEV packages (Dünnebeil et al., 2015) considered the power used in the fuel calculation. This would however be zero according to Regulation (EU) 2019/1242, which does not consider well-to-wheel (WtW) emissions, but rather tank-to-wheel (TtW) or vehicle-only emissions.

5 Costs presented for overhead catenary trucks (both O-HEV and O-BEV) assume that initial infrastructure costs would not come from manufacturers (Jöhrens et al., 2020).

Table 5
Reduction Potential Technologies‘ Penetration Rates for 2025 and 2030.

Penetration Rates and Reduction Potentials		Reduction		2025 Weighted Penetration				2030 Weighted Penetration				Comments
		Groups 4 & 9	Groups 5 & 10	Group 4	Group 5	Group 9	Group 10	Group 4	Group 5	Group 9	Group 10	
Aerodynamics	**Aero Package Mod**			90	100	90	90	90	100	90	90	Groups 4,9,10 my have more often bodies

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Table 5 (*continued*)

Penetration Rates and Reduction Potentials		Reduction		2025 Weighted Penetration				2030 Weighted Penetration				Comments
		Groups 4 & 9	Groups 5 & 10	Group 4	Group 5	Group 9	Group 10	Group 4	Group 5	Group 9	Group 10	
	Roof spoiler plus side flaps											mounted not suitable for spoilers and flaps
	Side and underbody panels at truck			50	100	50	50	70	100	70	60	Damage risk other groups
	Covers for rear truck wheels			75	90	75	75	85	95	85	85	time for-roll-out
	Closable front grill			100	100	100	100	100	100	100	100	potential has uncertainties
		-11,2 %	**-11,2%**	**50%**	**90%**	**50%**	**50%**	**70%**	**95%**	**70%**	**60%**	
	Aero Package Advanced											
	Rear-view cameras instead of mirrors			40	60	40	40	40	60	40	40	
	Long and rounded vehicle front			10	70	10	20	30	80	30	40	not all cabins can be redesigned 6-7 years
		-4,4%	**-3,9%**					**30%**	**60%**	**30%**	**40%**	
Tyres	**Low RR Mod**											
	Low rolling resistance tires on truck/tractor	**-7,9%**	**-6,2%**	**90%**	**100%**	**90%**	**90%**	**90%**	**100%**	**90%**	**90%**	some applications not allow optimized tires
	Low RR Adv											
	Tire Pressure Monitoring System (TPMS) truck			100	100	100	100	100	100	100	100	need bonus factor in VECTO, otherwise not included
	Wide base single tires			0	2	0	2	0	2	0	2	niche only
		-0,9%	**-0,7%**					**0%**	**2%**	**0%**	**2%**	see above reasons
L	**Lightweighting**											
	Strong reduction truck/tractor	**-2,5%**	**-1,4%**	50	80	50	50	**75%**	**90%**	**65%**	**65%**	not all chassis redesigned in 6-7 years
Auxillaries	**Auxilliaries**											
	Electric Hydraulic power steering			50	50	50	50	75	75	75	75	time for roll-out, complex
	LED lighting			100	100	100	100	100	100	100	100	no limitations seen
	Best air compressor			100	100	100	100	100	100	100	100	no limitations seen
	Best AC efficiency			100	100	100	100	100	100	100	100	no limitations seen
	Best Cooling fan			100	100	100	100	100	100	100	100	no limitations seen
	Best alternator			100	100	100	100	100	100	100	100	no limitations seen
	LED Electric System			100	100	100	100	100	100	100	100	no limitations seen
		-2,9%	**-2,2%**	**50%**	**50%**	**50%**	**50%**	**75%**	**75%**	**75%**	**75%**	
T	**Transmission**											
	Reduced drivetrain loses (lubricants, design)	**-1,4%**	**-1,5%**	**80%**	**80%**	**80%**	**80%**	**100%**	**100%**	**100%**	**100%**	time for roll-out, redesign
ADAS	**ADAS**											
	Engine Stop-Start (ESS)			25	25	25	25	0	0	0	0	reflect difference to PPC+ESS+Eco-roll
	PCC (w/ Eco-roll, w/o ESS)			25	25	25	25	0	0	0	0	reflect difference to PPC+ESS+Eco-roll
	PCC (w/ Eco-roll, w/ ESS)	**-3,3%**	**-2,3%**	75	75	75	75	**100%**	**100%**	**100%**	**100%**	time for roll-out, safety testing
	Speed Limiter 80 km/h	**-2,4%**	**-2,7%**	1	1	1	1	**1%**	**1%**	**1%**	**1%**	niche only (operators don't want
Engine	**Engine**											
	Improved Turbocharging and EGR			100	100	100	100	100	100	100	100	no limitations seen
	Improved SCR and optimized SCR heating methods			100	100	100	100	100	100	100	100	no limitations seen
	Friction reduction etc.			80	80	80	80	80	80	80	80	demanding design
	Improved lubricants			80	80	80	80	80	80	80	80	demanding design
	Downspeeding			100	100	100	100	100	100	100	100	no limitations seen
		-10,4%	**-8,9%**	**80%**	**80%**	**80%**	**80%**	**80%**	**80%**	**80%**	**80%**	
WHR	**WHR**											
	Waste Heat Recovery	**-2,0%**	**-2,1%**	0	5	0	0	**100%**	**100%**	**100%**	**100%**	niche in 2025, 100% possible by 2030
Hybrid	**HEV (only uses full hybrid)**											time for roll-out, some missions no benefit

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Table 5 (*continued*)

Penetration Rates and Reduction Potentials	Reduction		2025 Weighted Penetration				2030 Weighted Penetration				Comments
	Groups 4 & 9	Groups 5 & 10	Group 4	Group 5	Group 9	Group 10	Group 4	Group 5	Group 9	Group 10	
Mild Hybrid 48V	**-0,5%**	**-0,5%**	50	50	50	50	**70%**	**50%**	**65%**	**50%**	
Full Hybrid	**-6,1%**	**-4,2%**	10	5	10	0	**20%**	**5%**	**20%**	**5%**	Expensive tech, only for very ambitious 2030 goals, better for regional cycles (rigids)

Sources: 2025 (CE Delft, Directorate-General for Climate Action (European Commission), ICCT, TNO, TU Graz 2018). 2030 numbers extrapolated or kept constant based on these.

A.2 Appendix 2. Vehicles Sold per Manufacturer per Group

Table 6

Calculated Vehicles Sold per Manufacturer per GroupUsing
Sales mixes from 2018 from ICCT, including 1% of regulated vehicles sold from other companies. These numbers are not raw data-they are calculated from published sales mix percentages from 2018 and applied to registrations from the reference period.

Vehicle Group	DAF	Iveco	MAN + Scania	Mercedes	Renault + Volvo	Total	Total (with 1%)
4	1,554	1,893	3,223	3,211	2,646	12,528	12,638
5	8,391	5,311	19,734	15,788	14,241	63,465	64,153
9	1,246	2,756	6,105	5,927	4,075	20,109	20,286
10	1,626	319	4,421	1,827	2,812	11,004	11,110
Total Regulated	12,817	10,279	33,484	26,752	23,774	107,106	108,188
As Percent	12%	10%	31%	25%	22%	99%	100%

Source: Bieker et al., (2019), ACEA - European Automobile Manufacturers' Association (2020b), ACEA - European Automobile Manufacturers' Association (2020c).

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