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Abstract

Following the Paris Agreement, virtually all countries worldwide have committed themselves to undertaking efforts to limit global warming to 1.5°C. Within the European Union (EU), the recent "Fit for 55" policy package proposes ambitious greenhouse gas (GHG) mitigation policies for all sectors as part of the EU's contribution to limiting global warming. Yet, it is unclear whether the proposed policies are sufficient for the EU to limit global warming to 1.5°C and it remains an open policy problem how to translate global temperature targets into sector-specific emission budgets and further into sector-specific policies. Here, we derive GHG budgets for transport in EU27 and obtain GHG mitigation pathways for Europe consistent with 1.5°C global warming. We do not provide a comprehensive assessment of the "Fit for 55" transport package but we discuss the main policies for road transport in light of the GHG emission budgets, their level of ambition, and suggest amendments to these policies as well as improvements to the "Fit for 55" package. Our results suggest that parts of the "Fit for 55" for transport are still not ambitious enough to align with a 1.5°C scenario.

Key policy insights:

- A Paris-compatible residual carbon budget for EU transport is 10 – 12 Gt CO_2.
- The budget implies net zero emissions for EU transport by 2044 – 2048 latest.
- We find the current "Fit for 55" proposal for transport is not ambitious enough.
- A faster phase-out of cars and trucks with combustion engines is required and there is a need for ambitious standards for fast charging e-vehicles.
- CO_2 pricing of transport is not a substitute but a complement to fleet targets.

Keywords

Climate policy, transport emissions, battery electric vehicles

Contents

1 Introduction

In line with the Paris Agreement, the European Union (EU) is committed to the ambitious target of climate neutrality by 2050, and to keep global warming well below 2°C as well as making efforts to limit it to 1.5°C. This implies climate-neutral transport by 2050 unless large-scale negative emissions in other sectors are assumed (Axsen et al. 2020). Transport is responsible for about one-quarter of the EU’s energy-related greenhouse gas (GHG) emissions (EC 2021).

In July 2021, the European Commission presented its "Fit for 55" package, which contains several transport-related aspects: (1) more ambitious car fleet fuel efficiency standards (Regulation (EU) 2019/631), (2) the renewal of the Alternative Fuels Infrastructure Directive (AFID) to an Alternative Fuels Infrastructure Regulation (AFIR), (3) the revision of the Energy Taxation Directive, (4) the integration of maritime transport into the EU emission trading system (ETS), and (5) standardization processes for renewable and low-carbon fuels for aviation and navigation. Thus, the current situation provides a unique opportunity to re-think and re-align European transport policies to meet the EU's contribution to the Paris Agreement.

Previous attempts in the literature have generally reviewed GHG mitigation policies for road transport (e.g., Axsen et al., 2020) and provided impact assessments (e.g., Münzel et al. (2019) on electric vehicle incentives, and Fritz et al. (2019) and Breed et al. (2021) on the impact of CO_2 fleet standards on the uptake of zero-emission vehicles). But the Paris Agreement requires efforts to limit global warming to 1.5°C compared to pre-industrial levels, and despite several studies deriving GHG emission budgets for countries or regions, the translation into sector-specific policies remains an open policy problem. We focus on European legislation as the geographic scope is large enough to make a GHG emissions budget for EU27 transport meaningful and as there is a current revision of many European transport policies within the “Fit for 55” proposal.

More specifically, the present paper aims to (1) derive boundaries for future GHG mitigation policies for transport in EU27 from Paris compatible GHG emission budgets; and (2) discuss implications for road transport-specific European policies.

This work differs from previous research in several aspects. First, it is the first study to derive a Paris-compatible GHG emission budget for EU27 transport. Second, it provides a first example of how to translate GHG emission budgets into sector-specific policies.

The remainder of the paper is structured as follows. Section 2 provides a brief overview of the main existing and within “Fit for 55” proposed road transport policies. Section 3 outlines the methods to derive an EU transport GHG emission budget (with technical details in the Supplementary Material). Section 4 contains the results on GHG emission budgets. The policy discussion and potential policy implications are presented in section 5.1, followed by a general discussion of our findings in Section 5.2 and conclusions in Section 6.

2 Mitigation Options and Policies

2.1 Passenger Cars and Light Commercial Vehicles

In 2019, passenger cars were responsible for about 12% of the total EU GHG emissions and about 60% of transport GHG emissions (EC 2021). Data from 2019, while a bit old, is likely to be more representative than data from 2020 and 2021 due to the effects of COVID restrictions on passenger car travel. To reduce GHG emissions of passenger cars and light-duty vehicles, three main alternative drive technologies are available (T&E 2018, Searle et al. 2021): Battery electric vehicles (BEV), plug-in hybrid electric vehicles (PHEV) and fuel cell electric vehicles (FCEV). As BEV and FCEV have no tail-pipe emissions, they are also referred to as "zero emission vehicles" (ZEV). Biofuels and synthetic fuels in combustion engine vehicles may be an alternative as well, but given the limited resources and possible sustainability drawbacks (Darda et al, 2019) these are better used in other non-road transport sectors that have fewer options, such as aviation and shipping (Dahal et al 2021, Korberg et al 2021, Millinger et al. 2021). Accordingly, the same holds true for HDV (see next section). The crucial factor for the diffusion of BEV is the battery as it concerns two main purchase decision criteria: investment cost and the vehicle's all-electric driving range. PHEV use combustion engines to gain range and lower battery costs but are consequently still a non-negligible source of GHG emissions. The complex propulsion system may also increase the overall vehicle cost. Today, an average privately used PHEV drives less than 50% of its total annual distance on electricity (Plötz et al. 2021). FCEV are still in a very early phase of commercialisation and would require yet another public refuelling infrastructure (Plötz 2022). To achieve climate neutrality, the main options are either a total stock of BEV or a large share of BEV with some long-range PHEV using carbon-neutral fuels, e.g., biofuels or fuels from renewable electricity with air-captured carbon, for their remaining combustion engine operation.

Plug-in electric vehicles (PEV), i.e., BEV and PHEV combined, have seen a strong increase in sales shares in Europe in 2021 despite total car sales in Europe dropping (ACEA 2022). The global market leader in PEV sales shares is Norway, where new PEV car registrations exceeded 80% in 2021. The EU PEV sales share in 2021 was 21%, and a total of 2.2 million PEV were sold in Europe in 2021 (Schmidt 2022). It should be noted that the increase happened when overall sales of vehicles dropped during the COVID pandemic. The high sales share can be interpreted as PEV sales being less influenced by the restrictions or that the percentage might have been smaller during a "normal" year. Norway is an example of a country that has almost achieved the goal of phasing out combustion engine vehicles from newly sold cars through a long history of generous subsidies at the national and local levels (Figenbaum, 2017; Mersky et al, 2016). Norway may be exceptional due to its wealth, ironically largely derived from oil exports. Still, the large uptake of EVs has led to revenue losses for the government and a discussion of a possible reform of the vehicle taxation system to a road tax system (Fridström 2019).

CO_2 and fuel economy targets for passenger cars and vans are strong policies to reduce GHG emissions of newly sold vehicles (Axsen et al. 2020, Regulation (EU) 2019/631). These regulations have strongly increased the diffusion of PEV in Europe. For passenger cars, the average CO_2 emissions of newly sold passenger cars in Europe had to be 95 g CO_2/km (measured in the New European Driving Cycle) in 2021 if manufacturers wanted to avoid penalties. By 2030, the current regulation requires a 37.5% reduction compared to 2021 towards 59 g CO_2/km (measured in the New European Driving Cycle), which is about 70 g CO_2/km in real-world operation (Dornhoff et al. 2020). In the "Fit for 55" the target for 2030 is a reduction of 55% compared to 2019 and a 100% reduction by 2035.

Other major low-carbon policies on the EU level include the car labelling directive 1999/94/EC to address the vehicle demand side, the AFID 2014/94/EU to address the required infrastructure for alternative fuel vehicles, and the Renewable Energy Directive (RED II – Directive (EU) 2018/2001) for the role of low-carbon fuels. Within the "Fit for 55" package, new policies for alternative fuels infrastructure have been proposed: (1) the existing directive shall be replaced by a regulation, the AFIR, implying immediate legal impact in each member state; (2) to have infrastructure rollout follow the market diffusion, the EC proposed fixed kW of public chargers per PEV in stock; (3) and a minimum number of public chargers along the European road transport network. Sufficient infrastructure is a prerequisite for mass market diffusion of ZEVs, but by itself does not reduce GHG emissions from transport and is only indirectly derivable from GHG emission budgets for transport in Europe.

2.2 Medium and Heavy-duty Vehicles

Apart from drastic demand reduction, there are two general technological pathways to achieve low-carbon solutions for medium and heavy-duty vehicles (HDV): direct usage of electric energy in battery electric trucks (BET) and the introduction of CO_2-free fuels like hydrogen from renewable electricity. However, the market potential and the long-term individual contribution of individual technologies to the reduction of CO_2 are still under investigation (Plötz 2022).

In 2019, the EU adopted CO_2 standards for newly registered trucks and buses (Regulation (EU) 2019/1242). According to these standards, the average CO_2 emissions of newly sold HDV must be 15% lower by 2025 and 30% lower by 2030, compared to the base period of July 2019 to June 2020. Until 2024, manufacturers who launch zero- and low-emission trucks (ZLEV) receive multiple credits for each ZLEV when calculating their manufacturer-specific emission reduction target. From 2025 onwards, this so-called super-credit system will be replaced by a benchmark-based credit system. Consequently, only if a manufacturer exceeds a commonly defined ZLEV benchmark share over all its new HDV are its emissions adjusted downwards. For 2025, this benchmark is 2%, whereas the 2030 level will be defined later. To reach these CO_2 targets, the EU has defined a series of standards and measures to enforce compliance.

To meet the 2030 CO_2 fleet standards for trucks under regulation (EU) 2019/1242, at least 4 to 22% of newly sold HDV have to be ZEV (Breed et al. 2021). The actual value depends on the manufacturer's strategy: if significant diesel engine emission reductions are achieved, 4% ZEV will be sufficient. Full compliance with the target, however, seems not to be feasible with only improved diesel vehicles. Therefore, a ZEV favouring strategy is likely, resulting in up to 22% ZEV. This results in 1 to 11% of stock vehicles being ZEV by 2030.

BET are commercially available for short and medium distances of up to 300 km to date, and vehicles with higher ranges will come in the following years (IEA 2020). Yet, to cover several hundred kilometres per day, future BET must be able to recharge within the legally binding driving breaks of 45 minutes after 4.5 hours of driving. Additionally, social and behavioural barriers might need to be addressed to ensure full operability. If renewable electricity is used, BET operate CO_2 emission-free. However, they require large batteries to fulfil high daily mileage. In terms of infrastructure, a full-coverage fast-charging network is needed for long-haul trucking (Plötz et al. 2020b).

Today, fuel cell electric trucks (FCET) are being delivered on a small scale, and manufacturers have announced commercially available FCET within the next decade. Yet, FCETare less energy efficient than BET, resulting in higher primary energy demand and higher total costs of ownership (Gnann et al. 2017; NPM 2020, Plötz 2022). Large-scale demonstrators for zero-emission truck technologies, leading to an initial market diffusion, are planned within the next five years, e.g., in Germany and Sweden, among other countries. Decisions among the potential technologies can be expected in a few years (NPM 2020; BMVI 2020a, Plötz 2022).

Because of shorter vehicle ownership times by first-users compared to passenger cars, i.e., typically around 5 to 7 years (Gnann et al. 2017), a large-scale reduction of emissions from medium and heavy-duty transport seems possible but will probably not be on time. As the transition towards low emission trucks requires more time, emission reductions from newly sold diesel trucks are highly important. Further efforts to increase the efficiency of diesel engines and HDV, in general, can reduce emissions of newly sold vehicles while allowing manufacturers to meet the CO_2 targets with a limited number of ZEV trucks (Breed et al. 2021).

3 Methods

The IPCC report on global warming of 1.5°C (IPCC SR1.5) provides mitigation pathways with a 50% probability of no or limited overshoot for 1.5°C global warming (IPCC 2018), which can be argued to be in line with the Paris Agreement (Wachsmuth et al. 2018). Studies have derived Paris-consistent emission budgets, and trajectories for the EU, based on different global burden-sharing approaches (SRU 2020, Wachsmuth et al. 2019, Zaklan et al. 2021).

Here, we use the result of Zaklan et al. (2021) as a starting point to derive indicative GHG emission budgets for the EU transport sector. They use a burden-sharing approach between sectors based on cost-effectiveness, i.e., distributing the required emission reductions based on equal marginal abatement costs. We apply their methodology to the entire transport sector, which includes road transport, railways, inland navigation and intra-European aviation but excludes international aviation and shipping. The obtained GHG emission budgets thus cover road transport, railways, inland navigation and intra-European aviation but exclude international aviation and shipping. We focus on peak budgets here, i.e., limits to the cumulative emissions until net-zero emissions are reached, as one main approach to obtaining emission budgets (IPCC 2018). Given the EU's long-term target of reaching GHG neutrality in 2050, we calculate emission budgets for 2021 – 2050. The global IPCC pathways used 2015 as a base year. Therefore, we subtract the cumulative emissions for 2016 – 2020, which we estimate from the EU's official GHG inventories for 2018 (EEA 2021) and an extrapolation of trends to 2020 per subsector. We consider two pathways to reach the goal of 1.5°C warming during the 21st century: with and without temporal overshoot of the temperature goal.

Please note that GHG emissions from electricity generation or vehicles manufacturing are not part of the transport sector (only tail-pipe emissions) in GHG reporting. They are important emissions and need to be addressed by policies but are outside the scope of the present paper (the limitations of this approach are discussion in Section 5). Our discussion of policy implications from the derived GHG emission budgets is limited to road transport.

4 Results: Transport CO_2 Budgets and Emission Reduction Targets

We obtain a total energy- and process-related emission budget for the EU for 2021 – 2050 of about 37 Gt CO_2eq. and about 10 Gt CO_2eq. for transport. A second pathway is within 1.5°C of global warming by 2100 but allows for limited overshoot such that peak warming remains well below 2°C. In this second pathway, the overall GHG emission budget increases to about 44 Gt CO_2eq. with a share of about 12 Gt CO_2eq. for transport. In both cases, about 95% of the transport emission budget is allocated to road transport and almost half of the remaining budget is foreseen for intra-EU aviation, according to our methodology. These values are consistent with current shares of GHG from transport in 2015 (EC 2020) and comparable to earlier rough estimates of a transport GHG budget in T&E (2018). The budgets are summarised in Tables 1 and 2.

Table 1: EU GHG budget for the years 2021 – 2050 consistent with long-term warming of 1.5°C and the share of transport

EU GHG Budget in Gt $CO_{2eq.}$	Energy- and Process-Related Emissions Budget	Transport Emissions Budget
For 1.5°C with no overshoot	37.3	10.2
For 1.5°C with limited overshoot	44.3	12.1

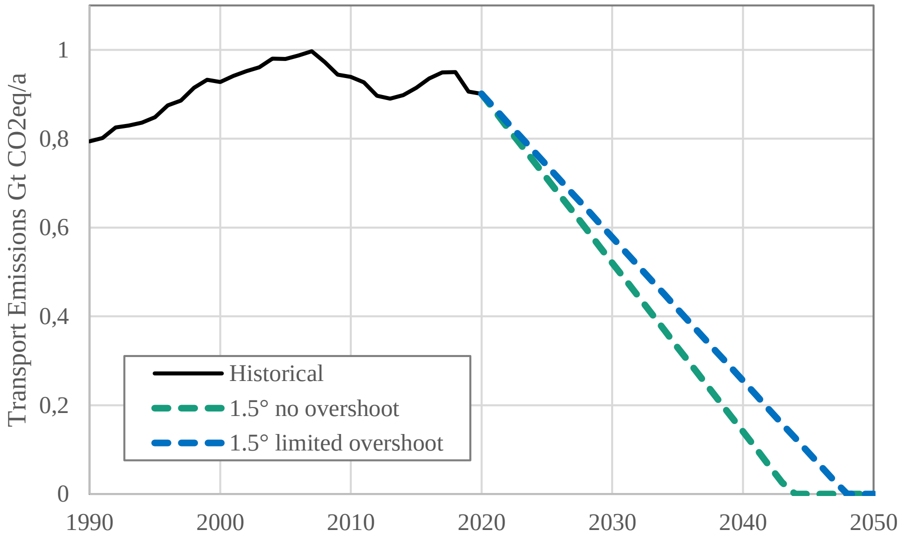
Table 2: Overview of GHG budget by transport mode

EU GHG budget in Gt CO_2eq.	Road	Aviation	Rail, Navigation and Other	Total Transport
For 1.5°C with no overshoot	9.7	0.24	0.29	10.2
For 1.5°C with limited overshoot	11.5	0.30	0.35	12.1

Present GHG emissions from transport in Europe are 0.9 Gt CO_2eq. annually in 2020 (excluding international bunkers for international navigation and aviation, EEA 2020 and Zaklan et al. 2021). At the present annual emission level, Europe's transport GHG emissions budget would be used up in 11 to 13 years, and all further emissions would contribute to global warming permanently above 1.5°C. This demonstrates the urgency of policy action.

The GHG emission budgets can be translated into emission pathways. We assume a linear reduction to zero from current emission levels, and the resulting trajectories for both pathways are shown in Fig. 1.

Figure 1: Historical and needed future transport GHG emissions within 1.5°C emission budgets.



The linear GHG emission reduction leads to GHG-neutral transport in the EU by 2044 if overshoot is to be avoided or by 2048 with limited overshoot. This is more ambitious than the current EU Sustainable and Smart Mobility Strategy (EC 2020), which aims at a 90% GHG reduction by 2050 (compared to today's emissions). Other non-linear GHG emission reductions over time are also possible, of course. For example, slower initial reduction implies much higher reduction efforts later as the total transport budget, i.e., the area under the curve, should be the same. On the other hand, if GHG emissions from transport were reduced faster early on, GHG neutrality could be achieved later than 2044 or 2048, respectively, as earlier reductions allow for later neutrality under a fixed total budget. Note, however, that the linear emission reduction is already quite ambitious, as it implies a 36 – 42% reduction by 2030 (corresponding to 0.52 – 0.58 $GtCO_2$/a by 2030) compared to today's GHG emissions levels from transport (Table 3). Furthermore, the derivation of GHG budgets is highly uncertain, and here we used estimates based on a 50% probability of limiting global warming to the above-mentioned target. Accordingly, the actual budget should not be fully used in order to increase the probability of actually meeting the target of limiting global warming. Thus, zero GHG transport clearly needs to be achieved before 2050 (Table 3).

The emission reductions required show that the European strategy to reduce GHG emissions from transport by 90% from 2020 to 2050 (i.e., to 0.1 $GtCO_2$/a) is not consistent with the remaining GHG emission budget for 1.5°C as required by the Paris Agreement. Instead, a 90% reduction must be achieved by 2045 at the latest (under the assumption of a linear emission reduction trajectory) to remain within the GHG emission budget for a 50% probability of limiting global warming to 1.5°C by the end of the century.

Table 3: Percentage reduction of transport GHG emissions and absolute transport emissions to stay within 1.5°C budget.

Scenario	**1.5°C no overshoot**				**1.5°C limited overshoot**			
By \ Compared to	1990	2005	2020	$GtCO_2/a$	1990	2005	2020	$GtCO_2/a$
2030	-34%	-47%	-42%	0.52	-27%	-41%	-36%	0.58
2035	-58%	-66%	-63%	0.33	-48%	-57%	-54%	0.42
2040	-82%	-86%	-84%	0.14	-68%	-74%	-72%	0.26
2045	-100%	-100%	-100%	0.00	-88%	-90%	-90%	0.09
2050	-100%	-100%	-100%	0.00	-100%	-100%	-100%	0.00

The obtained 2030 emission reduction can be compared to the aim to reduce Europe's total GHG emission by 55% compared to 1990. The former 40% reduction target was translated into a 43% reduction of GHG emissions compared to 2005 within the ETS and a 30% reduction of the non-ETS emissions (which include transport) under the Effort Sharing Regulation (EU) 2018/842 (note that the overall reduction target usually refers to 1990 as base year whereas ETS and ESR targets usually refer to 2005). It is unclear how the more ambitious 55% target will be translated to reduction targets for ETS and non-ETS emissions. The current "Fit for 55" package proposes a reduction of 61% in the ETS sectors and 40% in the non-ETS sectors compared to 2005, as well as the introduction of a separate ETS for transport and buildings with a reduction of 43% compared to 2005 (corresponding to 0.56 $GtCO_2/a$ by 2030). Graichen et al. (2020) discuss various scenarios and obtain a plausible range of 45 – 49% reduction in the non-ETS emissions by 2030 compared to 2005. If this emission reduction of at least 45% (instead of the proposed 43% reduction) in the non-ETS sector were applied equally to transport and buildings, it would be in line with the linear emission reduction to remain within a 1.5°C GHG budget.

Overall, the derived percentage reduction targets go beyond the current EU policy proposal and thus require tightening existing policies and potentially adding new policies for demand reduction and fast uptake of low-carbon transport technologies, as discussed in the following sections.

5 Discussion of Implications for Road Transport Policies

5.1 Passenger Cars and Light-duty Vehicles

Total car transport GHG emission reduction will be mainly achieved by electrification of vehicle stock, and sales diffusion is only the first step. As the average passenger car age in the EU is 11 years (ACEA 2022), high stock diffusion of PEV takes place several years after high sales diffusion of PEV. However, vehicle use is most intense in the first ten years, and the average vehicle lifetime is around 15 years. Accordingly, if a zero tail-pipe emission passenger car fleet is to be achieved by full direct electrification via PEV, all new passenger car sales need to be electric 15 years before 2044 or 2048, that is, by 2029 or 2033. Similar results have been obtained by the ICCT (2020) and T&E (2018). Likewise, the European Commission's long-term scenario (EC 2018) demonstrates that electrification of passenger road transport is the pathway to zero GHG emissions by 2050. Of course, to achieve zero GHG emissions, even the electrical power system must shift to zero-GHG emitting energy sources. However, given that this is another sector, policies to achieve this are beyond the scope of this paper.

For intermediate targets, the current reduction target of 37.5% by 2030 compared with 2021 will lead to a car stock with average fuel consumption higher than approx. 100 g CO_2/km (measured in the New European Driving Cycle or approx. 125 g CO_2/km acc. to the newer Worldwide Light-duty Testing Procedure). The time lag also implies that the reduction goal of 36 to 42% (by 2030 compared to 2020) for GHG emissions in road transport requires much higher GHG emission reductions of newly sold vehicles. This is consistent with a GHG reduction of 70% in newly sold vehicles until 2030 compared to 2021, as suggested in Mock & Miller (2018).

In conclusion, the new European CO_2 emission reduction targets for newly sold vehicles - update to Regulation (EU) 2019/631- need to be 0 g CO_2/km for newly sold cars by 2030 or, at the latest, by 2033 to be consistent with the 1.5°C GHG emissions budget for transport in EU27. This is earlier than 2035 in the "Fit for 55" package. This appears highly ambitious, but the currently accelerating market diffusion of PEV shows that it is possible. In addition, several European Countries have announced targets to phase out combustion vehicle sales by 2030 or 2035 (Plötz et al. 2019). Thus, zero-carbon car sales by 2030 or before 2035 are not only required to stay within Europe's emissions budget, but also feasible. Investments in charging infrastructure will be needed to accommodate these vehicles. The exact extent and placement of this infrastructure will depend on local and regional factors such as density and share of detached houses (Funke et al, 2019).

PHEV emit several times higher GHG emissions in real-world operation than expected from the manufacturer's specifications according to the official type approval certification scheme under the Worldwide harmonized Light vehicles Test Procedure (WLTP) or New European Driving cycle (NEDC) (Plötz et al. 2021). Thus, their potential role in the transition towards 100% ZEV is an open question. The first step in lowering GHG emissions is to increase the electric range of PHEV and the charging frequency to achieve higher electric driving shares. A second step could be to grant PHEV a slightly longer transition period, e.g., to ban cars with only combustion engines after 2030 but to allow PHEV sales until 2035, as in the UK. Again, in terms of the remaining GHG budget for transport, this is conditional on high electric driving shares, e.g., greater than 80%, of PHEV in real-world operation.

Total GHG emission reduction by the uptake PEV are partially countered by increased emissions from combustion engine vehicles due to the tremendous rise of SUV and off-road vehicles (with a tenfold growth in sales since 2001). There is at least one clear policy option to effectively reduce emissions of newly sold combustion engine vehicles and stimulating PEV growth separately: ZEV mandates. Major global markets such as China (5 phases of fuel efficiency regulation and the 'Made in China 2025' target), and California (2022 Advanced Clean Cars II regulation) use both CO_2 fleet targets for combustion engine vehicles only and ZEV mandates. This is an interesting option for Europe's passenger car CO_2 policies, but any implementation needs to define realistic targets for conventional and electric vehicles.

In summary, we demonstrate how to derive specific policy recommendations from GHG emissions budgets for passenger cars: the remaining GHG budget for transport implies a transition towards 100% ZEV by early 2033 at the latest for both cars and vans, ideally in combination with a drastic reduction of GHG emissions from the remaining combustion engine vehicle fleet. This can be achieved by introducing a strong CO_2 emission reduction target within the update of Regulation (EU) 2019/631or combining absolute CO_2 targets for combustion engine vehicles and ZEV mandates in parallel. The latter approach has the advantage that the ZEV transition and GHG emission reduction from the newly sold passenger cars can be directly controlled. The main policies for passenger cars and required ambition level are summarised in Table 4.

Table 4: Overview and discussion of main policies for zero GHG emissions passenger cars.

Policy or Option	Current State	Fit for 55 proposal	Required ambition
CO_2 fleet targets for newly sold cars	-37.5% by 2030 compared to 2021	-55% by 2030 compared to 2021 and 0 g CO_2/km in 2035	-70% by 2030 compared to 2021 and 0 g CO_2/km in 2033
PHEV as potential low GHG technology	Emission credits	No change	Gap between official and real-world emissions needs to be closed, long-term contribution unclear
ZEV mandates	Not implemented	Not proposed	Separate fuel efficiency increase in new combustion vehicles from PEV growth
Alternative Fuels Infrastructure	Alternative Fuels Infrastructure Directive	Alternative Fuels Infrastructure Regulation	Important and necessary condition but not reducing emissions directly

5.2 Medium and Heavy-duty Vehicles

The current CO_2 fleet regulation for trucks leads to a noteworthy increase of ZEV trucks in sales and stock, yet the remaining GHG emission budget for transport requires a higher ambition. The average age of medium-duty and HDV is 12.4 years, and an analysis of a recent ACEA report shows that 60% of HDV in stock in Europe are more than ten years old (ACEA, 2022). Due to the time required for stock turnover, a 100% reduction target for newly sold trucks in 2034 or 2038 would be consistent with zero GHG emission transport by 2044 to 2048, depending on the state of zero-carbon fuels and the possibility of temporal overshoot. Accordingly, a 55 – 67% emission reduction (in g CO_2/tkm) by 2030 for new trucks would be needed. This appears possible with a wide range of energy efficiency improvements for diesel engines, tyres, and aerodynamics, and especially with a fast transition to ZEV trucks.

Given an ambitious ZEV sales target, GHG emissions from combustion engine trucks in stock can be further reduced by (1) scrappage schemes to replace old highly emitting trucks faster; and (2) a combination of CO_2 fleet regulation for combustion vehicles and ZEV mandates, similar to policies for passenger cars in California and China. This combination would ensure low emissions from the remaining diesel fleet and a fast transition to ZEVs.

The AFID requires EU member states to assess the market diffusion of alternative fuels in vehicles and to ensure an adequate infrastructure build-up. To enable the market diffusion of ZEV trucks, the proposed AFIR explicitly considers charging infrastructure for HDV (with minimum requirements for installed charging capacity along the European highway network). For short- and medium-distance trucks, the installation of electric charging infrastructure is necessary, and plans for the installations are currently being devised (T&E 2020). For long distances, BEV, electric road systems trucks, and FCEV are possible and require additional infrastructure. Therefore, dependent on the market diffusion of vehicles, the installation of fast-charging infrastructure, electric road systems, and hydrogen fuel stations should be considered in the AFID revision.

The main policies for HDV and required ambition are summarised in Table 5.

Table 5: Overview and discussion of main policies for zero GHG emissions heavy-duty vehicles.

Policy or Option	**Current State**	**Fit for 55 proposal**	**Required ambition**
CO_2 **fleet targets for newly sold trucks**	-30% by 2030 compared to 2019/2020	No change proposed as revision is due end of 2022	-55 to -67% by 2030 compared to 2019/2020 and -100% or 0 g CO_2/tkm by 2033 – 2038
ZEV mandates	Not implemented	Not proposed	Separate fuel efficiency increases in new combustion vehicles from PEV growth
Alternative Fuels Infrastructure	Alternative Fuels Infrastructure Directive	Alternative Fuels Infrastructure Regulation	Important and necessary condition but not reducing emissions directly
Policy or Option	Current State	Fit for 55 proposal	Required ambition

6 Discussion

A European GHG budget for the transport sector can provide clear guidance for the required emission reductions. Currently, the transport sector is covered by the EU Effort-Sharing Regulation, which provides GHG emission reduction targets for the non-ETS emissions of all Member States. Setting up an individual ETS for the EU transport sector based on the GHG budget derived in this article would limit the option to delay GHG emission reductions in the transport sector to the future. The "Fit for 55" package proposes creating a joint ETS for transport and buildings with an aimed reduction of 43% by 2030 (compared to 2005). While ambitious, the target might not be enough to stay within the GHG emissions budget if no overshoot is allowed and if one considers that full compliance is only expected after 2026. Furthermore, our analysis is not a comprehensive assessment of the “Fit for 55” package. Instead, our focus is on GHG mission budgets (including road transport, railways, inland navigation, and intra-European aviation but excluding international aviation and shipping) and general implications for policy instruments according to GHG budgets.

The derived GHG emission budget for transport is to be understood within the UNFCCC emission accounting framework (IPCC 2006). Within this international standard for GHG emission accounting, a vehicle without tail-pipe is "zero emission" vehicle. Of course, additional electricity consumption in end-use sectors leads to higher electricity generation potentially (depending on the fuel mix) connected to higher GHG emission from the energy sector. Of course, for Europe's contribution to global warming, emissions should not be shifted from one GHG sector to the other. Thus, the overall approach used here with a division into different GHG emission sectors (1) follows international GHG accounting frameworks, but also (2) assumes that all GHG emission sectors reduce their GHG emissions to zero or near zero to achieve overall GHG neutrality by mid-century. Otherwise, the introduction of PEV would clearly reduce energy demand from transport but potentially shift GHG emissions to another sector. On the other hand, the strong and fast shift towards electricity in road transport requires large investments into distribution grids and demand shift measurements to ensure grid stability during the transition towards PEV. These also require additional policy effort but are beyond the scope of the paper.

To ensure that the transport GHG emissions budget is met, phasing-out conventional combustion engine vehicles is necessary but insufficient. As long as all vehicles are not ZEV, the activity volume measured in person-km and tonne-km will be important to address. Several modelling efforts at national (Larsson et al 2021, Brand et al, 2020) and global levels (Fulton et al. 2021; Creutzig et al, 2018) show that technological shifts such as increased electrification will not be enough to reach stringent emission targets but need to be coupled with lifestyle and demand side measures. The “Avoid-Shift-Improve” guidance (Schipper and Marie-Liliu, 1999) can provide a good framework for designing local, national and European policies. Avoiding trips might be achieved by better land-use planning and restricting car use in central areas. Shifting to more sustainable modes such as public transport, biking and mobility service could be achieved by extension and improved operation of public transport, better biking infrastructure and reformed parking policies. Focusing on these policies can also help address other issues such as health, equity, noise, and safety (Brand et al., 2020). This is a policy field where local action can be highly effective, e.g. in terms of urban access areas, parking fees and limiting parking spaces. Likewise, reduced motorisation and modal shift to low-carbon modes can yield important contributions to low-carbon transport (see Axsen et al. 2020, Creutzig et al. 2022, Hook et al. 2020) but are beyond the scope of the present paper.

Carbon pricing, such as a fuel carbon tax, can play an important role in travel demand reduction and mode shifting. High road transport prices reduce car and truck travel activity and make train and active travel more attractive. This, however, will not be sufficient since other factors, such as the quality of the train network and last- and first-mile issues may hinder a shift to other modes. Likewise, high taxation and carbon prices for aviation could shift transport to more sustainable high-speed and night trains. The existing targets for tripling passenger rail transport and doubling rail freight transport until 2050 are strong indicators of Europe's ambitious commitment to shift transport from road and air to railways. Infrastructure roll-out, a comprehensive night train network and strong pricing policies need to support this shift to more sustainable rail transport.

7 Conclusions and Policy Recommendations

A Paris-compatible GHG emissions budget for EU road transport requires zero-carbon transport before 2050. Emission budgets for GHG emissions of the EU27 in line with 1.5°C of global warming indicate 10 – 12 Gt CO_{2eq} for transport. At present annual emissions, EU27's road transport GHG emissions budget would be used up in 11 – 13 years, and all further emissions would contribute to global warming permanently above 1.5°C.

Currently, the EU is not on track for zero-carbon transport consistent with the Paris Agreement. To remain on track, transport emissions have to be reduced by 36 – 42% from current levels by 2030 and fall to zero by 2044 – 2048. By 2030, this linear reduction path is compatible with a plausible sectoral split of Europe's current goal of –55% in total GHG emissions by 2030 (compared to 1990). However, the current EU Sustainable Mobility Strategy aims at a 90% GHG emission reduction from today's levels by 2050 (compared to today), whereas a 1.5°C GHG emissions budget for transport requires a 90% reduction already by 2042 – 2045.

The following policy recommendations can be derived from our analysis for designing a policy mix for road transport compatible with Europe's commitment to the Paris Agreement.

- Accelerate the phase-out of combustion engine vehicles: 2033 the latest for passenger cars and 2034-2038 for trucks
- Ambitious European standards for fast charging electric cars and trucks,
- Carbon pricing, should be seen as a complement and not as a substitute to ambitious CO_2 fleet targets and quotas. Also, the changes to the Energy Taxation Directive will not be enough to compensate for the too-low fleet targets.

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A.1 Supplement: Method to derive emission budgets for the EU transport sector from global emission pathways

In the article, we present a globally cost-effective EU transport sector share of the global 1.5°C emission pathways based on data from the IPCC SR1.5, the corresponding scenarios as well as data from the POLES-Enerdata model, namely the 2018 Enerfuture global energy scenarios and associated marginal abatement cost curves (MACC) (See https://www.enerdata.net/solutions/poles-model.html for a description of the POLES model and https://www.enerdata.net/research/forecast-enerfuture.html for a description of the Enerfuture global energy scenarios). Our calculations are based on 1.5°C pathways with no or limited overshoot in the IPCC SR1.5 REF), which can be considered Paris-compliant (Wachsmuth et al. 2018). Here, we describe the technical details how we translate the global pathways into an emission budget for the EU transport sector step by step. We closely follow Zaklan et al. 2021 here, where the same approach has been applied to the EU ETS. In particular, we start with their global pathway for energy- and process-related GHG emissions based on below-1.5°C pathways in the IPCC SR1.5m, which is provided in the online supplementary material.

Step 1: Derive corresponding regional and sectoral emission pathways by applying a global carbon price pathway based on the POLES-Enerdata model (2018 version)

In each time step, we translate the global energy- and process-related GHG emission pathways for the perod 2025 – 2050 from Zaklan et al. (2021) into national emission levels by applying a globally uniform shadow carbon price pathway that yields the globally required emission reductions according to the MACCs coming from the POLES-Enerdata model. The resulting carbon price levels are 220 USD/t in 2025, 800 USD/t CO_2e in 2030 for the 1.5°C pathways with no overshoot, and 220 USD/t in 2025, 440 USD/t in 2030, 1000 USD/t in 2035 for the 1.5°C pathways with no or limited overshoot, respectively. The steep increases reflect a sharp abatement cost increase beyond a certain level of mitigation. For the years after 2030 and 2035, respectively, the required emission reduction exceeds the reduction at the maximum carbon price of 1200 USD/t in POLES-Enerdata. Therefore, we assume the existence of a backstop-technology (e.g. a negative emissions technology) and scale the minimum sectoral emission levels in POLES to the required level uniformly across sectors. Then the globally uniform shadow carbon price is applied to derive a cost-effective share of the global emission pathway for the EU. The described scaling of the emissions after 2030 is applied here as well. This results in energy- and process-related GHG emission level in the EU of 1.7 Gt CO_2e in 2030, 0.5 Gt CO_2e in 2040 and 0.1 Gt CO_2e in 2050 for the 1.5°C pathways with no overshoot and of 2.0 Gt CO_2e in 2030, 0.8 Gt CO_2e in 2040 and 0.4 Gt CO_2e in 2050 for the 1.5°C pathways with limited overshoot (see Table A-1).

Table A-1: Annual energy- and process-related GHG emissions of the EU in a cost-effective pathway compatible with a global below-1.5°C pathway

[Gt CO_2e]	2025	2030	2035	2040	2050
For 1.5°C with no overshoot	2.7	1.7	1.0	0.5	0.1
For 1.5°C with limited overshoot	2.7	2.0	1.4	0.8	0.4

Step 2: Derive a consistent evolution of the EU transport sector's GHG emissions

The ENERDATA-Poles model provides data at the sector level for the transport sector and at the sub-sectoral level for road transport, aviation and other modes. We apply the globally uniform shadow carbon price from Step 1 to the transport sector and its sub-sectors to derive a cost-effective share for each of the sectors in the EU. This results in EU transport emissions of about 0.51 Gt CO_2e in 2030, 0.16 Gt CO_2e in 2040 and nearly net-zero emissions in 2050 for the 1.5°C pathways with no overshoot and 0.56 Gt CO_2e in 2030, 0.23 Gt CO_2e in 2040 and 0.12 Gt CO_2e in 2050 for the 1.5°C pathways with limited overshoot (see table A-2).

Table A-2: Annual GHG emissions of the EU transport sector in a cost-effective pathway compatible with a global below-1.5°C pathway

[Gt CO_2e]	2025	2030	2035	2040	2050
For 1.5°C with no overshoot	0.70	0.51	0.30	0.16	0.02
For 1.5°C with limited overshoot	0.70	0.56	0.42	0.23	0.12

Step 3: Derive a cost-effective EU transport sector budget by calculating the cumulative emissions of EU transport sectors in a cost-effective pathway

The global IPCC emission pathways have used 2015 as a base year. Therefore, we extend the EU transport sector pathways to 2015 – 2050 based on the ENERDATA-Poles data for 2015 and 2020. In the calculation of the cumulative emissions for the period 2016 to 2050, we then assume a linear decline in 2015-2020, 2020-2025, 2025-2030, 2030-2040 and 2040-2050 For the calculation, we multiply the mean of the end and start year of the various periods with the corresponding number of years, and add up the results for all periods. Afterwards, we add half of the value in 2050 and reduce the result by half of the value in 2015 to obtain the result for the period 2016 to 2050. Therefore, we subtract the cumulative emissions for 2016 – 2020, which we estimate from the EU's official GHG inventories for 2018 (EEA 2021) and an extrapolation of trends (2005-2018) to 2020 per subsector. In this way, the cost-effective GHG emission budget for the EU transport sector is calculated to be about 10 Gt for the 1.5°C pathways with no overshoot and 12 Gt for the 1.5°C pathways with limited overshoot (see table A-3).

Table A-3: EU GHG budget for the years 2021 – 2050 consistent with long-term warming of 1.5°C and the share of transport by transport mode

EU GHG budget in Gt $CO_{2eq.}$	Road	Aviation	Rail, navigation and other	Total Transport	Total energy- and process-related emissions budget
for 1.5°C with no overshoot	9.7	0.24	0.29	10.2	37.3
for 1.5°C with limited overshoot	11.5	0.30	0.35	12.1	44.3