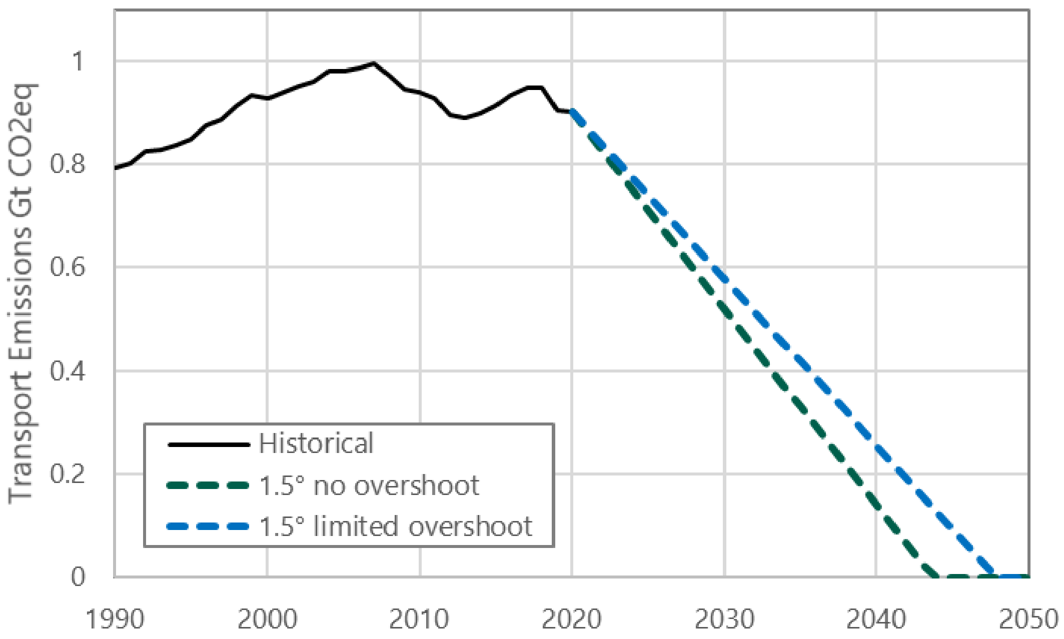

Net-zero-carbon Transport in Europe until 2050

Targets, technologies and policies for a long-term EU strategy

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Net-zero-carbon transport in Europe until 2050

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Summary

Background and Motivation

The European Union (EU) is committed to the ambitious target of climate neutrality by 2050, to keeping global warming well below 2°C, and to making efforts to limit it to 1.5°C. The long-term target of climate neutrality and the ambition of the Paris Agreement imply climate-neutral transport by 2050 unless large-scale negative emissions in other sectors are assumed. Transport is currently responsible for about one quarter of energy-related greenhouse gas (GHG) emissions in the EU.[1]

The recent European agreement to reduce GHG emissions by 55% until 2030 (compared to 1990 emission levels) and the Green New Deal make a reconsideration of EU transport policies very timely. Furthermore, the European Commission published its Sustainable and Smart Mobility Strategy in December 2020 (EC 2020) and the year 2021 will see new legislative proposals to meet the more increased -55% target for GHG emissions in 2030 (compared to 1990). Most importantly for transport, both the CO_2 fleet targets for newly sold passenger cars and light commercial vehicles for 2030 and the alternative fuel infrastructure directive (AFID) will be reviewed or revised in 2021. The current year thus provides a unique opportunity to re-think and re-align European transport policies to meet the EU's contribution to the Paris Agreement.

The present policy brief derives domestic transport emission budgets for the EU-27 until 2050 and presents implications for transport policies in Europe.

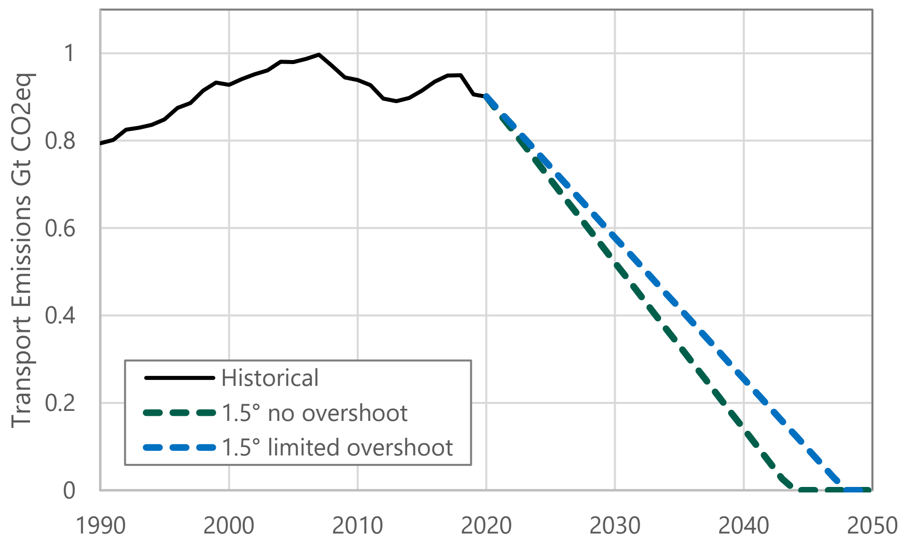
Main Findings

A Paris compatible greenhouse gas budget for Europe requires zero carbon transport before 2050. Domestic emission budgets for energy- and process-related GHG emissions of the EU-27 in line with 1.5°C of global warming indicate further 37 – 44 Gt CO2eq. can be emitted. Deriving a share for transport either based on abatement costs or on transport's current share in greenhouse gas emissions leads to 10.2 – 12.1 Gt CO2eq., where the range depends on whether limited overshoot of the 1.5°C target is allowed or not. Current GHG emissions from transport in Europe are 0.9 Gt CO2eq. annually (excluding international bunkers for international navigation and aviation). At current annual emissions, Europe's transport carbon budget would be used up in 11 – 13 years and all further emissions would contribute to global warming permanently above 1.5°C.

The EU is not on track for zero carbon transport consistent with the Paris agreement. To remain within the GHG emission budget, transport emissions have to be reduced by 36 – 42% from current levels until 2030 (or 41 – 47% compared to 2005) and go to zero until 2044 – 2048, if a linear emission reduction path is assumed. The more ambitious reduction path is for a scenario without overshoot of the 1.5°C target and the less ambitious scenario with limited overshoot. For 2030, this linear reduction path is consistent with Europe's current goal of –55% in total GHG emissions until in 2030 (compared to 1990 levels), if a similar reduction level is assumed for transport. However, the current EU sustainable mobility strategy aims at 90% GHG emission reduction from today's levels until 2050 (compared to today) whereas a 1.5°C carbon budget for transport requires a 90% reduction already until 2042 – 2045. The historical emissions since 1990 and the two linear reduction paths are shown in the following figure. The required percentage emission reductions are summarised in the following table.

[1] See EU (2020), these numbers exclude international maritime traffic departing from the EU-28 but include international aviation departing from the EU-28.

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



Source: Own calculations and UNFCC (2021) for historical data.

Table: Percentage change of transport GHG emissions for linear emission reduction.

Scenario	1.5° no overshoot			1.5° limited overshoot		
Until \ Compared to...	**1990**	**2005**	**2020**	**1990**	**2005**	**2020**
2030	-34%	-47%	-42%	-27%	-41%	-36%
2035	-58%	-66%	-63%	-48%	-57%	-54%
2040	-82%	-86%	-84%	-68%	-74%	-72%
2045	-100%	-100%	-100%	-88%	-90%	-90%
2050	-100%	-100%	-100%	-100%	-100%	-100%

Source: Own calculations.

Net-zero carbon transport before 2050 is feasible but existing policies need to be tightened. Several studies have already discussed the path to net-zero carbon transport until 2050. The current fast market uptake of plug-in electric vehicles and the statements of several major global vehicle manufacturers to phase out combustion engine sales in cars until 2035 and in trucks until 2040 show that a fast transition in road transport is possible. Policy makers can seize the current momentum to tighten existing CO_2 fleet targets for passenger cars and trucks. High speed rail and night trains offer the possibility to reduce future demand growth in aviation and rail transport is already mostly electrified. Yet, additional action is needed to achieve zero carbon aviation and shipping. Demand reduction and sustainable zero carbon fuels appear as the main options that should be quickly implemented.

CO_2 fleet targets for passenger cars and trucks need to be much more ambitious. For passenger cars, the 2030 targets are reviewed this year and a reduction of 80% until 2030 compared to 2021 as well as a transition to 0 gCO_2/km for cars no later than 2033 are consistent with a 1.5°C carbon budget for transport. Several major European manufacturers have already announced that more than two third of the newly sold vehicles will be electric in 2030. For trucks, the currently required 30% reduction until 2030 is too slow as the slow stock turnover requires a 100% reduction target for newly sold trucks already in 2034 or 2038 (depending on the state of zero carbon fuels and the possibility of temporal overshoot). Accordingly, a 55 – 67% reduction until 2030 for newly trucks would be needed. This appears possible as many technical options for energy efficiency improvements are available, e.g. for diesel engines, tires, and aerodynamics, as well as a fast transition to zero-emission trucks (the manufacturers have announced the target of 100 % ZEV trucks in sales by 2040).

Infrastructure and low-carbon fuel policies support the transition in road transport and reduce GHG emission from combustion engines. Fast infrastructure roll out for electric cars and alternative fuel trucks are required. The existing AFID offers a suitable framework and should set ambitious infrastructure targets for the EU Member States for electrification of both light and heavy-duty vehicles. Ambitious low-carbon fuel standards will reduce the emissions of the remaining combustion engine vehicle fleet.

New policies can accelerate the uptake of electric vehicles and ensure emission reduction of vehicles with combustion engines. A high share of zero-emission vehicles (ZEVs) allows highly emitting conventional vehicles (both cars and trucks) to enter the market and emit more CO_2 than expected from the fleet reduction targets. Ideally, a CO_2 emission reduction of newly sold combustion vehicles and the market uptake of ZEVs take place simultaneously in the next decade as the efficiency of both electric or combustion engine vehicles is relevant. The combination of CO_2 fleet targets purely for combustion engine vehicles and ZEV mandates, i.e. fixed ZEV sales quotas for vehicle manufacturers offers this possibility. Such an approach is already laid out in the Chinese dual-credit policy as well as in the Californian ZEV mandates. The EU should carefully assess the benefits and draw backs of such a policy combination in Europe.

Pricing and mode shift can support the transition to zero carbon transport. Deep GHG emission reduction targets can be supported by a shift to low-carbon modes and by travel demand reduction. Carbon pricing can play an important role in both aspects as high road transport prices reduce car and truck travel activity and make train and active travel by foot and bike more attractive. 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 for 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 the more sustainable rail transport.

A transition to sustainable zero carbon fuels is needed for aviation and navigation. Direct electrification of aviation and navigation even for domestic European transport is very unlikely in large stock shares until mid of the century for aviation and navigation despite already existing small scale electric ferries and first electric and hydrogen plane concepts. Strong carbon pricing can reduce additional growth of future travel activity and the introduction of quotas for sustainable zero carbon fuels allows a step-by-step pathway to carbon neutral navigation and aviation. However, more research is required on how to tackle non-CO_2 global warming effects of aviation in high altitudes.

Elements of a Policy Roadmap for a Future Low Carbon Transport Policy Mix in Europe

The following points can provide guidelines for designing a policy mix that fosters zero-carbon transport in line with Europe's commitment towards zero carbon transport that is compatible with Europe's commitment to the Paris Agreement, i.e. to pursue efforts to limit global warming to 1.5°C.

1. **CO_2 fleet targets for newly sold cars** in Europe have to be much more ambitious. An 80% reduction of the average emissions of newly sold vehicles until 2030 compared to 2021 is needed as well as a target of 0 gCO_2/km for cars no later than 2033. Similar targets hold for light-commercial vehicles.
2. **CO_2 fleet targets for trucks** need to be tightened. A 55 – 67% reduction until 2030 compared to 2020 for newly trucks is needed followed by a 100% reduction target for newly sold trucks already in 2034 – 2038.
3. **Infrastructure for alternative fuel vehicles** is required for a fast and successful transition to 100% ZEV in cars and trucks. An ambitious rollout and joined European standards are needed

for fast charging of electric cars and trucks. The role of fuel cell vehicles in road transport is still uncertain and requires adaptive planning and policies.

4. Aviation and Navigation require sustainable zero carbon fuels. This transition can be ensured by introducing **quotas for sustainable zero carbon fuels** that start as soon as possible and reach 100 % by 2044 – 2048, compatible with the linear reduction path of a 1.5°C GHG emission budget for Europe.
5. **Carbon pricing**, e.g. via taxation or an emission trading scheme in transport, can support the shift to low-carbon modes such as rail, public transit or bike, but will not alone deliver deep GHG emission reductions and should be seen as complement and not as substitute to ambitious CO_2 fleet targets and quotas.

1 Background and Motivation

Both Germany and the EU have recently committed to the ambitious target of climate neutrality by 2050. In addition, the recent European Council's decision from Dec. 2020 sets a more ambitious greenhouse gas (GHG) reduction target for 2030: A reduction by 55% compared to 1990 Emission levels in the EU. We have thus seen a recent increase in GHG mitigation ambition. The Paris Agreement calls for net-zero greenhouse gas (GHG) emissions in the second half of the 21st century, keeping global warming well below 2 °C and efforts to limit it to even 1.5 °C (UNFCCC 2015). All member states of the European Union have committed to the Paris Agreement.

The long-term target of climate neutrality and the ambition of the Paris Agreement imply climate neutral transport by 2050 unless large scale negative emissions in other sectors are assumed. Transport is currently responsible for one quarter of energy related GHG emissions in the EU (EU 2020; excluding international maritime traffic departing from the EU but including international intra-EU aviation). Transport is the only sector in Europe with GHG emissions still growing as all past efficiency improvements have been compensated by activity increase. Thus, GHG neutrality in transport appears particularly demanding.

The recent announcements on the European level make a reconsideration of EU transport policies very timely. The commission published its Sustainable and Smart Mobility Strategy in Dec. 2020 and the year 2021 will see new legislative proposals to meet the more increased -55% target for GHG emissions in 2030 (compared to 1990). Most importantly for transport, the CO_2 fleet targets for newly sold passenger cars for 2030 will be reviewed and the alternative fuel infrastructure directive will be revised in 2021. The current year thus provides a unique opportunity to re-think and re-align European transport policies to meet the Europe's contribution to the Paris Agreement.

The aim of the present policy brief is (1) to derive indicative GHG budgets for the European transport sector and (2) to outline implications for transport policies in Europe based on the derived transport GHG emission budget and existing scientific evidence on GHG mitigation policies in transport. The present report thus aims at to providing scientific input to the European policy discussion.

The outline is as follows. Section 2 derives indicative GHG budgets for the European transport sector. Section 3 provides a short overview of available technologies and their potential contribution to carbon neutral transport and discusses the implications for transport policies are discussed, followed by conclusions in Section 4.

2 An Indicative CO_2 Budget for Transport and Resulting Emission Targets

2.1 Indicative GHG Emission Budget for Transport

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 and co-workers (2021) as a starting point to derive indicative emission budgets for the EU transport sector. The authors 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 (see Zaklan et al. (2021) for details) to the transport sector and its subsectors road transport, intra-EU aviation and other, with the latter including rail and navigation in particular. We focus on peak budgets here, i.e. limits to the cumulative emissions until net-zero emissions are reached, as one main approach to obtain emission budgets (see 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 budgets refer to cumulative emissions since 2018. Therefore, we need to subtract the cumulative emissions for 2018 – 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. The first pathway is without overshoot to reach the goal of 1.5°C warming during the 21st century. Here, we obtain a total energy- and process-related emission budget for the EU of about 37 Gt CO_2eq. and about 10 Gt CO_2eq. for the transport sector. The 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 the second pathway, the overall GHG emission budget increases to about 44 Gt CO_2eq. with a share of about 12 Gt CO_2eq. for the transport sector. In both cases, about 95% of the transport emission budget are allocated to road transport and almost half of the remaining budget is foreseen for the intra-EU aviation according to our methodology. These values are fully consistent with current shares of the GHG from transport in 2015 (EC 2020). Please note that we exclude international aviation leaving the EU and international maritime transport, so-called bunkers, as these are separately regulated under the Paris Agreement.[2]

The total remaining GHG budget for transport in Europe is 10.2 Gt CO2eq. in the 1.5°C pathway without overshoot and 12.1 Gt CO_2eq. with limited overshoot. These values are comparable to earlier rough estimates of a transport GHG budget in T&E (2018). This and the mode specific budgets are summarised in the following Tables 1 and 2.

Current greenhouse gas emissions from transport in Europe are 0.9 Gt CO2eq. annually (excluding international bunkers for international navigation and aviation). At current annual emission level, Europe's transport carbon budget would be used up in 11 – 13 years and all further emissions would contribute to global warming permanently above 1.5 °C. This demonstrates the urgency of policy action.

[2] The most recent numbers for 2018 are as follows: intra-EU aviation 15.0 Mt CO_2eq., international aviation 129.2 Mt, road transport 786.2 Mt, railways 4.3 Mt, intra-EU navigation 16.6 Mt, international navigation 138.4 Mt and 5.9 Mt other transportation (EC 2020).

Table 1: EU and transport CO_2eq. budget for the years 2021 – 2100 consistent with long-term warming of 1.5°C

EU GHG budget in Gt CO_2eq.	Energy- and process-related emissions budget	Transport emissions budget
for 1.5 °C no overshoot	37.3	10.2
for 1.5 °C with limited overshoot	44.3	12.1

Source: Own calculations based on Zaklan et al (2021) and Wachsmuth et al. (2019).

Table 2: Overview of CO_2 budget by transport mode

Carbon budget in Gt CO2eq.	Road	Aviation	Rail, navigation and other	Total Transport
for 1.5 °C 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**

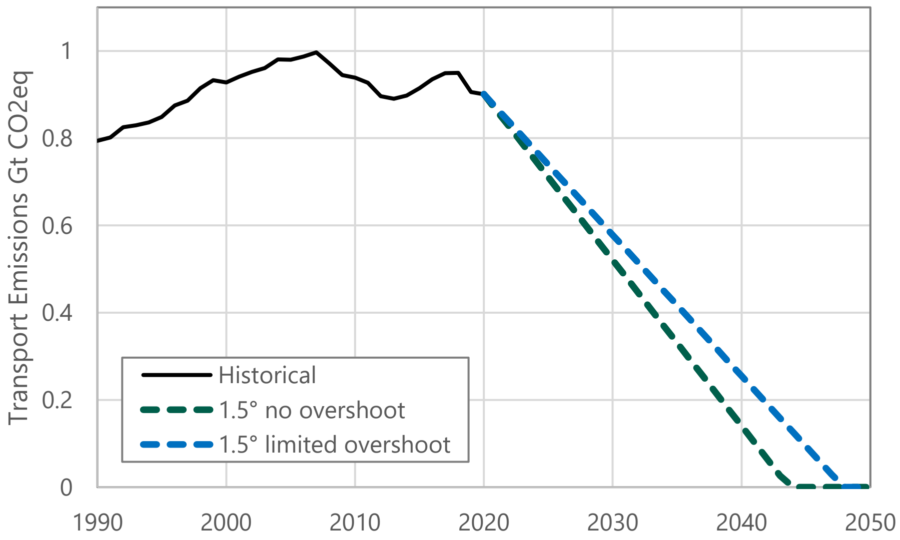
Source: Own calculations.

2.2 Emission reduction targets

The remaining GHG emission budget can be translated into GHG emission pathways over time. The simplest approach is to assume a linear reduction to zero from current emission levels. The resulting trajectory for both pathways, with and without limited overshoot, are shown in Fig. 1.

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

Historical GHG emissions from transport are shown in black and linear reduction trajectories without overshoot in green and with limited overshoot in blue.



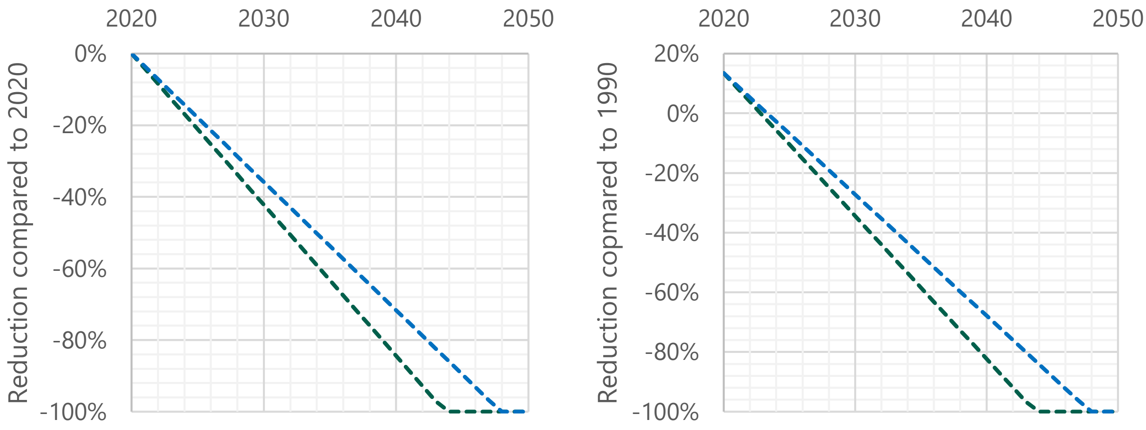
Source: Own calculations and UNFCC (2021) for historical data.

The linear GHG emission reduction leads to GHG neutral transport in the EU by 2044 if overshoot is to be avoided or by 2048 to be consistent with limited overshoot scenarios. This is more ambitious than the current EU "Sustainable and Smart Mobility Strategy" which aims at 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, is the same. On the other hand, if GHG emissions from transport would be reduced faster, GHG neutrality could be achieved later then 2044 or 2048, respectively. Note, however, that the linear emission reduction is already quite ambitious as it implies a 41 - 42% reduction until 2030 compared to today's GHG emissions levels from transport (cf. Table 3). Furthermore, the derivation of carbon emission 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 to increase the probability to actually meet the targeting limiting of global warming. Thus, zero GHG transport clearly needs to be achieved before 2050.

The emission reduction trajectories can be translated to percentage reduction trajectory as shown in Figure 2 and Table 3.

Figure 2: Required transport GHG emission reductions.

Linear percentage reduction trajectories without overshoot in green and with limited overshoot in blue compared 2020 (left panel) and 19990 (right panel) transport emission levels.



Source: Own calculations.

Table 3: Percentage change of transport GHG emissions.

Shown are the percentage changes in transport GHG emissions for linear emission reduction in scenarios with and without limited overshoot compared to emission levels in 1990 2005, and 2020.

Scenario	1.5° no overshoot			1.5° limited overshoot		
Until \ Compared to…	1990	2005	2020	1990	2005	2020
2030	-34%	-47%	-42%	-27%	-41%	-36%
2035	-58%	-66%	-63%	-48%	-57%	-54%
2040	-82%	-86%	-84%	-68%	-74%	-72%
2045	-100%	-100%	-100%	-88%	-90%	-90%
2050	-100%	-100%	-100%	-100%	-100%	-100%

Source: Own calculations.

The emission reductions required show that European strategy to reduce GHG emissions from transport by 90% from 2020 to 2050 is not consistent with the remaining GHG emission budget for 1.5°C as required by the Paris Agreement. Instead, a 90% reduction needs to 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.

The obtained 2030 emission reduction can be compared to the recent announcement to reduce Europe's GHG emission by 55% compared to 2005. The former 40% reduction target was translated into a 43% reduction of GHG emissions within the emission trading system (ETS) and a 30% reduction of the non-ETS emissions under the Emission Sharing Regulation (EU) 2018/842. It is not yet clear how the more ambitious 55% target will be translated to reduction targets for ETS and non-ETS emissions. Graichen et al. (2020) discuss various scenarios and obtain a plausible range of 45 – 49% reduction in the non-ETS emissions until 2030 compared to 2005. If this emission reduction in the non-ETS sector would be applied equally to transport and buildings, this would be in line with the linear emission reduction to remain within a 1.5°C GHG budget.

The derived percentage reduction targets require to tighten existing policies and potentially add new policies for demand reduction and fast uptake of low-carbon transport technologies as will be discussed in the following sections.

3 Technological Contributions and Policy Implications

3.1 Introduction

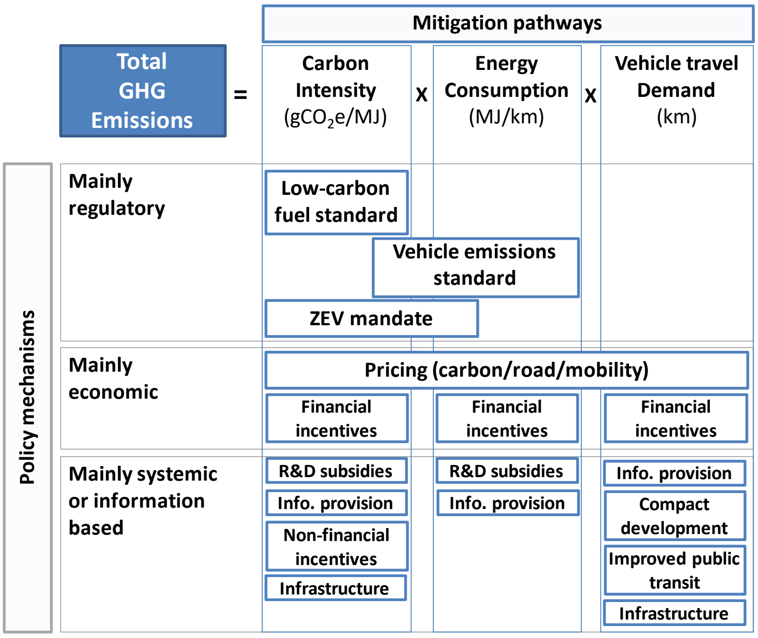
Overview

GHG emissions in transport are the product of transport activity (measured in km travelled), energy consumption (measured in MJ/km), and carbon content of the fuel (measured in gCO2/MJ). Emission reduction can thus be achieved by demand reduction, mode shift and more efficient vehicles, as well as low carbon fuels. Accordingly, transport GHG Emissions can be reduced by three levers:

1. Reduce the carbon content of the fuel. This is applicable to all modes and could mean the introduction and large scale deployment of, e.g., low-carbon or carbon free electricity, sustainable biofuels, and synthetic fuels.
2. Reduce the energy consumption per kilometre for all modes individually and shift demand to more efficient modes, e.g. from road to rail. On the policy side, potential instruments include fuel efficiency targets in new vehicles or zero-emissions vehicles (ZEV) quotas among many others.
3. Reduce travel demand in passenger and freight transport.

Figure 3 below summarises the three levers to reduce GHG emissions from transport and provides more examples for potentials policies (Axsen et al. 2020). Please note that this approach is similar to the "avoid-shift-improve" paradigm to GHG emission reduction in transport. There, "avoid" means to reduce travel demand, "shift" means to shift transport to more sustainable modes such as rail instead of aviation for long-distance intra-EU travel, and "improve" means higher efficiency or lower carbon content of existing modes.

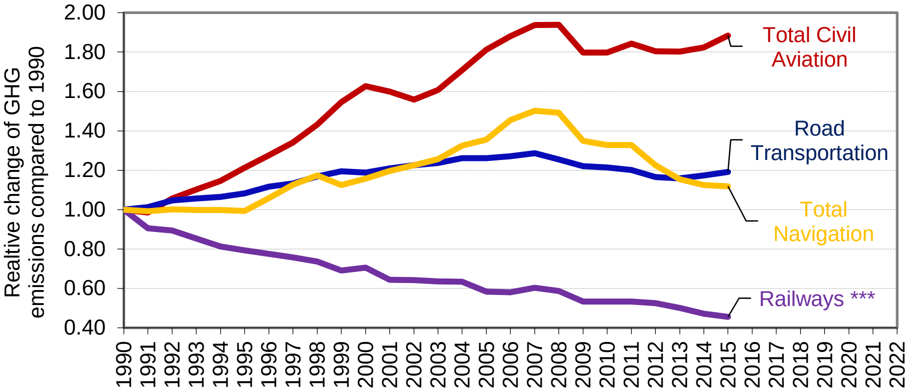
Figure 3: Mitigation pathways and example policies



Source: Axsen et al. (2020).

As the aim under discussion for the present policy brief is full GHG emission elimination in transport, travel reduction alone cannot be the solution as it would imply zero travel activity. However, strong activity growth over the past has led to GHG emission growth in all modes but rail (see Figure 4). Accordingly, travel demand reduction can clearly support the decarbonisation of transport and has thus to be addressed. This is in particular the case in modes that are technically difficult or expensive to convert to zero emissions in the next one or two decades.

Figure 4: GHG Emissions from transport in Europe by mode.



Source: EC (2020)

Much attention in the public discussion and scientific literature has been devoted to new highly efficient technologies. Yet, travel reduction and shift towards more sustainable modes are relevant options apart from replacing high-carbon technologies by low carbon options. We will discuss travel reduction, pricing and the shift to rail before a deeper look at mode specific technologies in the subsequent sections.

Travel reduction

Reduced vehicle travel activity reduces energy use and thus GHG emissions from transport. There are three general ways to achieve such vehicle travel reduction in passenger transport: (1) the support of cycling and walking, (2) improvement of public transport, and (3) more compact spatial planning and building (Axsen et al. 2020).

The shift to cycling and walking can be supported through policies on infrastructure improvements, safety measures and information campaigns (Aldred & Jungnickel 2014; Lanzendorf & Busch-Geertsema 2014). Yet, a very strong mode shift to bike requires decades of focussed infrastructure and pricing policies such as in the Netherlands (Gössling 2013). Accordingly, a shift to cycling can contribute to the required GHG emission reduction from transport but alone will not supply the very deep emission reductions (Zuehlke 2017; Maizlish et al. 2017; Zahabi et al. 2016).

The shift to cycling and walking can be supported through policies on infrastructure improvements, safety measures and information campaigns (Aldred & Jungnickel 2014; Lanzendorf & Busch-Geertsema 2014). Yet, a very strong mode shift to bike requires decades of focussed infrastructure and pricing policies such as in the Netherlands (Gössling 2013). Accordingly, a shift to cycling can contribute to the required GHG emission reduction from transport but cannot alone supply the very deep emission reductions (Zuehlke 2017; Maizlish et al. 2017; Zahabi et al. 2016) but they can contribute to a reduction of motorized vehicle travel.

Public transport can be mainly supported by pricing policies and infrastructure development. In practice, however, mode choice is determined by large number of factors including travel time, cost, comfort, safety, flexibility, luggage, and others. Accordingly, pricing and infrastructure policies can and do support the shift towards public transport but the existing evidence shows that the GHG impacts from public transit investment are very limited in developed countries (McIntosh et al. 2014; Liddle 2013; Carroll et al. 2019).

Finally, compact city development and spatial planning clearly impact the transportation choices of the inhabitants. Denser neighbourhoods lead to reduced vehicle kilometres. However, existing studies suggest only limited impact on vehicle travel in the long-term which are far away from deep GHG emission reductions (Ewing & Cervero 2010; Svens 2017). Again, then can contribute to the long-term goal of sustainable transport but they should not be expected to deliver noteworthy GHG emission reductions until 2050.

In summary, travel reduction alone will not be sufficient to reach deep GHG reduction as required by Europe's limited GHG budget. However, policies supporting active travel and reduction of vehicle kilometres travelled can reduce the pressure on technological options such as electrification, offset the additional emissions from otherwise upcoming vehicle activity growth and provides additional health and societal benefits (Marcotullio & Marshall 2007; Wang, et al. 2007; Axsen et al. 2020).

Pricing

Carbon pricing is a frequently discussed policy to reduce transport GHG emissions. But pricing alone has only a limited effect and is not sufficient for deep decarbonisation (Liliiestam et al. 2021). Most research on carbon prices in transport has focused on carbon taxes for the case of road transport amended by some studies of emission trading systems (Creutzig et al. 2011; Flachsland et al 2011; Verhoef et al. 1997).

A main aspect for a carbon price to contribute to deep GHG targets is the price level. There are very few examples of high prices such as Sweden (114 €/t), Switzerland (89 €/t), and Finland (62 €/t) (World Bank Group 2019). Road pricing, e.g. as road tolls, restricted area pricing, congestion-based pricing and parking prices are other means to reduce vehicle use. Existing studies show that high enough prices present over a long time can reduce CO_2 emissions by 2-13% and reduce vehicle travel by 4-22% (Axsen et al. 2020; Cavallaro et al. 2018; Rodier 2009).

In conclusion, carbon prices accelerate the transition in product choice, reduce vehicle travel and rebound effects as well as incentivise the shift to low carbon modes (Axsen et al. 2020). Yet, as very high carbon prices seem politically challenging and do not address other market failures that prevent a transition to low-carbon technology, carbon pricing can provide a complement to other strong climate policies as those outlined above.

Shift to from Air to Rail

High taxation and carbon prices for aviation could shift transport to more sustainable high-speed and night trains. The targets for tripling passenger rail transport and doubling rail freight transport until 2050 are strong indicators for 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 the more sustainable rail transport.

In summary, non-technical options can support the transition to sustainable zero carbon transport but will not alone be sufficient. Accordingly, we will briefly discuss the potential contribution due to the diffusion of new technologies in the different modes before we discuss policy implications.

3.2 Passenger Cars and light-duty Vehicles

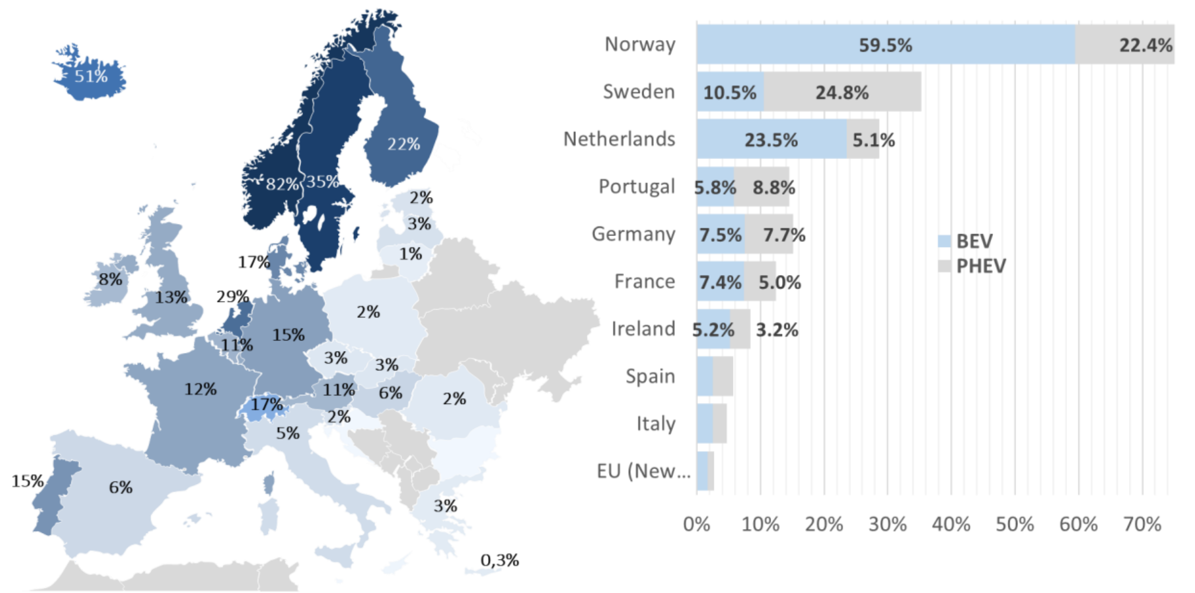
3.2.1 Technological Contribution

In 2020, passenger cars were responsible for about 12% of the total EU GHG emissions and about 60% of transport GHG emissions (EC 2020). To reduce GHG emissions of passenger cars and light-duty vehicles, three main alternative drive technologies are available: Battery electric vehicles (BEV), plug-in hybrid electric vehicles (PHEV) and fuel cell electric vehicles (FCEV). The crucial factor for the diffusion of BEV is the battery as it determines two main purchase decision criteria, the investment costs and the all-electric driving range of the vehicle. PHEV still use combustion engines to gain range and lower battery costs, but are consequently still an unneglectable source of GHG emissions. Today, an average privately used PHEV drives less than 50% of its total annual distance on electricity (Plötz et al. 2020). FCEV are still in a very early phase of commercialisation as sales are several orders of magnitude lower than for PEV and require yet an additional public refuelling infrastructure (whereas direct electrification can to some extend already use home charging options). To achieve climate neutrality, the main options are either a full stock of BEV or a large share of BEV with some long-ranged PHEV using zero-carbon fuels for their remaining combustion engine operation are options.

Plug-in electric vehicles (PEV), i.e. BEV and PHEV combined, have seen strong increase in sales shares in Europe in 2020 despite total car sales in Europe dropping by one quarter (ACEA 2021). Global market leader in terms of PEV sales shares is Norway where new PEV car registrations exceeded 70% in 2020 (see Figure 5). EU PEV sales share in 2020 were 12% but reached 16% in December 2020 (Mock et al. 2021) and a total of 1.5 million PEV were sold in Europe in 2020 (ACEA 2021).

Most important for the role of PEV in low carbon road transport in Europe is the future market diffusion in sales and stock. We derived projections of future PEV sales for all European countries under the assumptions of (1) future PEV sales shares can reach 100% and (2) sales growth follows and S-shaped diffusion curve that is influenced by local PEV incentives and energy prices.[3] The resulting PEV sales shares projections for European and selected European countries are shown in Figure 6.

Figure 5: National PEV sales shares in Europe in 2020



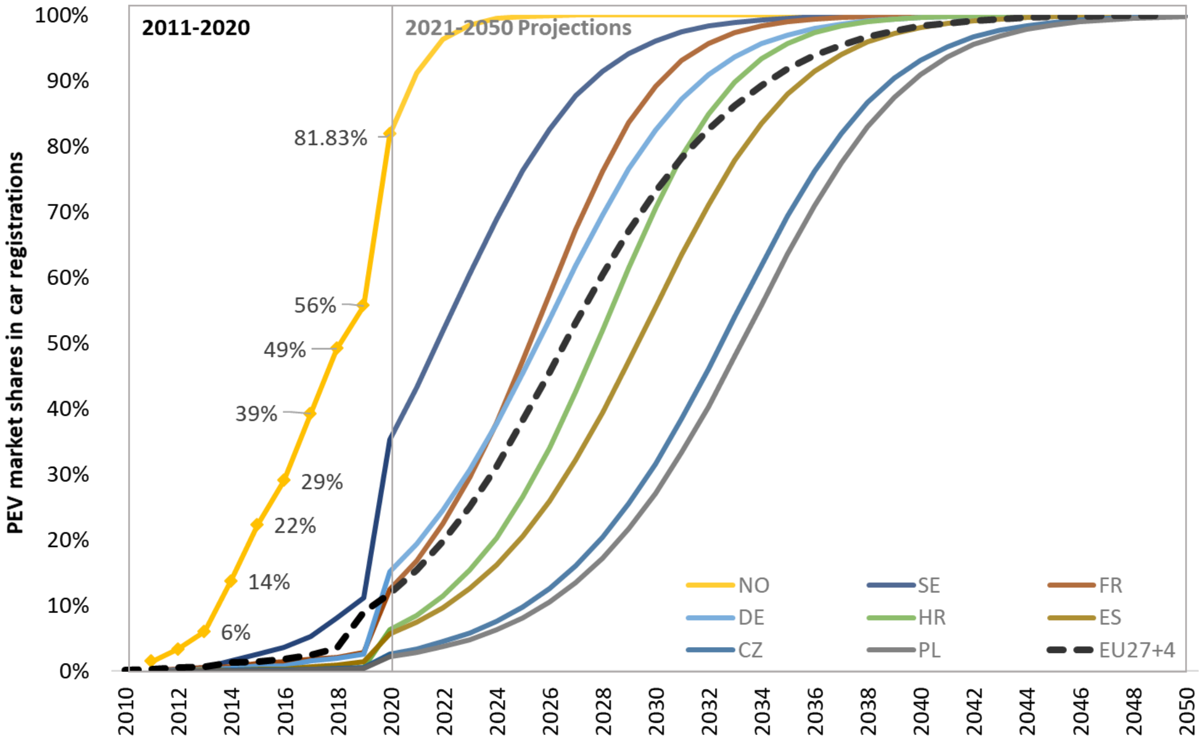
Source: ACEA 2021

Figure 6 demonstrates that Europe could reach 70% PEV sales share in 2030 and 90% in 2035 if the current market dynamics and existing incentives are projected into the future. Thus, current market development allow for more ambitious GHG reduction targets in passenger car sales.

[3] Methodologically, we fitted a logistic function to the Norwegian sales share data. Future projections of PEV market diffusion curves from 2021 to 2050: were calculated by modification of the diffusion curve parameters from Norway based on empirical country specific data from 2011 to 2020. The country specific growth rates were adapted to national monetary incentives and national electricity and fuel prices according to results of Münzel et al. (2019). Historical data from (Münzel et al. 2019) and 2020 car registration data from (ACEA 2020). Further details in (Neuner & Plötz 2021).

Figure 6: Historical and projected PEV sales shares in Europe

Shown are PEV sales shares over time for EU27+4 (UK, Norway, Iceland, and Switzerland) and selected European countries. Historical data until 2020 and projections from 2021 onwards.



Source: Own calculations.

Total road transport GHG emission reduction will be achieved by highly efficient vehicle stock and sales diffusion is only the first step. As the average passenger car age in EU is 11 years (source: ACEA) the electrification of the total vehicle fleet is shifted behind. However, vehicle use is most intense in the first ten years of usage and average vehicle lifetime is around 15 years. Accordingly, if zero GHG emission passenger car fleet were to be achieved by full direct electrification via PEV, all new passenger car sales need be electric 15 years prior to 2044 or 2048, that is by 2029 or 2033. Similar results have been obtained by the ICCT (2020) as well as T&E (2018) which study a 90% electrification of passenger vehicle and light-duty vehicle stock by 2050. Likewise the European Commission long term scenario (EC 2018) demonstrates that an electrification of passenger road transport is the pathway to zero GHG emission till 2050.

There is large uncertainty about the role shared automated electric vehicles can play in the future transport system (Sperling 2018). Krail et al. (2021) show that automation could reduce per kilometre energy consumption but might also lead to drastically increased vehicle usage if not controlled for by policies (Sperling 2018).

3.2.2 Existing and Additional Policies

There is a broad spectrum of existing policies to foster highly efficient light-duty vehicles and to incentivise the use of energy-efficient vehicles. The following discussion is not comprehensive but will focus on some of the most important policies.

Following the three levers to reduce GHG emission from transport, the CO_2 fleet target for passenger cars and vans[4] are strong policies to reduce GHG emissions and energy consumption of newly sold vehicles. Despite potential drawbacks in the implementation, such as growing discrepancy between actual and official fuel consumption, 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 have to be 95 g CO_2/km (measured in the New European Driving cycle) in 2021 if manufacturers want to avoid penalties. The manufacturer specific target will be translated to a g CO_2/km value in the new Worldwide Harmonized Light Vehicles Test Procedure (WLTP). For 2030, the regulation requires a 37.5% reduction compared to 2021 towards 59 gCO_2/km in NEDC which is about 70 gCO_2/km in real-world operation (Dornhoff et al. 2020).

As the stock turnover takes time, the average GHG emissions of vehicles in stock will be higher. About 55% of vehicles are scrapped at the age of 15 and 97% when they are 20 years old (T&E 2021). With an average car lifetime of approx. 15 years and new vehicles driving more than older vehicles, the GHG emissions from the car stock lack at least 15 years behind, maybe more.

The time lag for low carbon vehicles to diffuse into stock has clear consequences for GHG emission reduction targets in transport. A zero emission car fleet by 2044 or 2048, depending on the acceptance of overshoot or not within the 1.5°C target, implies 100% ZEV sales in 2029 or 2033 unless synthetic GHG neutral fuels will be available in large quantities, which appears unlikely given the long time for development and building of industrial synthetic fuel production. Thus, the current reduction target of 37.5% by 2030 vs. 2021 will lead to a car stock with average fuel consumption higher than approx. 100 gCO_2/km in NEDC or approx. 135 gCO_2/km. The time lag for new sales to move into stock implies that the reduction goal of 36 to 42% (until 2030 compared to 2020) for GHG emissions in road transport consistent with a linear reduction trajectory within 1.5°C of global warming (see table 3), requires much higher GHG emission reduction of newly sold vehicles. For example, a linear path to 100% ZEV sales in 2033 implies a target of approx. 80% reduction compared to 2021 or 14 gCO_2/km for newly sold cars in real world operation in 2030. This is consistent with the suggestions of 70% GHG reduction in in newly sold vehicles until 2030 compared to 2021 as suggested in Mock & Miller (2018).

In conclusion, the new European CO_2 fleet targets need to be 0 gCO_2/km for newly sold cars in 2030 or latest in 2033 to be consistent with 1.5°C GHG emission budget for transport in Europe. This appears highly ambitious, but the currently accelerating market diffusion of PEV shows that this is in principle possible. In addition, several car markets have announced to phase out combustion vehicle car sales until 2030 or 2035 (Plötz et al. 2019). For example, California and the UK will only allow 100% ZEV sales from 2035 onwards (Axsen et al. 2020). Furthermore, car manufactures can only produce a limited number of propulsion technologies and e.g. Audi has announced to stop producing combustion engines around 2030 to 2035 (electrive.net 2021), General motors has announced to phase out combustion engine sales until 2035 and to become carbon neutral by 2040 (GM 2021), and other manufacturers have announced similar ambitious targets.. Thus, zero carbon car sales by 2030 or 2035 are not only required to stay within Europe's carbon budget, but it is seem also possible.

As recent studies have shown that PHEV emit several times higher GHG emissions than expected from certification (Plötz et al. 2020a), the potential role of PHEV 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 exclude cars with only combustion engines after 2030 but to allow PHEV sales until 2035, as the UK has announced. Again, in terms of the remaining GHG budget for transport this is conditional on electric driving shares, e.g. greater 80%, of PHEV in real-world operation.

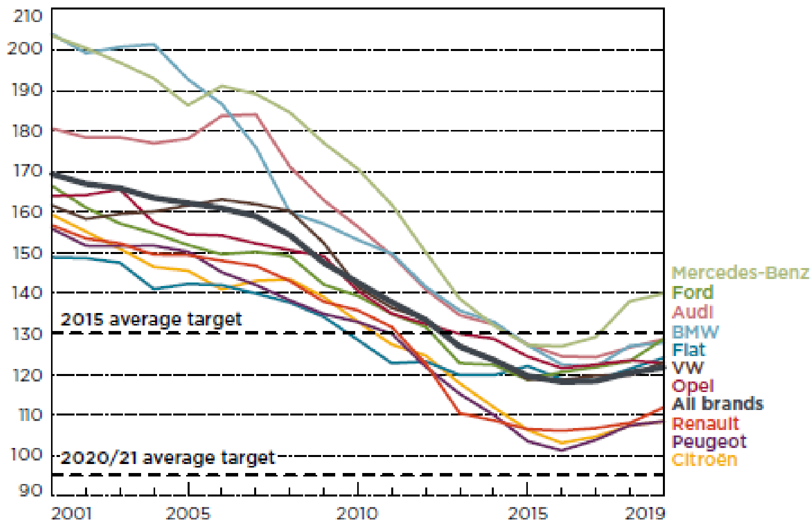
Another important aspect of a remaining GHG emission budget for transport is that the transition to 100% carbon neutral transport will take longer and be more difficult if the remaining new conventional

[4] Regulation (EC) 443/2009 and Regulation (EU) 2019/631 for CO2 emission performance standards for new passenger cars and new vans for 2025 and 2030.

combustion vehicles use more conventional fuel as these vehicles stay in the fleet for many years. However, the tremendous rise of SUV and off-road vehicles over the past, with a tenfold- growth in sales since 2001, has led to growing emissions from conventional passenger cars (see Figure 7) while meeting the CO_2 fleet target with high shares of PEV and their double counting due to super credit. There is one clear policy option to disentangle fuel efficiency increase in new conventional cars while stimulating PEV growth at the same time: Zero emission vehicle (ZEV) mandates. Major global markets such as China and California use a both CO_2 fleet targets for combustion engine vehicles only and ZEV mandates at the same time. In the light of the required ambitious GHG emission reduction, this appears as an interesting option for Europe's passenger car CO_2 policies.

Figure 7: Average NEDC CO_2 emissions of newly sold passenger cars in Europe

Shown are average CO_2 emissions in gCO_2/km by car brands.



Source: ICCT (2020).

Other major low-carbon policies on EU level include the car labelling directive 1999/94/EC to address the vehicle demand side, the alternative fuels infrastructure directive (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.

In summary, the remaining GHG budget for transport implies a transition towards 100% ZEV until early 2033 latest both for cars and vans, ideally in combination with a drastic reduction of GHG emissions from the remaining combustion engine vehicle fleet. This can be achieved either by the introduction of strong CO_2 fleet targets or by a combination of absolute CO_2 targets for combustion engine vehicles and ZEV mandates in parallel. The latter approach has the advantage that both the ZEV transition and the GHG emission reduction from the newly sold passenger cars can be directly controlled.

3.3 Heavy-duty Vehicles

3.3.1 Technological Contribution

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

Battery electric trucks (BEV) are commercially available for short and medium distances of approximately 200 km to date. Vehicles with significantly higher ranges have been announced for the next years (IEA 2020). Yet, to cover several hundred kilometres per day, future vehicles must be able to recharge within the legally binding driving breaks of 45 minutes. The efficiency of the electric drivetrain permits low operating costs. If renewable electricity is used, BEV operate CO_2 emission free during operation can be completely reduced. However, BEV require large batteries to fulfil high daily use with high mileages which is energy intense and has to be taken into account. In terms of infrastructure, a full-coverage fast-charging network is needed for long-haul trucking (Plötz et al. 2020b).

Catenary hybrid vehicles (CHV) are currently tested on public road transport in several countries, i.e. (Germany, Sweden, and the USA), and are considered for road transport electrification in the UK (Ainalis et al. 2020), the Netherlands (Otten et al. 2020), and Italy (Green Car Congress 2018), amongst others. Using a pantograph, trucks receive energy from an overhead line. In order to travel without the overhead line, the vehicles can be equipped either with a battery of sufficient size or an internal combustion engine. As a major advantage, electric energy can be used cost efficiently without the need of large batteries. Analogous to the BEV, the CHV can drive completely electric. However, this will require an extensive overhead line infrastructure (Hacker et al. 2020).

Today, fuel cell electric trucks (FCEV) are being delivered in small scale, e.g. in Switzerland and China. European manufacturers have announced commercially available FCEV within the next decade. A high range of several hundred kilometres as well as a short refuelling duration of approximately 10 minutes are advantageous compared to other alternatives. Still, FCEVs are less efficient than BEV and CHV, resulting in higher energy demand and higher total costs of ownership (Gnann et al. 2017; NPM 2020). To operate CO_2 -neutral, hydrogen from renewable sources has to be produced in sufficient quantities. Concerning the infrastructure, a network with stations for several trucks per hour is necessary (Kluschke et al. 2020).

Currently, all technologies, especially for long-distance use, are still in a research and development phase. Large-scale demonstrators, leading to an initial market diffusion, are planned within the next five years, e.g. in Germany and Sweden. According to vehicle manufacturers' announcements, mostly BEV trucks will be available in larger quantities in the next years (IEA 2020) and high-power fast charging stations are currently being planned (Plötz et al. 2020b). Decisions for or against one of the three potential technologies BEV, FCEV and CHV technologies for low-carbon heavy-duty road freight transport can be expected in a few years (NPM 2020; BMVI 2020a).

As the transition towards low emission trucks requires more time, emission reduction from newly sold diesel trucks are highly important. Further efforts to increase efficiency of diesel engines and heavy duty vehicles in general can reduce emissions of newly sold vehicles but at the same time allow manufacturers to meet the CO_2 targets with a limited number of ZEV trucks (Breed et al. 2021).

In principle, synthetic fuels from renewably energy sources (e.g. through import from countries with favourable production conditions in North Africa or the Middle East) could also ensure carbon neutrality and constitute an important option to shift transport towards climate neutrality. However, due to the limited availability of green energy and plant capacity, these do not represent a suitable instant measure to decarbonize road freight transport until 2030. After 2030, these fuels could play a role but as their use in road transport will be more expensive than direct electrification (high production costs and low efficiency of combustion engines compared to electric motors), they should be used in modes that cannot not rely on direct electrification such as aviation and shipping.

3.3.2 Existing and Additional Policies

In 2019, the EU adopted CO_2 standards for newly registered trucks and busses (Regulation (EU) 2019/1242). According to these standards, the average CO_2 emissions of newly sold heavy-duty vehicles must be 15 percent lower in 2025 and 30 percent lower in 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. Depending on the emission level, and consciously formulated in a technology-open format, the multiplier varies between 1 and 2 whereas a maximal total credit of 3 percent is specified to preserve the environmental integrity of the system. 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 its entire new heavy-duty vehicles, its emissions are adjusted downwards. For 2025, this benchmark is initiated with 2 percent whereas the 2030 level will be defined later. To reach these targets, the EU has defined a series of standards and measures to enforce compliance with the CO_2 targets. Financial penalties are in place for non-compliance with CO_2 targets or mandatory standardized fuel consumption meters.

To meet the fleet target 2030, at least 4 to 22% of newly sold heavy-duty vehicles have to be ZEV (Breed et al. 2021; see Figure 8). The actual value depends on the strategy of the manufacturers: If diesel vehicles remain in the focus of R&D and lead to the realisation of noteworthy diesel engine emission reductions, 4% ZEV will be sufficient. Full compliance with the target seems not 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 in 2030.

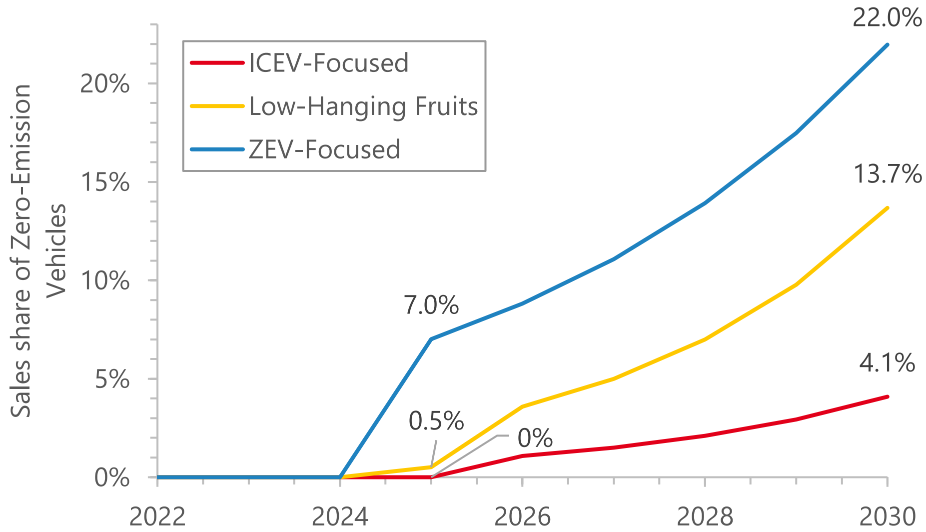
Truck manufacturers are currently actively working on the transition towards 100% ZEV trucks. Quite recently, the European Automotive Association (ACEA) announced a target of 100% ZEV truck sales in 2040 and Scania has announced a 50% sales share target for ZEV trucks in 2030 (Scania 2021).

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. According to ACEA, the average age of medium and heavy-duty vehicles 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. Thus, a GHG neutral truck fleet in 2044 or 2048 latest (as required by zero emission transport – see table 3), requires a 100% ZEV target in HDV sales before 2040 as the stock turnover requires additional time. Due to the time stock turnover requires, a 100% reduction target for newly sold trucks about ten years earlier, i.e. in 2034 or 2038 would be consistent with zero carbon transport until 2044 to 2048, depending on the state of zero carbon fuels and the possibility of temporal overshoot. Accordingly, a 55 – 67% reduction until 2030 for newly trucks would be needed. This appears possible with a wide range of energy efficiency improvement for diesel engines, tires, and aerodynamics as well as a fast transition to ZEV trucks.

Given an ambitious ZEV sales target, the 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) individual policies for the GHG emission of combustion engine trucks and ZEV sales shares. Similar to policies for emission reduction of passenger cars in California and China, a combination of CO_2 fleet regulation for combustion vehicles and ZEV mandates would ensure low emissions from the remaining diesel fleet and a fast transition to ZEVs.

Figure 8: Minimum ZEV truck sales share in different manufacturer strategies

Shown are sales shares of ZEV trucks under the current EU regulation in the manufacturer strategies on how much to further improve diesel trucks.



Source: Breed (2020)

Directive 2014/94/EU, also known as the Alternative Fuels Infrastructure Directive (AFID), requires EU member states to assess the market diffusion of alternative drivetrains and to ensure an adequate infrastructure build-up. For heavy-duty vehicles, the focus over the past years has been on natural gas and the required refuelling infrastructure. However, natural gas vehicles cannot achieve the required deep reductions to meet ambitious long term CO_2-targets (Yuan & Ou, 2019). To enable a ZEV truck market diffusion, the upcoming AFID revision in 2021 will explicitly consider charging infrastructure for heavy-duty vehicles, too. For short- and medium-distance trucks, the installation of electric charging infrastructure is necessary and plans for the installations are currently created (T&E 2020). For long distances, BEV, CHV and FCEV are possible and also require infrastructure. Therefore, dependent on the market diffusion of vehicles, the installation of a fast charging infrastructure, overhead catenaries and hydrogen fuel stations should be taken into account in the AFID revision.

A further important policy to reduce road transport emissions and accelerate the transition to ZEV is the Eurovignette Directive (Directive 1999/62/EC on the charging of heavy goods vehicles for the use of certain infrastructures) that is currently under revision. The next version might allow higher charges on highly emitting vehicles and thus providing additional incentives for operators to use low emitting vehicles. A preliminary agreement on this point was achieved at the end of 2020 (BMVI 2020b).

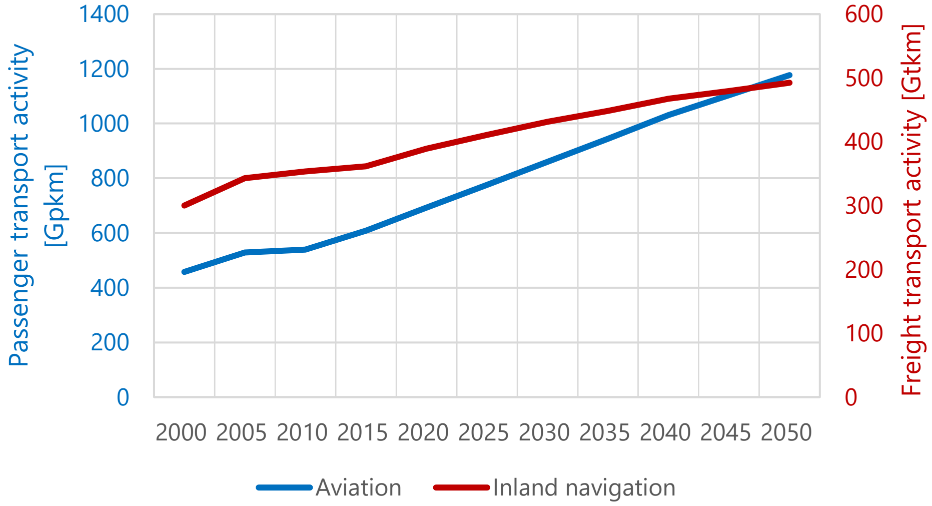
3.4 Navigation and Aviation

3.4.1 Technological Contribution

The estimation of the total energy consumption or GHG emissions in navigation is difficult, since ownership, usage and hosting of flags varies and also refuelling may not happen in the port of registry (Heitmann and Khalilian 2011). For this reason, a good estimation of ship usage in transport is through the voluntary reporting of "international bunker fuels" for maritime transport. The same holds for the total amount of fuels for aviation. Figure 9 shows the transport activity for aviation and inland navigation in Europe based on (EC 2016). Although inland navigation is only a small share of worldwide navigation, the trends are very clear: Navigation almost doubles between 2015 and 2050 while aviation will increase by 50 – 60%.

Figure 9: Transport activity in aviation and inland navigation in the Europe

Shown are historical and expected future activity data for passenger flights in Gpkm and freight navigation within the EU in Gtkm for the EU27 and the UK.



Source: Own illustration with data from (EC 2016).

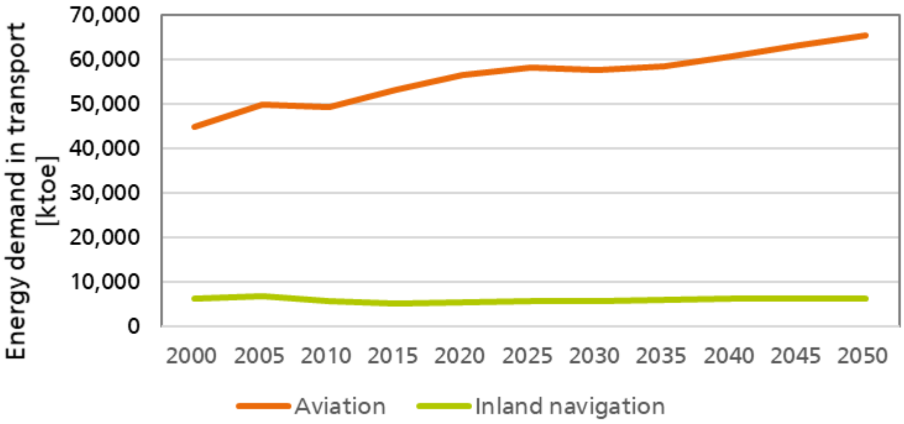
There are some technical energy efficiency gains that can be levered for both transport modes. With a higher propulsion efficiency, improvements in aerodynamic, design and materials, some 20-30% in efficiency gains until 2050 are possible for new airplanes (National Academies of Sciences, Engineering, and Medicine 2016). In navigation, a more energy efficient fuel usage is possible through a number of behavioural and organizational changes such as slow steaming, reduced times in ports, weather routing, optimized autopilots, hull coating and usage of shore power (Crist 2009, Halim et al. 2018). These measures combined can decrease the energy use of ships in stock by 10 – 15%. Efficiency technologies such as sails, kites, and design changes may further decrease energy use by some 10%, but will only affect new ships and only in some applications as, e.g., sails will not be easy to install on container ships (Crist 2009, Halim et al. 2018). Some changes in user behaviour (slow steaming, weather routing or the reduction of turnover times in ports) could also improve energy efficiency in maritime transport by 10-20% (OECD 2009).

These efficiency gains may balance the expected activity growth in navigation and thus keep the energy demand in navigation stable between 2000 and 2050, which is also observable in Figure 2 with projections from (EC 2016). The energy demand in aviation is expected to grow further despite the efficiency improvements.

The use of alternative drive trains for both modes of transport is limited due to the limited space for energy storages on ships or airplanes. Also the long lifetimes of ships and airplanes of 25-30 years require fast solutions for noticeable changes in stock until 2050.

Figure 10: Energy demand in transport

Energy demand measured in ktoe (1000 tonnes of oil equivalent).



Source: Own display with data from (EC 2016).

A use of electricity stored in batteries will either decrease the weight of transported goods or the range of an airplane or ship. Currently, there are only hybrid solutions in discussion for ships to use electricity in emission control areas or in ports; for aviation there only first concepts for small airplanes with less than 50 passengers until 2050. The use of hydrogen decreases the volume of transported goods or the range. Ammonia is a further option as energy carrier currently discussed for shipping and future studies should clarify which role it can and should play. Currently, there are no applications for the use in ships in discussion; for airplanes, again only small to medium sized concepts are discussed on the mid- to long-term. The use of natural gas would slightly decrease the volume or range reduction, however a use of LNG seems more probable than the use of hydrogen. For this reason, these solutions will only be applicable in short-distance flights until 2050.

A further problem in aviation are the non-CO2 effects of aviation at high altitudes. These are currently not included in the bunkers and further research is required to measure, treat and reduce the non-CO_2 effects of climate warming.

In summary, technology improvements will maximally be able to stabilise energy demand and emissions from navigation and aviation. The only viable technological solution for GHG neutral aviation and navigation are thus synthetic or bio-fuels, as they have the required energy density and can be used as drop-in fuels in the short- to medium-term.

3.4.2 Existing and Additional Policies

The aviation sector is obliged to participate in the EU ETS since 2010, however the effects are limited with the currently moderate CO_2 price. The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) agreement aims at a GHG neutral growth, an own emission trading system and annual final energy savings of 2% in aviation (Bopst et al. 2019; Bullerdiek and Kaltschmitt 2020). Note, however, that only additional growth should be GHG neutral in the agreement, and existing emissions are not being reduced. The offsetting price in CORSIA is expected to be even smaller than current EU ETS prices.

In navigation, there are so called emission control areas (ECA, currently on the north American coasts, the Baltic and the north sea) in which especially the emission of sulphur is controlled. Since 2015, a sulphur share in fuels of less than 0.1% is obligatory within the ECAs, since 2020, the sulphur share in fuels has to be below 0.5% also outside the ECA (IMO 2020b). This forces ship builders to either use scrubbers or catalysers for exhaust emission cleaning of heavy fuel oil powered ships or to use low sulphur fuel oil. In addition, there are obligatory Ship Energy Management Plans that contain efficiency measures and the Energy Efficiency Design Index (EEDI) for new ships that require 10% more efficiency compared to 2010 in 2020 and 30% in 2030 (IMO 2020a).

Aviation and navigation are both excluded from energy taxes to allow for international competitiveness.

The current policy measures, however, do not contain binding targets or regulations that will effectively change the market conditions for alternative fuels or decrease GHG emissions by large. Strong additional policies are needed for deep GHG emission reductions in aviation and shipping. As a first step, energy taxes and a carbon tax would attenuate further demand and emission growth in both aviation and navigation. Carbon taxes are a widely discussed instrument in the scientific literature and one key finding is that real impact in transport is only achieved with carbon prices of at least 100 €/ton (Axsen et al. 2020; Lillistam et al. 2021). A second step to achieve GHG neutral aviation and navigation is the introduction of carbon neutral fuel quotas.

Minor additional policies measures include the support of zero emission ferries for short distance as currently deployed in Norway (with 31 currently in operation and 55 planned for this or next year, see. Øystese 2021) and strong incentives to use electricity while in ports which also reduces local air pollution.

4 Elements of a 1.5°C Transport Policy Mix for Europe

The following points could be a few elements of a low carbon policy mix in Europe to get on track towards zero carbon transport that is compatible with Europe's commitment to the Paris Agreement, i.e. to pursue efforts to limit global warming to 1.5°C.

1. CO_2 fleet targets for newly sold cars in Europe have to be much more ambitious. An 80% reduction of the average emissions of newly sold vehicles until 2030 compared to 2021 is needed as well as a target of 0 gCO_2/km for cars no later than 2033. Similar targets hold for light-commercial vehicles.
2. CO_2 fleet targets for trucks need to be tightened. A 55 – 67% reduction until 2030 compared to 2020 for newly trucks is needed followed by a 100% reduction target for newly sold trucks already in 2034 – 2038.
3. Infrastructure for alternative fuel vehicles is required for a fast and successful transition to 100% ZEV in cars and trucks. Ambitious and single European standards are needed for fast charging of electric cars and trucks. The role of fuel cell vehicles and the amount of required infrastructure in road transport is still uncertain.
4. Aviation and Navigation require sustainable zero carbon fuels. This transition can be ensured by introducing quotas for sustainable zero carbon fuels that reach 100 % by 2044 – 2048, compatible with the linear reduction path of a 1.5°C GHG emission budget for Europe.
5. Carbon pricing, e.g. via taxation or an emission trading scheme in transport, can support the shift to low-carbon modes such as rail, public transit or bike, but will not alone deliver deep GHG emission reductions and should be seen as complement and not as substitute to ambitious CO" fleet targets and quotas.

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