# WORKING PAPER

## COST-EFFECTIVE REDUCTION OF FOSSIL ENERGY USE IN THE EUROPEAN TRANSPORT SECTOR: AN ASSESSMENT OF THE FIT FOR 55 PACKAGE

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# Cost-effective reduction of fossil energy use in the European transport sector: An assessment of the Fit for 55 Package*

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**Abstract**

This paper surveys climate and energy policy in the EU transport sector covering the road, aviation, and shipping sectors. We summarise current policies, focusing on the Fit for 55 Package, and categorise them according to their targeted decision stage (consumption, investment, or research) and the type of instrument being used (e.g. cap-and-trade, tax, mandate, performance standard, or subsidy). Next, we analyse the cost-efficiency of the different policies and instruments. We find that they address a range of market inefficiencies, but that there are still a number of aspects that can further improve the cost-effectiveness of current EU climate policies in the transport sector. For example, higher taxes and an emission performance standards for aviation and shipping, the right combination of R&D investments and learning-by-doing policies, and balancing implicit carbon prices by revising the road tax system and adding congestion tolls and charges. Finally, European policy has important side effects on the rest of the world that need to be taken into account in the selection of policies. This improved set of policies can support a sustainable recovery and reach the European Union's climate targets at the lowest cost.

**Keywords**: European energy policy, European climate policy, European transport policy, road transport, aviation, shipping, Fit for 55 Package

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# 1 Introduction

The European Union's Fit for 55 Package is an unprecedented set of policies and instruments to reduce greenhouse gas emissions in 2030 by 55% compared to 1990 and to be on the road to net-zero by 2050. Because climate change is a multi-dimensional challenge touching every aspect of society, this set of policies targets all domains, ranging from energy and transport to land use and taxation. In this paper, we discuss the different policy proposals in the European transport sector – covering cars, vans, trucks, aviation, and shipping – and analyse their cost-effectiveness. The transport sector stands for 27% of total EU greenhouse gas (GHG) emissions in 2017. Within the transport sector, the major sources of emissions are the car and van sector (51%), followed by the truck and bus sector (21%), aviation (14%), and shipping (13%).[1] Policies to decrease carbon emissions in the EU transport sector should therefore focus on all four sectors.

In an imperfect world, there are dozens of market failures and inefficiencies that cannot only be addressed by a carbon tax. In addition to the negative externality from carbon emissions, there is consumer inattention, congestion, network effects, knowledge and learning-by-doing spillovers, market power, local air pollution and noise, as well as energy security issues. Finally, there are political constraints imposed by decision making with 27 member states. It is therefore no surprise that the European Union uses a range of policies and instruments to combat climate change (Creutzig et al. 2020, Finon 2019, Fischer & Newell 2008, Gerarden et al. 2017, Gillingham & Stock 2018, Parry 2007, Parry & Small 2005, Proost & Van Dender 2001, Stiglitz 2019, Tinbergen 1952). Some policies target consumption decisions, while others focus on investment decisions, or support research and innovation (R&I).

In this paper, we summarise current policies in the EU transport sector, with a focus on the proposals of the Fit for 55 Package, and put the different policies in a unifying economic framework. We show that the set of policies aims to reduce carbon emissions from transportation by targeting i) consumption decisions, ii) investment decisions, and iii) research and innovation (R&I) efforts. We also categorise the policies according to the type of instrument being used (cap-and-trade, tax, mandate, performance standard, obligation, subsidy, etc.) We discuss how each policy instrument targets specific market inefficiencies. For example, the EU emissions trading system (EU ETS) and the proposed transportation and heating ETS address the carbon emissions externality; the electric charging capacity mandate addresses network effects; future sustainable aviation fuel mandates address dynamic cost aspects; and Horizon 2020 funding addresses R&I spillovers.

[1]Emissions from rail transport account for just 1.5% of transport's GHG emissions, of which only 0.6% is through direct diesel consumption.

Next, we analyse the cost-efficiency of this set of policies and focus on four issues: the current implicit carbon price, the options for cost-efficient trading with other emission sectors, the interaction with other externalities in the road transport sector, and finally the dynamic cost aspect and its policy implications. We identify the possibilities to improve the cost-effectiveness of current EU climate policies in the transport sector. We find that trading emission reductions with other sectors, like buildings, is inefficient, because there is an imbalance in the implicit carbon price of different transport sectors and fuels. Congestion tolls and charges can fix both the unbalanced implicit carbon prices and avoid that electric cars and more fuel-efficient cars make congestion problems worse. Furthermore, European policy needs to take into account its important side effects on the rest of the world. Finally, we discuss how the Just Transition Mechanism and the Social Climate Fund can cost-effectively mitigate the impact of climate policies on vulnerable groups in society.

This paper is structured as follows. Section 2 characterises EU climate policies in the transport sector according to the decision stage and the type of instrument being used. All Fit for 55 policies are summarised in tables and discussed in relation to the specific market inefficiencies they target. Next, section 3 links market inefficiencies to ideal instruments and discusses if they are addressed in each transportation sector. Section 4 analyses the different policies and instruments that do not perfectly follow economic cost-efficiency prescriptions. Based on this analysis, section 5 concludes and provides recommendations for further improvement of these policies to reach the European Union's climate targets at the lowest cost.

# 2 European climate policies in the transport sectors

In this section we regroup the different European climate policies that have a bearing on the transport sector and focus on consumption decisions (2.1), investment decisions (2.2), and research and innovation decisions (2.3) .

## 2.1 European climate policy focusing on transport consumption decisions

European climate policies that focus on consumption decisions either encourage or mandate good consumption decisions – emitting less or no carbon – or discourage or prohibit bad consumption decisions, like consuming gasoline, diesel, kerosene, or natural gas. Table 1 shows that the European Union uses four types of instruments to steer consumption decisions in the cars, trucks, aviation, and shipping sectors towards zero- or low-carbon alternatives. First, there is a cap-and-trade system that establishes a price of carbon emissions on flights within the European Economic Area (EEA) since 2012.[2] The legislation was designed to apply to emissions from flights from, to, and within the EEA, but the EU decided to limit the scope of the EU ETS to flights within the EEA to support the development of the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), see below. Depending on the operationalisation of CORSIA, EU ETS would revert back to its original full scope from 2024 onwards (European Commission 2021*k*). Between 2023 and 2025, emissions from shipping within the EEA, half of the emissions from extra-EU voyages, and emissions occurring at berth in an EU port are gradually phased into EU ETS. As of 2026, shipping companies have to surrender 100 % of their verified emissions, which was around 90 million tons of $CO_2$ in 2020. As of 2025, there will also be a new separate ETS for transport and buildings, with a cap on emissions set from 2026. Because there are millions of users of fossil fuels in these sectors, this new system will regulate upstream fuel suppliers rather than households and car drivers, and all permits are auctioned to avoid windfall profits at the distributors level. The cap in the new ETS will be reduced annually to yield emissions reductions of 43% in 2030 compared to 2005.

Second, the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), developed by the United Nations' International Civil Aviation Organization, requires all airlines based in a participating country to offset the growth of GHG emissions above the 2019 level, by canceling voluntary emissions reduction certificates. By 2021, more than 100 countries were participating voluntarily, meaning that flights between them are subject to CORSIA. Starting in 2027, participation is mandatory.

Third, the proposed update of the European Energy Taxation Directive (European Commission 2021*b*) aims to remove outdated non-harmonised exemptions and reduced rates that currently encourage the use of fossil fuels and distort the internal market. Specifically, the updated directive would end the current mandatory exemption of the aviation and waterborne navigation and fishing sector, as well as increase the minimum rates for motor fuels to €10.75/GJ by 2023 for non-sustainable fuels and by 2033 for natural gas, non-sustainable biogas, and sustainable food and feed crop biofuels and biogas. Sustainable non-food and low-carbon fuels will be subject to lower rates. The €10.75/GJ rate is equivalent to around €0.41 per liter of gasoline, diesel or kerosene. Heating fuels will continue to have lower minimum tax rates.

Fourth, there is non-price regulation that directly regulates certain characteristics of the consumed energy. European Commission (2021*e*) requires that the amount of renewable

[2] Note that EU ETS' cap is not fixed anymore, because of the cancellation policy, such that abatement policies can change cumulative emissions (Bruninx et al. 2020, Bruninx & Ovaere 2021, Perino 2018).

**Table 1.** Summary of the European Union climate policies focusing on the **consumption** decisions for cars, trucks, aviation, and shipping in the Fit for 55 Package.

| Instrument | Cars/Vans | Trucks | Aviation | Shipping |
|---|---|---|---|---|
| **Cap-and-trade** | Under a separate transportation and heating ETS as of 2026 (European Commission 2021*d*) | | Intra-EEA flights under EU ETS since 2012 (European Union 2018) | Intra-EEA, half of extra-EEA and emissions at berth phased into EU ETS in 2023-2015 (European Commission 2021*d*) |
| **Offset** | / | / | Intra- and extra-EEA flights under CORSIA as of 2021 (European Commission 2021*c*) | / |
| **Tax** | Removing exemptions and reduced rates. Set minimum tax level for non-sustainable fuels of €10.75/GJ as of 2023 (European Commission 2021*b*) | | | |
| **Mandate** | Decreased GHG intensity of transportation fuels of 13% by 2030 (European Commission 2021*e*) | | | |
| | | | Share of SAF: 2%-5%-20%-32%-38%-63% in 2025-2050 (European Commission 2021*h*) | Decrease GHG intensity of energy used on-board by 2%-6%-13%-26%-59%-75 % in 2025-2050 (European Commission 2021*j*) |

*Notes*: ETS = Emissions trading system, EEA = European Economic Area, CORSIA = Carbon Offsetting and Reduction Scheme for International Aviation, SAF = Sustainable aviation fuels, GHG = greenhouse gas fuels and renewable electricity supplied to the transport sector leads to a greenhouse gas intensity reduction of at least 13 % by 2030. The reduction is calculated by summing the contribution of GHG emissions savings from biofuel, biogas, renewable fuel of non-biological origin, recycled carbon fuels, and renewable electricity supplied to all transport modes. This 2030 target is supported by a number of complementary policies. First, across the transport sector, the share of advanced biofuels and biogas produced from the feedstock should be at least 0.2 % in 2022, 0.5 % in 2025 and 2,2 % in 2030, and the share of renewable fuels of non-biological origin should be at least 2.6 % in 2030 (European Commission 2021*e*). Second, a minimum 5 % share of sustainable aviation fuels in the aviation sector by 2030 (European Commission 2021*h*). This share is required to increase to 63 % by 2050, of which 0 % - 0.7 % - 5 % - 8 % - 11% - 28 % should be synthetic aviation fuels in 2025-2050. Third, a decrease of the GHG intensity of energy used on-board (grams of $CO_2$ equivalent per MJ) of at least 6 % by 2030 (European Commission 2021*j*), compared to the fleet-average greenhouse gas intensity of the energy used on-board by ships in 2020. This reduction target increases gradually to 75 % by 2050.

The four policy instruments being used are a combination of price-based instruments and command-and-control non-price instruments. Price-based instruments, like cap-and-trade or a tax, encourage good consumption decisions by making bad consumption more expensive. Non-price instruments, on the other hand, directly regulate certain characteristics of the consumed energy, like the maximum GHG intensity of a transportation fuel or the minimum share of sustainable or synthetic fuels being consumed. If the only market inefficiency is the negative externality from carbon emissions, a price on emission – either in the form of a tax or a cap-and-trade – would be economically efficient (Pigou 1920). However, non-price instruments are needed when there is, i.a., consumer inattention, bounded rationality and information failures (Allcott et al. 2014), or uncertainty about the marginal costs and benefits (Baumol 1972, Weitzman 1974).

## 2.2 European climate policy focusing on transport investment decisions

Similar to the consumption-focused policies of section 2.1, European climate policies that focus on investment decisions either encourage or mandate investments in zero- or low-carbon technologies or discourage or prohibit investments in high-carbon technologies. Table 2 shows that the European Union uses three types of instruments to steer investment in the cars, trucks, aviation, and shipping sectors towards zero- or low-carbon alternatives. First, there is an emission performance standard for the sales of cars, vans, and trucks. For cars, the standard requires every manufacturer to decrease its sales-weighted average emissions of new passenger cars registered in the EU by 55 % in 2030, compared to the $CO_2$ emission limits applicable in 2021. For vans, the 2030 target is a 50 % reduction. By 2035, all new passenger cars and vans registered in the EU should be zero-carbon (European Commission 2021*f*). To stimulate the sales of zero- and low-emission vehicles (ZLEV), Regulation (EU) 2019/631 provides a credit system where ZLEV are counted more than once in the calculation of the average specific emissions of a manufacturer. For new heavy-duty vehicles, the standard is less ambitious: a 15 % reduction of the EU-wide emissions in 2025 and a 30 % reduction in 2030, compared to the reference emissions in the period of 1 July 2019 to 30 June 2020 (European Parliament and Council 2019). These targets have not been updated in the Fit for 55 Package. Both performance standards provide penalties for manufacturers whose average $CO_2$ emissions exceed their specific emission target, but manufacturers can pool their emissions to jointly meet their emissions target.

Second, the Fit for 55 Package has infrastructure mandates that require member states to provide minimum coverage of publicly accessible electric recharging, and hydrogen and LNG refueling stations within their territory and along the TEN-T core network and comprehensive network. European Commission (2021*i*) requires member states to meet specific targets on the number of recharging and refueling stations and their minimum capacity, following the uptake of battery electric, plug-in hybrid, hydrogen, and LNG light-duty and heavy-duty vehicles. For example, for each battery electric light-duty vehicle registered in its territory, a member state should provide a total power output of at least 1 kW through publicly accessible recharging stations. In addition, along the TEN-T core network, European Commission (2021*i*) requires member states to install recharging stations every 60 km and hydrogen refueling stations every 150 km in each direction. Along the TEN-T comprehensive network, the targets are 60 km for electric light-duty vehicles, 100 km for electric heavy-duty vehicles, and 450 km for hydrogen vehicles. For aviation, European Commission (2021*i*) mandates that airports provide electricity supply to stationary commercial aircrafts at all gates by 2025. Similarly for shipping, European Commission (2021*i*) mandates that ports install an appropriate number of LNG refueling points by 2025 and meet 90% of shore-side energy demand with electricity by 2030.

Third, there are a two European facilities that provide investment subsidies in the form of grants and loans to sustainable transport infrastructure. The Connecting Europe Facility provides €22.9 billion to fill the missing links in Europe's transport backbone, while the €723.8 billion Recovery and Resilience Facility, which was established to mitigate the economic and social impact of the coronavirus pandemic, provides €86 billion to transportation.

Together, the three policy instruments provide incentives for consumers to buy zero- and

**Table 2.** Summary of the European Union climate policies focusing on the **investment** decisions for cars, trucks, aviation, and shipping in the Fit for 55 Package.

| Instrument | Cars/Vans | Trucks | Aviation | Shipping |
|---|---|---|---|---|
| **Firm-level emission performance standard of new vehicles** | Reduction of 50% (vans) or 55% (cars) in 2030 and 100% in 2035, compared to 2021 (European Commission 2021*f*) | Reduction of 15% in 2025 and 30% in 2030, compared to 2019-2020 (European Parliament and Council 2019) | / | / |
| **Infrastructure mandate** | Minimum coverage of publicly accessible electric recharging, and hydrogen and LNG refueling stations in each MS and along the TEN-T core network and comprehensive network (European Commission 2021*i*) | | Provide electricity supply to stationary commercial aircrafts at all gates by 2025 (European Commission 2021*i*) | Meet 90% of shore-side energy demand with electricity by 2030 and install an appropriate number of LNG refueling points by 2025 (European Commission 2021*i*) |
| **Investment subsidies** | The Recovery and Resilience Facility provides €86 billion of grants and loans to sustainable transport and charging stations (including rail) (Bruegel 2021) Connecting Europe Facility provides €22.9 billion for transport infrastructure (including rail) for 2021-2027 (European Parliament and Council 2021). | | | |

*Notes*: EPS = emission, performance standard, TEN-T = Trans-European Transport Network, MS = member state, LNG = liquefied natural gas

low-emission vehicles, for manufacturers to provide them at costs that are competitive compared to gasoline or diesel vehicles, and for companies to invest in recharging and refueling infrastructure. In the case of cars and vans by 2035, this is even a strict ban on new sales. Obviously, consumption-focused instruments also have an effect on investment decisions, but when decision makers, like consumers or firms, are not perfectly intertemporally optimizing, the valuation will be imperfect (Gillingham et al. 2021) and non-price instruments focusing on investment decisions are required (Allcott & Greenstone 2012, Gillingham & Palmer 2014).[3] The combination of the infrastructure mandate and the investment subsidies ad-

[3] Note that there is no unanimity in the literature. For example, Grigolon et al. (2018) found rational consumer and producer behaviour on the EU car market and in that case it is more difficult to defend a performance standard when there are already high implicit carbon taxes in place.

dresses the 'chicken-or-egg' indirect network effects between complementary products (Li et al. 2017, Springel 2022).

### 2.3 European climate policy focusing on transport research and innovation decisions

There are also a number of European Union climate policies that focus on research and innovation in cars, trucks, aviation, and shipping. First, through Horizon Europe, the EU provides funding for fundamental research and innovation into clean and competitive solutions for all transport modes. The budget is €511 million in 2021-2022.

**Table 3.** Summary of the European Union climate policies focusing on **research and innovation** in cars, trucks, aviation, and shipping.

| Instrument | Cars/Vans | Trucks | Aviation | Shipping |
|---|---|---|---|---|
| **Research subsidies** | Horizon Europe €511 million funding in 2021-2022 for clean and competitive solutions for all transport modes (European Commission 2021*a*) | | | |
| **Research partnerships** | €615 million for Towards Zero-emission Road Transport (2ZERO) | | €1.7 billion for Clean Aviation2 | €530 million for Zero-emission Waterborne Transport |

Second, the EU also supports R&I in clean transportation technologies by establishing partnerships in specific industries. Over the 2021-2027 period of the Research Framework Programme Horizon 2020, the EU provides €615 million to road transportation, €1.7 billion to aviation, and €530 million to shipping.

The two R&I subsidies together address the market failure of limited appropriation of fundamental research, which limits R&I efforts. In addition, research partnerships intensity knowledge spillovers in specific industries.

## 3 Going for the right instrument

The EU is a market economy. It relies on an energy market where competition laws are enforced. But this is insufficient to address the different market inefficiencies that exist. Table 4 lists the ideal instrument for the different market inefficiencies. It also shows to what extent the Fit for 55 Package, discussed in Tables 1, 2, and 3, follows these first-best prescriptions. Specifically, we indicate if a market inefficiency is present and addressed by EU transport policy ('Yes'), present but not addressed ('Missing'), not present but addressed ('Yes, but

**Table 4.** An overview of the market inefficiencies (1) and the ideal instrument (2) to address them, categorized by consumption and investment decisions. Columns (3)-(6) indicate for each transportation sector if this market inefficiency is present and addressed by EU transport policy ('Yes'), if it present but not addressed ('Missing'), not present but addressed ('Yes, but not needed'), or not present and not addressed ('X').

| | Market inefficiency (1) | Ideal instrument (2) | EU transport policy<br>Cars/Vans (3) | <br>Trucks (4) | <br>Aviation (5) | <br>Shipping (6) |
|---|---|---|---|---|---|---|
| **Consumption decisions** | Climate emissions | Carbon tax or emissions permit price | Yes, but **linked to buildings** | Yes, but **linked to buildings** | Yes, but **extra-EEA missing** | Yes |
| | Road congestion | Time of use pricing | **Missing** | **Missing** | X | X |
| | Other air pollution, accidents, etc. | Vehicle regulation | Yes | Yes | Yes | Yes |
| **Investment decisions** | Myopic decision makers | Emission performance standard | Yes | Yes, but **not needed** | X | X |
| | ??? | Mandate GHG intensity decrease | Yes, but **not needed** | Yes, but **not needed** | Yes, but **not needed** | Yes, but **not needed** |
| | Learning by doing | Long-term carbon price guarantee | Yes | Yes | Yes | Yes |
| | Network effects | Investment mandate | Yes | Yes | X | X |
| | Network coordination | Coordination between MS | Yes | **Missing for electric motorways** | X | X |
| | Tenant-landlord | Investment mandate | X | X | Yes | Yes |
| | R&D spillovers | Innovation subsidies | Yes | Yes | Yes | Yes |

*Notes*: GHG = greenhouse gas, MS = member state, and R&D = research and development not needed'), or not present and not addressed ('X').[4] This summarizing table shows that there are six aspects of EU climate policy that do not follow the economic prescriptions for cost-efficiency (indicated in bold). First, there will be a cap on road transport emissions, but it also caps heating of buildings, which faces very different implicit carbon prices. Second, extra-EEA flights are not yet taxed or capped, but their growth is capped. Third, there are very few incentives to limit road congestion, although it will increase when fuel intensity decreases. Fourth, emission performance standards are not needed for trucks, because professional transport forms do correctly value future energy efficiency benefits. Fifth, a mandate to decrease the GHG intensity of transportation fuel is not targeting any market inefficiency, so it is not needed. Sixth, there is no focus on catenary electric motorways, which might be a possible option for truck decarbonisation. In section 4, we will specifically discuss some of these inefficient aspects of EU policy in more detail.

# 4 Cost-efficiency assessment of the European policy proposals to reduce fossil energy use in the transport sector

In this section we assess the cost-efficiency of the actual EU policy proposals to reduce fuel energy use in the transport sector in more detail. We focus on four aspects. First, section 4.1 analyses the implicit carbon price in different sectors and how this influences cost-efficiency of EU policy. Next, in section 4.2 we evaluate the options for cost-efficient trading of abatement efforts in the transportation sector with other emission sectors. Then we discuss in section 4.3 how a single focus on decreasing fossil energy use and carbon emissions might lead to inefficient levels of other transportation externalities, like congestion and air pollution, because of a rebound effect. Finally, section 4.4 discusses dynamic cost efficiency and how to stimulate long-term decarbonisation of cars, trucks, air transport and shipping, beyond 2030.

## 4.1 Implicit carbon prices are very different across sectors

The policy world tends to focus on the explicit carbon tax or the existence of an emission trading system to judge the cost-efficiency of policies in the transport sector. Explicit carbon prices and permit prices are indeed important but are insufficient to judge policies. Except

[4] In addition to the correct choice of instrument, one also needs to determine the optimal intensity of the instrument but this needs a modelling approach that goes beyond the survey ambition of this paper.

for EU ETS and the proposed transportation and heating ETS, explicit taxes are set by member states (European Commission 2021*b*), as unanimous agreement of all member states is needed for explicit tax decisions at the EU level. But in addition to explicit carbon taxes, there are all kind of levies and excise taxes on fossil energy that are proportional to the quantity of fossil energy used, and they act as an implicit tax on carbon. As a result, they add up to any explicit carbon tax and signal to consumers that the fuel is more expensive than the producer price. So neither the name nor the use of the revenues of the implicit carbon tax (finance road construction, finance public transport) are relevant to determine the implicit carbon tax.

Economists like (implicit) carbon taxes and permit prices because they give the right consumption and investment incentives. It makes users of fossil fuels consider the climate damage and makes them reduce the polluting activity, it increases the supply of fuels that are less carbon intensive (e.g. biofuels) and stimulates firms to offer less carbon-intensive user technologies. These incentives work best in a fully-competitive market where there are no other market distortions (monopoly margins, other externalities, etc.).

In Figure 1 we compare the implicit carbon taxes on different oil products and electricity for buildings and transportation, using tank-to-wheel emissions for transport. This illustration uses Belgian data, but other OECD countries would lead to the same conclusion that implicit carbon taxes differ across sectors and across fuels within the same sector, and that the implicit carbon price is often much larger than the explicit carbon tax (OECD 2019).[5]

Having different prices for the same pollutant is in general a signal of poor cost-efficiency in abatement. It means that the abatement costs differ among sectors so that shifting efforts across sectors reduces the total abatement cost. Imposing the same explicit tax on different sectors or putting sectors under the same tradable emission system guarantees a cost-efficient solution. So total emission costs can be reduced by equalizing prices of pollution.

Three elements of the FIT for 55 package have direct bearing on the implicit carbon taxes and on the cost-efficiency within the transport sector. First, the Energy Taxation Directive (European Commission 2021*b*) sets minimum tax rates for non-sustainable fuels but the minimum tax rate proposed for heating fuels is much lower than the implicit carbon taxes for road fuels. So the tax directive will not equalize implicit carbon taxes. Second, there are plans to set up a separate ETS platform for heating and transportation fuels. This could, at first sight, bring about an equalization of abatement costs but we show in section 4.2 that a simple trading mechanism will not improve the cost-efficiency. Third, extra-EEA

[5] There are also sizeable taxes on electricity, around €82 per MWh in Belgium in 2020, but we do not include them in the figure, because they are not proportional to the quantity of fossil energy used. A lower carbon emission intensity of electricity would lead to a higher implicit carbon price.

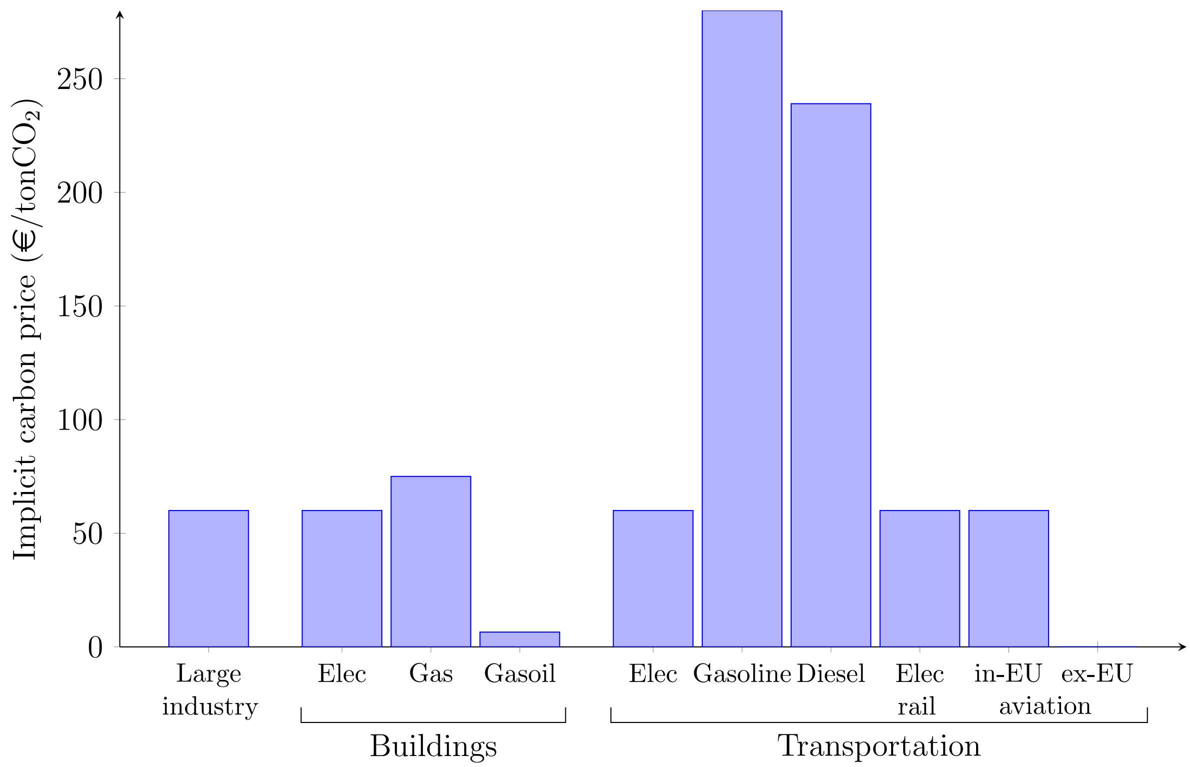


**Figure 1.** Implicit carbon price in large industry, buildings and transportation sectors in Belgium (excluding value-added tax - not on kerosene for aviation). We take an ETS price of €60 per ton (Bruninx & Ovaere 2021).

flights will be integrated into a CORSIA offset system and shipping will be integrated into the ETS system. This is a clear improvement.

The high implicit carbon taxes on road transport are often defended on other grounds than climate: source of tax revenues, tax on conventional air pollution for fossil driven cars, congestion tax etc. A question we address in section 4.3 .

## 4.2 How to cost-efficiently connect abatement efforts in the transportation sector with other sectors

Whenever abatement costs differ strongly among sectors in an economy, there is a potential for cost reductions. The easiest way is to use a carbon trade system that covers several sectors. As discussed in section 2.1, the European Commission proposes a new ETS that caps both transport and buildings. Similarly, Germany already launched a new national ETS for heating and transport fuels in 2021 (ICAP 2021) and started with a provisionally fixed permit price of €25 per ton of carbon. The motivation to separate this ETS system from the EU ETS on electricity generation and large industrial producers is to improve the cost-efficiency, to increase the certainty with which the emission reduction objectives are achieved, and to guarantee additional permit revenues for social climate purposes.

Using Figure 2, we will explain how the transport and buildings ETS is not cost-efficient. The main problem is that one establishes trade between two sectors with very different marginal abatement cost, because one sector (buildings) has very low implicit carbon taxes and another sector (road transport) has already very high carbon taxes and rather stringent performance standards.[6] For simplicity, suppose there is only one heating fuel (gasoil) and one transportation fuel (diesel) and that they have the same constant production cost, that we normalise to zero. Figure 2 shows the marginal abatement cost (MAC) curve of buildings ($MAC_B$, from left-to-right) and of transport ($MAC_T$, right-to-left). This means that the x-axis represents the abatement effort, while the y-axis represents the total price of the fuel to users in the building sector (left axis) and in the road transport sector (right axis).[7] The MAC curve represents the amount of carbon abatement (x-axis) given some price on carbon (y-axis) and the area below the curve is the total abatement cost to reach a certain level of abatement.

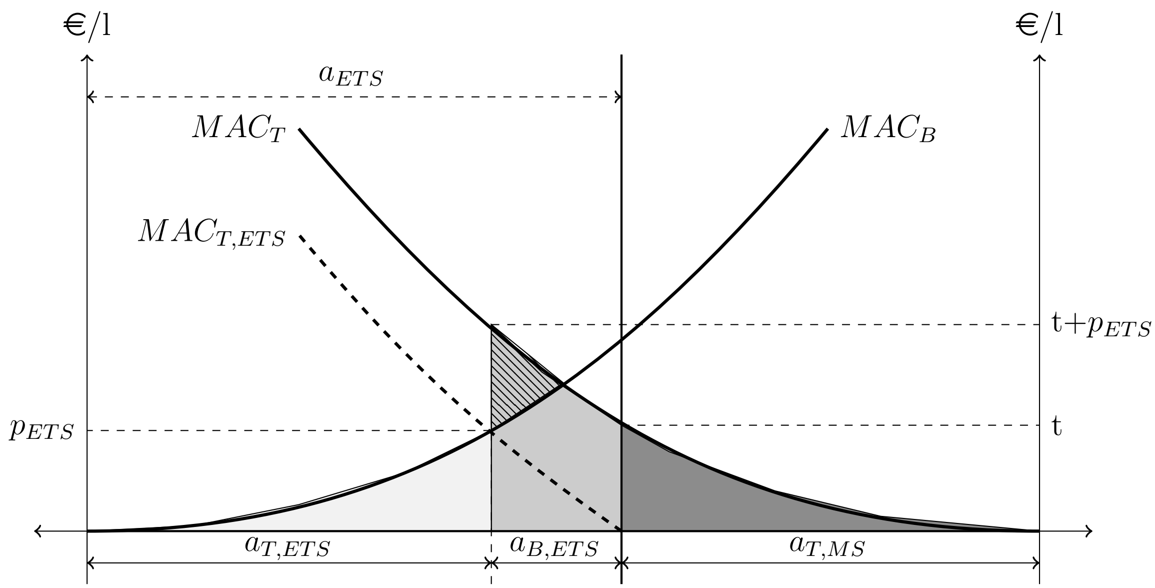


**Figure 2.** Illustration of the inefficiency (dotted triangle) of a joint cap-and-trade on transport and buildings ($a_{ETS}$) in the presence of road fuel taxes $t$.

Before focusing on the effect of a joint cap on transport and buildings, recall that there is

[6]As already discussed in section 4.1, the same is true within the transportation sector, where the implicit carbon price, and therefore the cost of emission reductions, varies strongly across transport modes: from an ETS price of €60 per ton of $CO_2$ for intra-EU aviation or electric vehicles up to €240 for diesel trucks and more than €280 per ton of $CO_2$ for gasoline car use (see Figure 1).

[7]We present the costs per litre of fuel but there is a direct correspondence with a cost per ton of $CO_2$. A €0.1 permit price per liter corresponds to €37 per ton of $CO_2$.

already a high implicit carbon tax in the transportation sector (see section 4.1) in the form of e.g. excise taxes at the MS level. Assuming that the implicit carbon tax is $t$, there will be $a_{T,MS}$ tons of carbon abatement in the transport sector and the total abatement cost is the dark gray area below $MAC_T$ – all this before the new ETS is implemented. In the building sector, on the other hand, there are currently almost no taxes on heating fuels.

When a joint cap on transport and buildings is added, the transport and buildings sector will start from different points on their MAC curve. But both sectors have to acquire emission rights, so the price of emission rights will be added to the existing implicit carbon tax and lead to additional abatement. Suppose that the total required abatement in this new ETS is $a_{ETS}$, which will be reached by abatement in the transport sector ($a_{T,ETS}$) and the building sector ($a_{B,ETS}$). How much each sector abates is determined by the intersection of $MAC_B$ and $MAC_{T,ETS}$. The price in this new ETS is $p_{ETS}$ and total abatement cost of the transportation sector is the sum of the dark and light gray areas below $MAC_T$, while the total abatement cost of the building sector is the very light gray area below $MAC_B$. In the optimum, however, abatement by the transport and buildings sector are determined by the intersection of $MAC_B$ and $MAC_T$, which shows that the combination of the implicit carbon tax on transportation and the joint cap on transport and buildings leads to too much abatement in the transport sector and too little in the building sector, compared to a joint cap only. The inefficiency is equal to the dotted Harberger triangle.

There are multiple ways to fix this cost-inefficiency. One can abolish the high fuel taxes on motorfuel use so that the ETS can work properly without distortions. Replacing the current fuel taxes on road transport by a more differentiated set of taxes (congestion, other air pollution, accidents, etc.) would be a good long-term objective. In this case, only the permit price (charged at the level of the fuel supplier) would be directly linked to the fossil fuel use. In the short term, it is better to keep the current fuel taxes and use a different instrument to stimulate the building sector to make the extra efforts imposed on the transport sector, e.g. building performance standards or a building ETS. This way, the government can reorganise the road tax system and prepare the transport sector for entering an intersectoral ETS that improves overall cost-efficiency.

A similar cost-efficiency reasoning is also true for trade of abatement efforts between EU ETS and the transport and buildings ETS. A joint cap is only efficient if there is no difference in carbon tax policies in the different participating sectors.

### 4.3 A single focus on decreasing fossil energy use might lead to inefficient levels of other transportation externalities

The implicit carbon tax is much higher in the road sector than in other transport sectors. One possible motivation are the important other externalities associated with car and truck use.

Figure 3 compares the tax on car use with the different externalities associated to car use and this for a gasoline and for a battery electric car.[8] The user tax for a gasoline car is the gasoline tax. The climate cost associated with the use of a gasoline car is the same in the peak and the off-peak period as it is directly proportional to the use of gasoline. External congestion costs are very high in the peak period and are almost nonexistent in the off-peak period. We see that the gasoline tax is much higher than the climate damage cost (here counted at €100 per ton of $CO_2$) but is insufficient to address the major externality (here congestion). This mismatch is well known in the transport economics literature[9], but insufficiently recognized in energy and climate policy.[10]

To see the policy problem, consider the following two thought experiments. Take a gasoline car that uses, because of the emission performance standard only half as much fuel as before. This will reduce the climate costs but leaves the other external costs largely untouched.[11] It can even increase the congestion costs as the rebound effect increases car use. The rebound effect, which is the % increase in car use when the fuel efficiency is increased by 1%, can be of the order of 0.07 to 0.2 (Small & Van Dender 2007, De Borger et al. 2016) so that a 50 % more fuel efficient car would induce an increase in volume of car use of 3 to 10 % and therefore save less carbon emissions and more importantly also increase congestion costs by 3 to 10 %.

Or consider that gasoline car owners are incentivised by the higher gasoline tax to switch to electric cars. We see in Figure 3 that the mismatch between user tax and the different external costs becomes larger when gasoline cars are replaced by battery electric cars as they

[8]There are methodological and estimation issues for the marginal external costs of car and truck use. Values also differ in function of place, time, vehicle properties etc. Estimates for EU countries can be found in European Parliament and Council (2019). We avoid the discussion on the precise values as what really matters here is the very poor correlation between motor fuel taxes and the other externalities.

[9]There are cities with road pricing where this mismatch is corrected (Singapore, London, Stockholm, Milan, Goteborg..) but they remain the exception.

[10]See among others, Proost & Van Dender (2001), Parry et al. (2014), Santos (2017). Parry (2007) suggests setting the gasoline tax equal to the carbon externality plus the other mileage related externalities that are avoided when a car user reacts to a gasoline tax by reduced driving. This way of computing a second-best fuel tax runs into problems when car users switch to electric cars or switch to very fuel-efficient cars as these pay much less for the mileage related externalities.

[11]The other air pollution costs associated to fossil fuel use (particles, tropospheric ozone, etc..) depend strongly on the pollution equipment of the car and much less on the quantity of fossil fuel used.

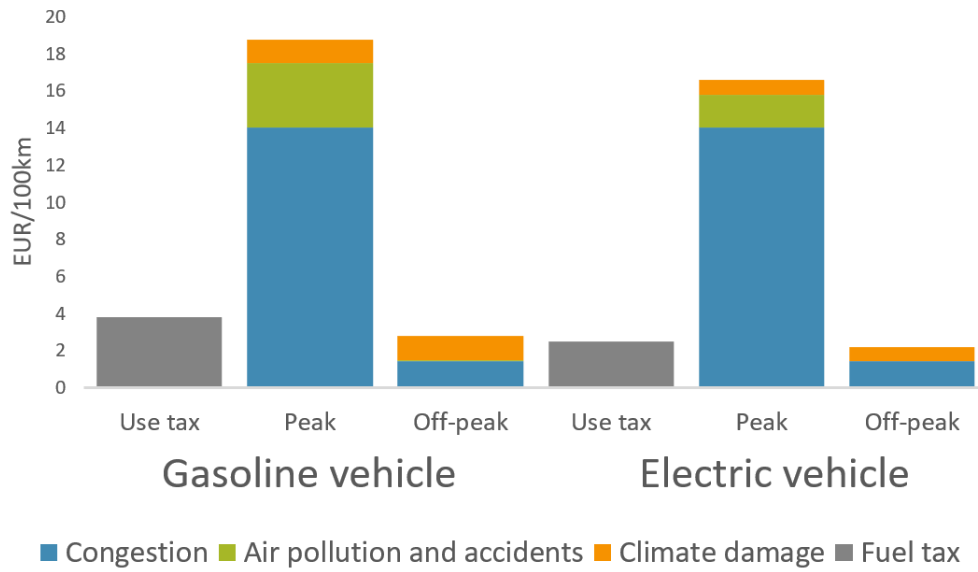


**Figure 3.** Comparing the tax on car use with the different externalities associated to car use (in peak and off-peak), for a gasoline and for a battery electric vehicle.

are cheaper to use for short trips in urban areas and these tend to generate more congestion externalities. Promoting the use of electric cars reduces climate emissions and other air pollution emissions but will make the other transport problems worse as its variable user costs are much lower. This was demonstrated for the case of Oslo where the use of electric cars is strongly promoted but where this promotion is actually welfare reducing (see Wangsness et al. (2020)).

For trucks, the problem is somewhat less acute because most countries have already a second charging instrument in place: distance taxes. The distance taxes are modulated to tackle external costs like wear and tear of roads as well as air pollution. Distance taxes do not yet charge for congestion costs but could be adapted to charge for congestion.

In conclusion, current decarbonisation policies aggravate other road transport externalities and this makes climate policies in the road sector less efficient. The European Commission advocates also a modal shift to public transport and land use planning as complementary strategies to reduce carbon emissions and other road use externalities. Part of the investment policies (see Table 2) focus on public transport infrastructure. For public transport there is some potential on high density corridors mainly because of its effects on road congestion, but this strategy remains difficult and costly as long as congestion pricing is not introduced. Land use planning has also some potential but it is a strategy for the very long term and then cars may already be mainly electric driven.

### 4.4 Reaching dynamic cost efficiency by stimulating innovation for decarbonisation of cars, trucks, air transport and shipping

While the 2030 target of -55% carbon emissions can be reached using current technology, the ambitious net-zero carbon emissions goal for 2050 will require an important innovation effort. Vehicles and fuels can become less carbon intensive through technical progress. This has been demonstrated for solar panels and batteries, as well as for many other energy supply and demand appliances. This means that, considered over a longer period, the full cost of a new technology can become cheaper than the existing technology, i.e. the discounted sum of development, production and user cost is smaller than the discounted cost of continuing to use the existing technology (Gillingham & Stock 2018). This technological progress will be crucial for achieving the decarbonisation target at the lowest cost. But research tells us that we need the right combination of two mechanism: pure R&D and learning by doing. As shown in Table 4, the two mechanisms require two types of instruments: subsidies to support the R&D process and a long term price on the pollutant to reward the successful clean innovation.

First, one needs to improve the technology itself (higher conversion efficiency, other production process) by pure R&D investments. This requires subsidies in the different phases of the R&D process because there are important spillovers leading to too low R&D investments by private firms and member state governments. In the case of spillovers, individual firms can not fully capture the market value of their innovation via patents and this would lead to too low innovation efforts in the absence of subsidies. The results of innovation are by their nature highly uncertain, so it pays off to bet on many different technologies.

Second, one needs to be able to decrease the production and distribution costs of the new technology by learning by doing and by increasing the production scale. The best clean innovation is the one that offers to the market a product that has the lowest total cost, which is the sum of production and distribution cost plus the external pollution cost. This requires a high implicit pollution tax or pollution permit price in the long term. High permit or fuel prices in the future are needed to make the new technology succeed in the market. As the innovation and scale-up phase require important up-front investments, it is important that the commitment to a high long term pollution price is credible. For cars and trucks, the importance of current tax revenues make a high implicit carbon tax a credible signal for the future carbon prices. For aviation and shipping, one has to rely on the future ETS and CORSIA to stimulate innovation. EU ETS is well-established and its long-term target is credible, but the long term fate of the CORSIA scheme for aviation emissions is less clear.

The right mix between the R&D efforts and the learning by doing is difficult to know, but there are decreasing returns in the use of the two components of the knowledge production. Nordhaus (2014) warns for a naive use of experience curves that attribute the decline in the average cost of a new technology to only the cumulative total number of vehicles, i.e. learning-by-doing. When only the cumulative number of vehicles would matter, it is sufficient to subsidise (tax) the purchase of new (old) vehicles and this would generate the cost reductions we are looking for. Technological progress, through Learning by doing, is clearly at work in the automobile industry (Aghion et al. 2016), stimulated by the high fuel prices in the road sector. It is also stimulated by the strong investment subsidies (of the order of €100 billion) in the Recovery and Resilience facility and the Connecting Europe facility (Table 2). But there may still be an imbalance with the R&D subsidies that are of the order of only €1 or €2 Billion (see Table 3).

Sections 4.4.1 to 4.4.4 will discuss in more detail how the European instruments support long-term research and innovation for cars, trucks, aviation, and shipping.

### 4.4.1 Dynamic cost-efficiency for cars

At present, there are two important climate policies for cars. There is the high implicit carbon tax on gasoline and diesel (see Figure 1) and the tradable (among manufacturers) carbon emission standard for cars (European Parliament and Council 2019) that forces the manufacturers of new cars in the EU to reduce carbon emissions from some 110 grams per vehicle-kilometer in 2019 down to 59 grams per vehicle-kilometer in 2030 and 0 emissions in 2035 (see Table 2). This objective can be reached in two ways: by reducing the emissions of fossil-fueled cars and by selling more electric vehicles (EV). EVs count for 0 emissions because electricity generation is included in the ETS. This is often understood as a mandate to selling in 2030, 50 % EVs and 50 % gasoline or diesel cars with current emission rates as this makes it possible to satisfy the emission constraint. But the objective is not to sell more electric cars but to reduce the average emission per vehicle-kilometer and to do this at lowest cost.

Littlejohn & Proost (2019), using a model with the two mechanisms for technology improvement (pure R&D and learning by doing ), compare the dynamic abatement costs of two possible options to reach the 2030 target of reducing the carbon emissions of new cars by 50 %. First, a mandate to sell in 2030 a mix of 50 % EV and 50 % fossil-fueled cars. Second, reaching a 50% decrease of emissions in 2030 and car manufacturers can choose the share of EVs and investment in fuel-efficient fossil cars. Littlejohn & Proost (2019) find that the 2030 target can be achieved with 20 % EVs and 80 % fossil-fueled cars with an increased fuel-efficiency.[12] In the optimum, the car manufacturers invest in R&D and subsidise the sales of EVs, either internally, by cross-subsidisation from fossil-fueled cars, or by using the trade in emission standard permits among car manufacturers or importers. This illustrates that the policies for dynamic efficiency need to be carefully crafted and that one best relies on a technology-neutral mandate.

Some EU member countries and cities want to accelerate the sales of EVs by additional subsidies for EVs or taxes on fossil fueled cars. Some countries and cities are adding a strict obligation for the sales of electric cars: at least 50 % should be electric or even a ban on the sales of fossil-fueled cars is considered. As the European car manufacturers face a constraint on the average new car sold in the EU, the extra incentives of member states have no net effect. Member states tend to forget that the car manufacturers have to meet a European wide average, when a member state is more ambitious, the manufacturers can reduce their efforts in other member countries. This mechanism was demonstrated in the USA where 14 states set more ambitious targets for greenhouse gases (the so called "Pavley" limits). Goulder et al. (2012) showed that 65 to 74 % of the efforts leaked away at the federal level.

There is also an important spillover to the rest of the world in terms of technology transfer. The EU is a technology leader, and this implies that car manufacturers in the rest of the world are forced to follow this standard when they want to sell cars in the EU.

### 4.4.2 Dynamic cost-efficiency for trucks

Similar to cars, the EU has imposed an emission performance standard for new trucks (European Parliament and Council 2019), requiring that firm-level average emissions of trucks decrease by 15 % in 2025 and 30 % in 2030. Contrary to cars, the choice of technology is not yet clear. There are two choices to be made. The first is to rely or not on Sustainable aviation fuels (SAF) (biofuels and synthetic fuels). SAFs of the biofuel type lead to a reduction of emissions but are not carbon neutral. In addition, this policy has only a limited low-cost potential if the biofuel has to be produced in a sustainable way. Second, when one does not rely on biofuels, one will rely on a fuel that is either electricity itself or derived from electricity.[13] One can use the electricity either directly or use a substitute fuel derived from electricity. The main substitute fuels are hydrogen (used in fuel cells or in new types of combustion engines), and power-to-liquid and power-to-methane, which are produced by combining hydrogen and captured $CO_2$. The substitute fuels have one major disadvantage

[12] Breed et al. (2021) make a similar point but for trucks.

[13] Under a fixed ETS cap, additional electricity demand will not increase carbon emissions, but note that the EU ETS cap is punctured and is expected to continue to be punctured for many more years (Bruninx et al. 2020, Bruninx & Ovaere 2021, Perino 2018).

compared to the direct use of electricity: direct electricity has an overall conversion efficiency (electricity to truck engine power) of 80 %, while hydrogen has an efficiency of only 40 %, and power-to-liquid or power-to-methane have an efficiency of only 25 %. Compared to battery-only trucks, the substitute fuels have an advantage in terms of range and can in principle use off-peak electricity. But off-peak electricity will not be for free as there are alternative uses. In addition, using an electrolyser or fuel synthesizer only in the off-peak periods of renewable electricity production will be expensive. These are the main reasons why the direct use of electricity to fuel trucks will be the most likely development and also the most cost-effective (Ainalis et al. 2020, IEA n.d.).

Once one opts for the direct use of electricity to fuel trucks, there are two competing options. To supply the electricity to the truck, one can rely on batteries only or on a combination of smaller batteries and catenary supply along motorways. As long-distance trucks are very intensively used (100,000 kilometers per year), this has two effects. First, electric trucks have a low variable cost, which makes electricity an interesting option if the cost of batteries decreases. Second, a truck that is intensively used has very little time for refueling and this is a disadvantage of battery-only electric trucks. The high cost of batteries and the time lost in refueling makes catenary trucks probably a more cost-effective option.

Börjesson et al. (2021) studied the potential of catenary roads for electric trucks in Sweden. In such a system, electric trucks have a battery to make smaller trips to locations off the motorways, but they are mostly charged on the motorways. An electric (catenary) road is characterized by high economies of density (high investment cost and low marginal cost to supply an extra user) and considerable economies of scope (the benefit per kilometer electric road depends on the size of the network). They find that the electric roads appear as a cost-effective means to significantly reduce carbon emissions from heavy trucks when a value of €114 per ton of $CO_2$ is used. But this public investment is risky as very favorable battery development or hydrogen technology developments may decrease the number of users of the electric infrastructure. Ainalis et al. (2020) come to the same conclusion in their analysis of decarbonising truck use in the UK.

Littlejohn & Proost (2019) look into the international coordination issue of electric roads which is important as international trucks represent, in smaller countries, more than half of the total truck distance covered for the growing share of international trucking. Member countries can, via the distance charges, discriminate between trucks in function of their environmental performance but not in function of the nationality of the truck.

Decarbonising trucking via electric motorways has a clear potential and could even come at a lower abatement cost than electric cars because trucks are much more intensively used than cars. As manufacturers are still investing in different technologies and as cross-border traffic is very important, there is a crucial coordination role for the European Union in terms of technology choice and infrastructure development. The Fit for 55 infrastructure plan (Table 2) seems to provide the wrong refueling infrastructure mandates. It foresees a mandate for electricity recharging, hydrogen, and LNG, but does not include catenary lines as an important option.

#### 4.4.3 Dynamic cost-efficiency for aviation

The share of climate emissions from aviation is still limited but is expected to grow quickly because the demand for aviation has a high-income elasticity and because there are no easy substitutes for kerosene.

The EU is a forerunner in climate policy but has not yet decided on its long-term strategy for aviation. There are three policy instruments. First, carbon emissions from intra-EU aviation are included in the ETS bubble and are therefore priced. Second, there is the promotion of the substitution of aviation by High Speed Rail via the investment subsidies (Table 2). Third it imposes a growing blending of kerosene with renewable fuels for EU aviation (European Commission 2021*h*). Policy instruments focusing on fuel blending are now not only targeting the intra-EEA flights but also the flights departing from the EU to non-EU destinations will be included. This extension is important as intra-EEA flights represent only 15 % of the carbon emissions of all flights departing from an EU airport (EUROCONTROL 2020).

High-speed rail (running on electricity) and EU aviation are part of the same ETS trading system and this reduces the need for additional modal change policies.[14] This implies that the substitution between rail and short-distance aviation in the EU has in theory no net effect on carbon emissions. But there is an important concern about the accounting of the GHG emissions from aviation. The GHG emissions of electric power plants and cars are well known, but the total GHG emissions of aviation is still a topic of considerable debate. Aviation activity also emits $NO_X$ that contributes to ozone formation (a greenhouse gas) and generates contrails (Grewe et al. 2017). The net effect is not proportional to the $CO_2$ emission, so a simple non-$CO_2$ multiplier is suboptimal. There is also a second concern about the public subsidies for airports, airlines, and high-speed rail (HSR) investment and operation, especially in the post-Covid recovery. Subsidies can be efficient, but we are still lacking a fair assessment of the subsidies for long-distance travel projects. Proost et al. (2011) made an assessment of the European long-distance projects, including many HSR

[14] Fageda & Teixido-Figueras (2020) found that the introduction of air transport into the ETS reduced the supply of seats on low cost airlines by 7 % and on routes where intermodal competition exists, the reduction in seats is even 23 %.

projects and airports and found rather poor benefit/cost ratios.

The blending mandate increasing the share of SAF from 2 % to 63 % in 2050 (Table 1) is considered by the Commission as the major policy instrument to reduce carbon emissions in aviation and this raises questions of cost-efficiency. Of course, one can hope that the production cost of substitute fuels for aviation decreases very strongly as did the costs of batteries and photovoltaic panels, but we deal here with very different technologies, so there is no guarantee that this success story will be repeated. Different policies for attaining a minimum sustainable aviation fuel share have been proposed but there are three difficulties. The first problem is to take into account the complex sustainability requirements for biofuels that constitute by far the cheapest way to produce SAFs. Second, there are the uncertain costs and potentials of feedstock supply. Finally, producing SAFs for decarbonisation strategies in other sectors (road transport, heating,..) is less costly, so it may be more efficient to use the limited biofuels potential in other sectors than aviation.

Mayeres et al. (2021) show that policies that aim to achieve a minimum share of 3.5 % or 5.25 % sustainable aviation fuels by 2030 in the EU are 5 to 10 times more expensive to reduce greenhouse gas emissions than a simpler emission trading mechanism assumed to operate at a price of €25 to €50 per ton of $CO_2$. A kerosene tax or permit price reduces kerosene use by a combination of lower air transport activity, more fuel efficiency and less carbon intensive fuels.

Given the limited potential and high cost of the SAF route and the uncertainty in the compliance with the CORSIA agreement, the EU should also look into a credible long-term carbon price and the potential of efficiency standards for aircrafts, as it has been doing for cars. Compared to the production of cars, aircraft production is concentrated mainly into the hands of a duopoly: Airbus and Boeing. Moreover, aircraft use is mainly concentrated outside of the EU: counting all flights inside the EU and outbound the EU, this represents less than 25 % of all civil aviation emissions (Graver et al. 2020). Ovaere & Proost (2021) explore this option.

More fuel-efficient fossil engine aircrafts are only the first step in decarbonisation. A carbon-neutral aircraft requires substitute fuels like hydrogen used either in fuel cells or used directly in new engines. The first carbon neutral aircrafts will be narrowbody aircrafts for less than 100 passengers and a small range (below 1000 km) (Schäfer et al. 2019). Prototypes are promised for 2035 - 2050.

In the medium time a higher tax on kerosene combined with a performance mandate may be a more cost-effective and less risky option to reduce emissions in aviation than an increasing blending mandate.

### 4.4.4 Dynamic cost-efficiency for shipping

For shipping, the main policy instrument to reduce emissions is again a high blending mandate for SAFs (see Table 1). The same arguments in favor of a simple emission tax apply here. In the medium term, price increases for shipping fuel, obtained via ETS mechanisms are much more cost-efficient. This does not preclude R&D efforts into alternative fuels. A second policy instrument could be performance standards for ships.

# 5 Conclusions and policy implications

The European Union uses a range of policies to reduce fossil energy use and carbon emissions in its transport sector. In total we identified and categorised nine different policy instruments targeting cars, trucks, aviation and shipping. First, *consumption* decisions are steered towards low- or zero-carbon transportation fuels using a cap-and-trade, minimum tax rates in member states on non-sustainable fuels, mandates for transportation fuels with decreased GHG intensity, and mandates for a share of sustainable aviation fuels. For aviation, there is also an offsetting requirement for emissions above the 2019 level. Second, *investment* decisions are steered towards low- or zero-carbon technologies using a performance standard on cars, vans, and trucks; a mandate for electric, hydrogen, and LNG infrastructure for road transport, aviation, and shipping; and different investment subsidies for sustainable transport infrastructure projects. Third, *research and innovation* efforts are steered towards low- or zero-carbon technologies using research subsidies and using research partnerships that bring together all key players in each industry.

Our analysis showed that the European policies and instruments address a range of market inefficiencies, in line with economic prescriptions dating back to Tinbergen (1952). However, there are still a number of aspects that can be further improved to implement a sustainable recovery (Gillingham et al. 2020) and reach the European Union's climate targets at the lowest cost. First, there is a striking unbalance in implicit carbon prices in the transport sector. The transport and building ETS, which adds permit prices to the existing high excise taxes in transportation, will be more efficient when the road tax system is revised. We urgently need congestion tolls and charges that avoid that electric cars and more fuel-efficient cars make congestion problems worse. These could replace part of the existing excise taxes on gasoline and diesel without strongly affecting the lowest income groups (Heyndrickx et al. 2021).

Second, the unbalance in the tax system calls for higher taxes on aviation and shipping. These are foreseen by their integration into the ETS system. As SAFs are at present still very costly, the blending mandate (European Commission 2021*h*) is not cost-effective, and one should consider replacing the emission abatement generated by the blending mandate by specific higher taxes on kerosene. Also note that the blending mandates for aviation and shipping, in combination with the emission performance standard for cars and trucks, will most likely make the 13% decreased GHG intensity target (European Commission 2021*e*) not binding.

Third, emission performance standards for cars can make sense, because consumers could undervalue future fuel costs. But this reasoning does not hold for, trucks, shipping, and aviation, because large firms are perfectly valuing future consumption cost decreases. However, a performance standard can be a good second-best instrument for aviation and shipping, when the rebound effect is limited, as they operate in an international environment with low carbon prices because of fuel tankering abroad. Such an EU performance standard for aviation is best coordinated with the USA (Ovaere & Proost 2021). The resulting technological progress in Europe (and the US) can spill over to the rest of the world. As emissions in the rest of the world are five times larger than the emissions in the EU, the spillover effect may be more important for worldwide emissions than the emission reduction in the EU (Barla & Proost 2012).

Fourth, the sectoral origin of carbon emissions does not matter. In the long term, a common ETS with the transport, residential building, industry and power production sector guarantees a cost effective emission reduction, but only if the existing fuel tax system in the road sector is reformed.

Fifth, reaching the carbon reduction target of 2030 can rely on existing technologies, but to achieve the 2050 objective of net-zero emissions, technological developments will be crucial. This requires the right combination of R&D investments and learning-by-doing policies. For example for electric trucks, that have a large decarbonisation potential as international trucks are used very intensively, there are three options: electric battery trucks, hydrogen trucks, and catenary trucks. Electric battery trucks are more cost-effective than hydrogen trucks (Ainalis et al. 2020, Börjesson et al. 2021) when one can solve the recharging and battery weight problems. Catenary trucks are much lighter, but this requires European infrastructure coordination.

Finally, this paper focused on cost-efficiency of European climate, transport and energy policy, but the equity of these policies is of equal importance. The EU uses two tools to ensure a just and widely-supported transition for all. First, the Just Transition Mechanism – consisting of the Just Transition Fund, the InvestEU programme, and the Public Sector Loan Facility – which provides more than €50 billion of investment in and support for regions that are the most carbon-intensive or with the most people working in fossil fuels. This money will go towards, i.a., reskilling workers, improving energy-efficient housing, investing in the creation of new firms, and investing in low-carbon technologies. Second, the Social Climate Fund (European Commission 2021*g*) will address the social impacts that arise from the transport and buildings ETS. Around €144 billion[15] will go towards temporary direct income support for vulnerable households and emission reductions of buildings and road transport to reduce costs for vulnerable households, micro-enterprises and transport users. As earlier experience with environmental and redistribution policy has shown (Borenstein & Davis 2016), it will be challenging, but necessary, to distribute this money to those without the means to make the transition towards climate neutrality.

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[15] The EU allocates €72.2 billion, or 25% of the expected revenues of the ETS, and the member states match this with national funding.

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