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European dieselization: Policy insights from EU car trade

Ignacio del Rosal

Department of Applied Economics, University of Oviedo, Avenida Del Cristo, S.n., 33006, Oviedo, Spain

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ABSTRACT

European dieselization, i.e. the sustained increase in the diesel share in the passenger car fleet, is associated with the first EU strategy to reduce CO2 emissions from passenger cars. This paper aims to contribute to the literature on dieselization by looking at EU international trade flows in passenger cars, a perspective seldom found in the literature. Trade data confirm that the bulk of EU diesel trade flows occurs between EU partners, although diesel imports from other, non-EU countries are also significant. Besides, the external competitiveness of the EU car industry is clearly based on petrol cars. The analysis of trade data also reflects previous findings on the increase in car size. On the policy side, the divergence between CO2 from new car registrations and total CO2 emissions from passenger cars during the dieselization era proves that strategies for decarbonization should not rely exclusively on efficiency gains, demand policies are also needed. The dieselization phenomenon warns of the major inertia that road transport policies can have. The analysis of EU car trade also underlines the need to coordinate environmental policy with other relevant countries in the international car market.

1. Introduction

Controlling greenhouse gas (GHG) emissions is the cornerstone of climate change mitigation. In 2010, 10% of direct global GHG emissions were caused by road transport, showing an increase of nearly 50% since 1990 (Sims et al., 2014). Road transport plays a similar key role in European Union (EU) GHC emissions, accounting for 27% of carbon dioxide (CO2) emissions in 2019, reflecting an increase of 24% between 1990 and 2019 (EEA, 2021a). Passenger cars were responsible for approximately 60% of GHG emissions from road transport in 2018 (EU, 2020).

Within the context of the first global efforts to combat climate change in the early 1990s, e.g. the adoption of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992 (UN, 1992), the EU established its first strategy to reduce CO2 emissions from passenger cars (EC, 1995). The main pillar of the EU strategy was the signing of voluntary agreements with the automobile industry to achieve a reduction in CO2 emissions from new passenger cars. The two other pillars of the strategy were the promotion of fuel efficiency through fiscal measures and fuel economy labelling. From the very beginning, it was acknowledged that, although diesel cars perform better than petrol cars in terms of CO2 emissions, the sole increase in the share of diesel cars in the car fleet would not enable CO2 targets to be met (EC, 1995, p. 5). Hence, the reduction in emissions was assigned to technological developments to be made by automobile manufacturers.

The voluntary agreements signed by the European Commission (EC) and the automobile industry are usually considered the main cause of EU dieselization, i.e. the sustained increase in the diesel share in new passenger car registrations that occurred from the mid 1990s onwards, also known as the European diesel car boom (Fontaras and Samaras, 2007; Schipper and Fulton, 2013; and Cames and Helmers, 2013; among others). The dieselization phenomenon has been extensively studied in the literature and the general conclusion that emerges is that the EU's passenger car policy has failed to achieve a substantial reduction in CO2 emissions. Fig. 1 shows some key trends between 1995 and 2018. The share of diesel cars in new passenger car registrations more than doubled in a context in which the fleet was steadily increasing. Total CO2 emissions from passenger cars in the EU did not show a clear reduction over the entire period, even though the official CO2 emissions of new diesel cars, with an increasingly prominent presence, decreased (CO2 emissions from petrol cars also decreased; see EEA, 2020). European dieselization shrank in later years, especially after 2016.

The automobile industry's efforts to reduce CO2 emissions from new passenger cars proved to be insufficient and the European dieselization strategy failed in its attempt to mitigate global warming, in line with the commitments the EU signed up for in the Kyoto Protocol and the Paris Agreement, within the UNFCCC (UN, 1998, 2015). The EU is currently setting up a more ambitious strategy on adaptation to climate change. With the 'European Green Deal' political initiative, the EU has committed itself to achieving climate neutrality by 2050 and proposed

E-mail address: irosal@uniovi.es.

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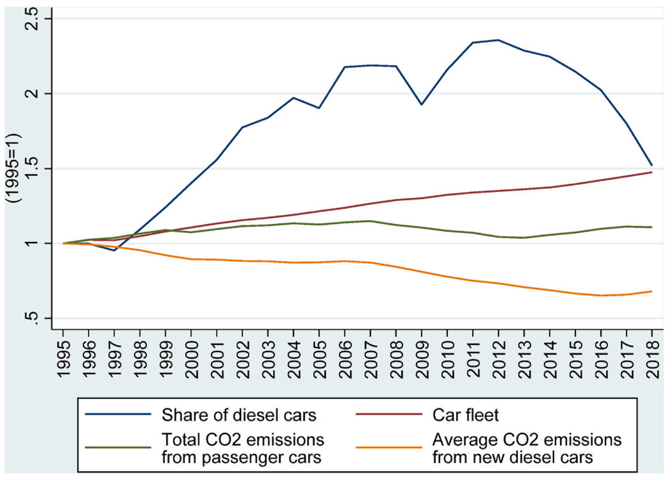

Fig. 1. EU trends in the share of diesel cars, total CO2 emissions from passenger cars, car fleet and average CO2 emissions from new diesel cars (1995 = 1). Sources: Diesel car share, Eurostat; total CO2 emissions and car fleet, EU (2020); average CO2 emissions from new diesel cars, EEA (2017, 2018, 2020) and EC (2005).

an intermediate target for reducing GHG emissions by at least 55% compared to 1990 levels by 2030 (EC, 2019; 2020a). The recently approved 'European Climate Law' (Regulation (EU) 2021/1119) has made these targets legally binding. This new EU strategy, currently in development, will have profound consequences for both car manufacturers and users.

EU policies and the automobile industry's performance alike have been soundly criticized (Cames and Helmers, 2013; Hooftman et al., 2018; and Helmers et al., 2019; among others). The conclusion that emerges is that "from today's perspective, Europe chose the wrong alternative by promoting diesel cars instead other powertrains and fuels which were available at the time" (Helmers et al., 2019, p. 130), and that this alternative had prevented Europe "from exploring alternative and more sustainable pathways such as hybridization and electrification" (Cames and Helmers, 2013, p. 18). The EU and the industry "created a European 'diesel island' with no equal worldwide" (Hooftman et al., 2018, p. 14). It is now clear that the European dieselization strategy failed to make any significant progress in reducing total CO2 emissions from passenger cars. However, analysis of the dieselization phenomenon may contribute to learning some basic lessons that can be useful in shaping policies for sustainable mobility. There are uncertainties about the transition path to zero-carbon road transport and several decisions have to be taken. For instance, the phasing out of internal combustion engine vehicles has to be established. Similarly, the transitional role of low emission cars such as plug-in hybrid electric vehicles (PHEVs) needs to be clarified. Besides, the divergence between total CO2 emissions from passenger cars and average CO2 emissions from new car registrations depicted in Fig. 1 clearly shows that the strategy for decarbonization should not rely exclusively on efficiency gains. A permanently growing vehicle fleet of larger and more powerful cars, used more intensely over larger distances, can offset any advances made in energy efficiency. A growing consensus in the literature underlines the need for demand side policies (Sorrell, 2015; Creutzig et al., 2018; Anable and Goodwin, 2019; Lamb et al., 2021). Car-based mobility should be reduced and other forms of sustainable mobility have to be promoted instead.

This paper aims to contribute to the dieselization literature by bringing attention to the EU's international trade flows in passenger cars. Trade flows in cars have seldom been analysed in this literature. International trade databases offer information at a reasonably disaggregated level, allowing the analysis of petrol and diesel cars by size, for instance. In some respects, the bulk data contained in trade databases are limited because many details of a particular trade flow are lost. Besides, bilateral trade flows are so numerous, generating a very large number of observations that facilitate the statistical identification of policy effects, for instance.

This paper focuses on EU car trade in order to examine several issues to be found in the literature. For instance, it examines EU trade in cars to verify whether import and export flows by size reflect the phenomenon of the increase in car size observed in the EU fleet, reported in a number of papers. It also qualifies several statements in the literature regarding the role that car trade relationships with other non-EU countries played in the European dieselization process.

To this end, a brief review of the literature is first presented in Section 2 in order to provide a minimum background to the subject of EU dieselization. Subsequently, Section 2 also reports the main trends in EU car trade. Section 3 presents the methodology employed, namely the gravity equation for international trade, as well as the data used for the analyses. The results are presented and discussed in Section 4. Finally, the main conclusions and policy implications can be found in Section 5.

2. Background

2.1. Literature review

The period 1998–2008 appears to be an important phase in the dieselization phenomenon (Zachariadis, 2013). In 1998, the European Automobile Manufacturers Association (ACEA) signed a commitment regarding CO2 emissions from new passenger cars within the framework of the 'environmental agreement' with the European Commission (EC) (EC, 1998). This voluntary agreement is usually identified as the beginning of the European dieselization process (Fontaras and Samaras, 2007; Cames and Helmers, 2013). The average CO2 emissions target from new passenger cars sold in the EU was set at 140 g/km, to be met in 2008. In1999,[1] the EC signed similar agreements with Japanese and Korean automobile manufacturers associations, with the same emissions target for 2009. Although some reductions in emissions were achieved during the first few years, the targets were not met by the industry. Consequently, the EU enacted binding legislation[2] in 2009 (Regulation (EC) No. 443/2009), setting the limit of 130 g/km for average CO2 emissions from new car registrations to be met in 2015, and the stricter target of 95 g/km to be met in 2021, with a phase-in from 2020 (Regulation (EU) 2019/631). This current EU regulation also set future reduction targets for 2025 (15%) and 2030 (37.5%), taking 2021 average emissions as the baseline. Recently, the European Commission has proposed a tightening of the binding target for 2030 by establishing a 55% reduction of 2021 emission levels (EC, 2021), in line with the requirements of the European Climate Law. Furthermore, the proposal also includes a de facto ban on any type of internal combustion engines by 2035 by establishing a 100% reduction of the 2021 baseline emissions, i.e. zero emissions from new cars.

The evolution of EU CO2 standards and the advances made by car manufacturers have been reviewed in detail in the literature (see the recent papers by Ajanovic et al., 2016; Fontaras et al., 2017; Hooftman et al., 2018; and Helmers et al., 2019). Car manufacturers have improved average CO2 emissions from new passenger cars and the 2015 target of 130 g CO2/km was met by 2013. Data for more recent years show that average CO2 emissions were rising in the years 2017–2019 (EEA, 2020 and 2021b). In 2020, however, average CO2 emissions decreased significantly and got close to the target of 95 g/km (EEA, 2021c; Wappelhorst et al., 2021). This 2020 reduction of the average

[1] The three agreements were officially enacted in 1999 and 2000 (EC, 1999, 2000a and 2000b).

[2] The development of Regulation (EC) No. 443/2009 and the preceding agreements have been analysed from a political science view by Gulbrandsen and Christensen (2014).

CO2 emissions may be related to the sharp increase in new electric vehicles registrations and the flexible compliance mechanisms (such as 'super-credits', which allow manufacturers to increase the weighting of low-emission cars in the calculation of emission averages) included in the EU emissions regulation for phasing in CO2 targets (Wappelhorst et al., 2021). In contrast, there is ample evidence regarding the increasing divergence between real-world and 'official' type-approval CO2 emissions (Tietge et al., 2017; Fontaras et al., 2017). CO2 emissions have been certified using a laboratory conditions test based on the New European Driving Cycle (NEDC) that is reported to be quite unrepresentative of real-world driving conditions. The NECD test is being gradually replaced by another laboratory test, the Worldwide Harmonized Light Vehicles Test Procedure (WLTP), which will provide more realistic CO2 emissions values (Tietge et al., 2017; EEA, 2016); see also the in-depth discussion in Fontaras et al. (2017) and Hooftman et al. (2018).

European dieselization has also been favoured through more lenient tailpipe emission standards (Cames and Helmers, 2013). Vehicle tailpipe emissions (nitrogen oxides, hydrocarbons, carbon monoxide and particulate matter including black carbon) have been regulated in the EU via the 'Euro' regulations since the introduction of Euro 1 in1992.[3] Initially, the limit for hydrocarbons and nitrogen oxides (NOx) was established in common for diesel and petrol cars. Since Euro 2, however, less stringent NOx and particulate matter limits for diesel cars have favoured their ownership over petrol cars (Cames and Helmers, 2013; Minjares et al., 2013; Hooftman et al., 2018). The introduction of Euro 5 and, especially, Euro 6 has led to the tightening of emissions limits and has reduced the margin for diesel cars (see, e.g., Williams and Minjares, 2016). The European Commission is currently developing stricter emission standards, through the Euro 7 regulation, in line with the European Green Deal (Mulholland et al., 2021).

The reduction in tailpipe emissions in the EU and US has been notable over the last three decades (Winkler et al., 2018). However, there is also clear evidence of the divergence between emissions during certification and in real-world use, particularly for NOx emissions (see, e.g., Degraeuwe and Weiss, 2017, and the references therein). In parallel with CO2 emissions certification, the NEDC test has been replaced by the WLTP test, while a Real Driving Test (RDE) procedure has been introduced to complement laboratory certification (see the details in, e.g., ICCT, 2018; and Hooftman et al., 2018). The appearance in 2015 of what has been called 'Dieselgate', i.e. the unmasking of the use of defeat devices in diesel cars sold by the Volkswagen Group in the US (Zachariadis, 2016; and Skeete, 2017), has certainly speeded up ongoing certification improvements in the EU.

Preferential tax treatment has been another important driver for European dieselization. The literature has largely focused on asymmetric fuel taxation, with lower excise duties on diesel fuel (Schipper et al., 2002; Sterner, 2007; Kalinowska et al., 2009; EFTE, 2011; Burguillo-Cuesta et al., 2011; Mayeres and Proost, 2013; Ajanovic et al., 2016; and Santos, 2017). With the exception of the UK, all EU countries have taxed diesel fuel with lower excise duties than those applied to petrol fuel. Fewer papers analyse the role of car acquisition taxes (such as registration taxes) and ownership taxes (such as annual road or circulation taxes) (Kalinowska et al., 2009; Mayeres and Proost, 2013; and Ajanovic et al., 2016), possibly due to the great variation in taxation across the EU. For the majority of European countries analysed in Kalinowska et al. (2009), the overall tax burden was lower for diesel cars. Car tax systems in the EU countries are even more diverse and complex nowadays, being increasingly based on CO2 emissions and/or fuel consumption (ACEA, 2019a and 2019b).

In addition to voluntary agreements, permissive pollutant standards and preferential tax treatment, there is another key factor underlying EU dieselization that is linked to all the others: diesel fuel economy. Diesel engines are inherently more efficient than petrol engines (see, for instance, the brief explanation in Wallington et al., 2013) and operate with lower fuel consumption and less CO2 emissions (although this advantage can be qualified taking into account CO2 equivalent emissions due to other pollutants). In fact, there have been significant efficiency improvements in both diesel and petrol car engines over the last decades (Schipper, 2011; Ajanovic et al., 2012; and Schipper and Fulton, 2013). Fuel efficiency in diesel engines improved notably with the spread of direct injection in mid 1990s (Cames and Helmers, 2013; see also Fig. 4 in Beise and Rennings, 2005). Besides, several papers in the literature linked technological improvements in fuel efficiency with the introduction and/or tightening of emissions standards (Clerides and Zachariadis, 2008; Berggren and Magnusson, 2012; and Klier and Linn, 2016; among others). However, there is ample evidence in the literature showing that improvements in fuel efficiency have not been fully translated into aggregate fuel consumption and CO2 emissions due to 'rebound effects' (reviewed in Greening et al., 2000; Sorell et al., 2009; and Ajanovic et al., 2016). Efficiency improvements in new car models were offset by more intensive vehicle use (more kilometres driven) and the switch to larger, more powerful cars (Schipper et al., 2002; Ajanovic and Haas, 2012; Ajanovic et al., 2012; Matiaske et al., 2012; Schipper and Fulton, 2013; and De Borger et al., 2016). This took place both for petrol and diesel cars, but the latter case is especially highlighted in a number of studies (Schipper et al., 2002; Ajanovic et al., 2012; Schipper and Fulton, 2013).

The offsetting effect of the rebounds effects is a reminder that car use is a crucial determinant of total CO2 emissions. In the past, improved energy efficiency has been misleadingly equated with reduced energy demand (Sorrell, 2015), but there is growing consensus that demand side policies are also essential for rapid and effective climate change mitigation (Sorrell, 2015; Creutzig et al., 2018; Anable and Goodwin, 2019; Lamb et al., 2021). In a literature review on the mitigation potentials of changing consumption patterns, Ivanova et al. (2020) show that the highest mitigation potential of demand reductions is found precisely in the domain of transport. In the case of passenger cars, demand-side initiatives enable and encourage people to use the private car less and thus bring about changes in behaviour and lifestyles (Sorrell, 2015; Anable and Goodwin, 2019), moving away from a car-dependent transport system (Mattioli et al., 2020). Demand side measures may have a key role to play in the period of transition to zero-carbon mobility, reducing pressure on policy while clean technologies still have high costs and limited deployment (Pye et al., 2014; Brand et al., 2019).

The absence of demand-oriented policies to accompany new vehicle technology led, among other consequences, to the increase in new-car size and power underlined many times in the literature (Cuenot, 2009; Zachariadis, 2013; Ajanovic et al., 2012; and Schipper and Fulton, 2013). This phenomenon has seldom been related to international trade in cars. Cuenot (2009) hypothesised that the EU exported larger and fuel-inefficient cars to third countries. Furthermore, IEA (2009) reported the importance of used cars exports from OECD countries to less developed countries.

2.2. *EU car trade*

In principle, two equivalent data sources can be used to analyse EU[4] country trade in cars: Eurostat's Comext database and the UN's COMTRADE database.[5] Both provide information on the value, weight and units of bilateral trade flows. The main difference is that Comext does

[3] See, for instance, https://www.transportpolicy.net/standard/eu-light-duty-emissions/[Accessed 30 September 2021].

[4] Henceforth, the definition of the EU evolves in the study period according to the EU Enlargements, from EU-12 to EU-15, EU-25, EU-27 and EU-28.

[5] See Eurostat (2020) and https://comtrade.un.org/[Accessed 30 September 2021].

not offer information about trade flows between non-EU countries, whereas COMTRADE has a world-wide coverage. Trade data are provided at different levels of disaggregation, using product classifications for customs purposes. In COMTRADE, trade data are provided according to the 6-digit Harmonized System (HS), an international product classification developed and maintained by the World Customs Organization. HS heading 8703 comprises passenger cars, including seven 6-digit codes for diesel and petrol cars, depending on car size. Comext provides trade data according to the 8-digit Combined Nomenclature (CN), a European classification based on the 6-digit HS, i.e. sharing the first six digits in common. Thus, the CN is more disaggregated and, in the case of passenger cars, distinguishes between new and used cars. Besides, the information on units and weight is more complete in the Comext database. More details regarding data availability, product classifications and other details are provided in Appendix A.

The first thing to note is that EU dieselization can be tracked by looking at the share of diesel cars in EU car imports. Fig. 2 plots the diesel car share both in EU new passenger car registrations and car imports from both EU and non-EU countries. The similarity of the two plots is quite high and they show the same trends: EU Dieselization took off in the mid-1990s, growing steadily until the 2008–09 crisis. After that, the shares in diesel cars recovered and then began to fall. Besides, EU dieselization stands out when the role of diesel cars is compared with other countries. To this end, Fig. 3 compares the share of diesel cars in EU and Rest-of-World (comprising all non-EU countries) car imports, computed using trade value in this case. The difference is noteworthy; the diesel car share in EU total value of imported cars may be 5–6 times higher than the equivalent Rest-of-World value.

The role of petrol and diesel cars in EU trade flows is shown in Figs. 4 and 5. Fig. 4 plots import and export flows with the Rest of the World. As can be seen, petrol car flows between the EU and the Rest of the World are much more significant, especially in the case of EU exports to the Rest of the World. Fig. 5 focuses on intra-EU trade, taking export flows as the reference. Intra-EU trade flows in diesel cars grew between 1990 and 2007, reaching the level of petrol car trade flows, which were more stable over the same period. Interestingly, the growth in diesel cars in intra-EU trade is quite similar to that of petrol cars exported to the Rest of the World in terms of the volume reached, but the growth of diesel car flows with the Rest of the World also grow notably (in fact, in relative terms, these flows are somewhat more intense before 2008). The latter years in Fig. 5 show that the role of petrol and diesel cars in intra-EU trade flows balanced out more evenly.

The contrast between Figs. 4 and 5 clearly shows that EU dieselization was mainly fed by intra-EU trade flows, although imports from third countries are not negligible. Table 1 shows the main EU partners in

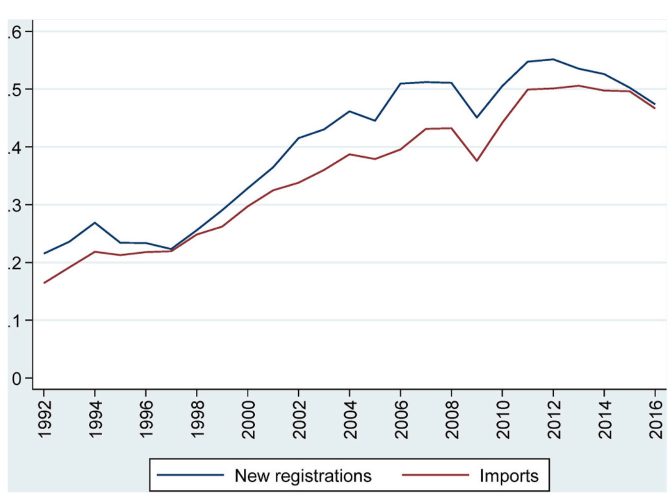

Fig. 2. Diesel car share in EU new passenger car registrations and car imports. Sources: Comext and Eurostat.

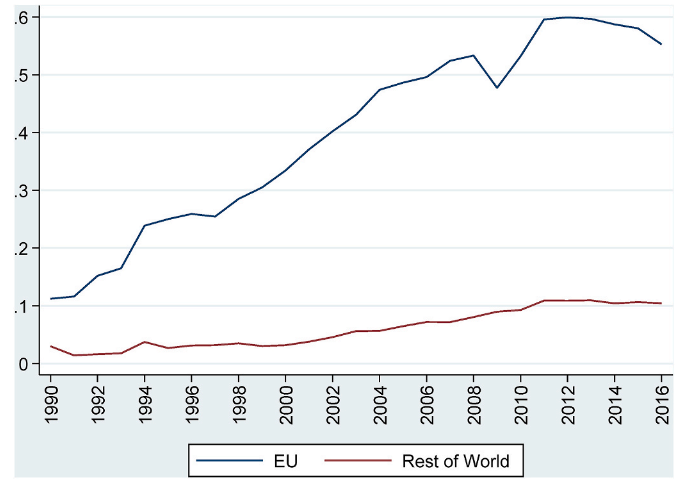

Fig. 3. Diesel car share in EU and Rest-of-World car imports (in value). Source: COMTRADE.

petrol and diesel car trade flows with the Rest of the World over the period 1990–2016. Although EU car exports are less concentrated than imports, Table 1 reveals that the main market for EU petrol cars, by far, is the US, with nearly 35 million cars, whereas Japan stands out as the main supplier in terms of petrol and diesel cars, with 18 and 6 million cars, respectively. It is also worth noting that Japanese, US and Korean diesel exports to the EU totalled 13.2 million cars. The agreements between the EC and Japanese and Korean automobile manufacturers associations are clearly reflected in trade flows. The EU may be a "diesel island" (Hooftman et al., 2018), but other relevant producers significantly contributed to the European dieselization process.

It has been argued that EU dieselization has conditioned the competitiveness of the European car industry (Hooftman et al., 2018; Cames and Helmers, 2013). However, Fig. 4 and Table 1 already showed that petrol cars are by far the main EU car exports to the Rest of the World, a likely outcome in view of the minor role that diesel cars play in other countries. This issue can be illustrated in a more conclusive way by looking at the EU trade balance in cars with the Rest of the World (see Fig. 6). The EU as a whole has a substantial trade surplus in passenger cars, and Fig. 6 reveals that the surplus is generated almost entirely by petrol cars.

EU cars can also be analysed by size. The HS and CN product classifications distinguish between three size categories of diesel cars, depending on engine size measured as cylinder capacity. Small diesel cars would be those with a cylinder capacity not exceeding 1500 cm3; medium diesel cars, those with a cylinder capacity between 1500 and 2500 cm3; and large diesel cars, those with a cylinder capacity exceeding 2500 cm3. In the case of petrol cars, product classifications distinguish between four size categories, including a category for very small cars. For ease of comparison, however, the same three size categories are also used for petrol cars: small (cylinder capacity not exceeding 1500 cm3); medium (cylinder capacity between 1500 and 3000 cm3): and large (cylinder capacity exceeding 3000 cm3).[6]

Figs. 7 and 8 show the respective size distribution of EU car trade with the Rest of the World for imports and exports. The size distribution of imported petrol cars is markedly different, with small cars playing a major role. The size distributions of the other trade flows are quite

[6] A narrower segmentation based on other criteria (such as engine power) would allow a more nuanced analysis, but size categories of the HS and CN product classifications rely exclusively on engine displacement (see Appendix A). It is worth noting that the European Environmental Agency also uses a size classification based on engine displacement for reporting trends in new passenger car registrations (see, for instance, EEA, 2018).

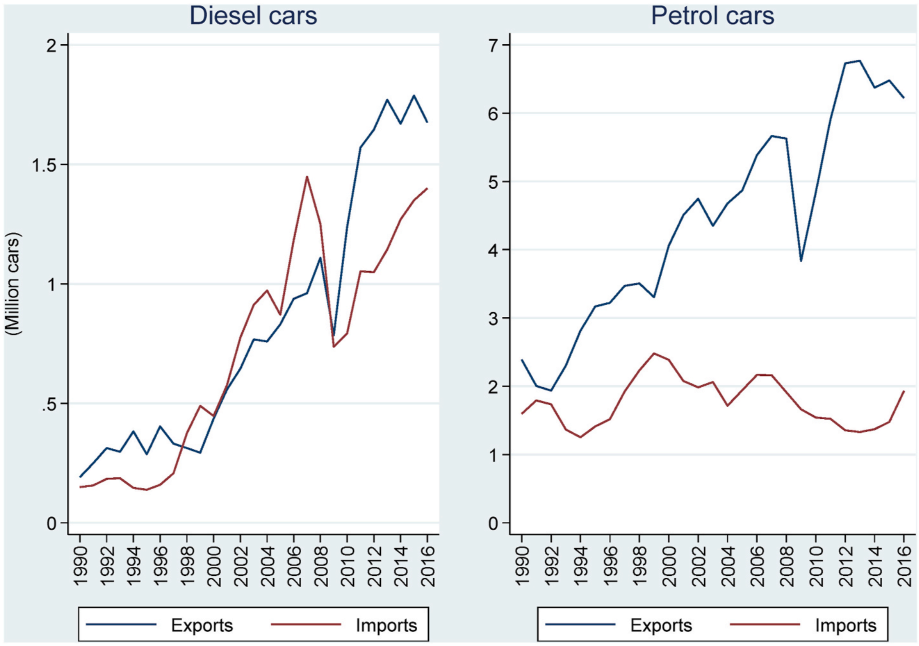

Fig. 4. EU car trade flows with the Rest of the World (million cars). Source: Comext.

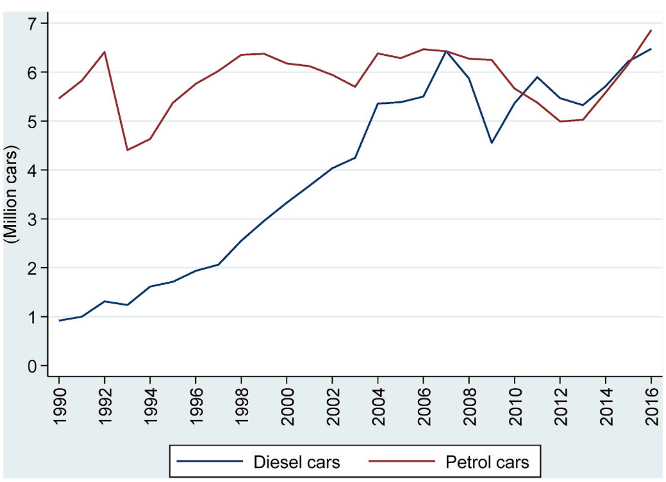

Fig. 5. Intra-EU trade (export flows). Source: Comext.

similar, with a clear predominance of medium-sized cars, although large cars are more significant in diesel imports. Analysing European car production data for the period 1995–2005, Cuenot (2009) suggested that the European car industry would be exporting large, high CO2 emitting vehicles. The size distributions of EU exports in Fig. 8, which is based on cylinder capacity, do not allow a clear conclusion in this regard. The large category in exported petrol cars shows an increase between 1993 and 2006, though not very intense, and the share of large diesel cars actually showed a certain reduction between 1997 and 2005, playing a somewhat more prominent role after 2007. Furthermore, comparison of Figs. 7 and 8 reveals that, in relative terms, EU imports of large diesel cars have been more significant than exports of large diesel cars to Rest-of-World countries. At the end of the period the relative importance of large diesel cars is more similar in both trade flows.

Looking at the average size of cars in trade flows, measured as tons of curb weight, may complete the picture. Fig. 9 plots the weighted avera ge size of EU imported and exported cars, using trade values as weights. Fig. 9 resembles the increase in car size analysed in a number of papers (e.g. Schipper et al., 2002; Ajanovic et al., 2012; and Schipper and

Table 1
The EU's main partners in trade of cars, 1990–2016 (number of cars). Source: Comext.

EU Exports (1990–2016)			
Diesel cars		Petrol cars	
Turkey	2,735,729	USA	34,924,586
Switzerland	1,585,594	Japan	9,160,459
Norway	1,497,121	China	7,405,146
Korea	1,242,610	Russian Fed.	6,744,648
Russian Fed.	1,104,318	Switzerland	5,181,069
Australia	915,408	Australia	3,556,638
USA	906,982	Turkey	3,247,044
Algeria	885,622	Canada	3,097,090
Morocco	703,063	Iran	2,445,460
Belarus	593,907	South Africa	2,207,411
South Africa	586,521	Poland	1,869,900
Serbia	536,416	Norway	1,824,814
Poland	499,359	Taiwan	1,777,195
Croatia	466,831	Israel	1,645,922
Romania	390,601	Brazil	1,641,934
OTHER	7,557,779	OTHER	32,438,666
TOTAL	22,207,861	TOTAL	119,167,982
EU Imports (1990–2016)			
Diesel cars		**Petrol cars**	
Japan	6,333,350	Japan	18,082,099
USA	3,930,393	Korea	7,272,996
Korea	3,006,836	USA	3,894,115
Turkey	2,476,484	Turkey	2,684,401
Mexico	840,982	Poland	2,091,023
Czech Rep.	479,730	China	2,020,301
Morocco	331,473	India	1,929,555
Slovakia	329,588	Czech Rep.	1,244,004
South Africa	328,688	Mexico	1,045,019
Serbia	260,001	Brazil	820,663
Brazil	195,418	Slovenia	807,060
Slovenia	163,556	South Africa	781,553
India	139,095	Slovakia	617,775
Thailand	137,112	Taiwan	601,439
Switzerland	105,045	Hungary	585,514
OTHER	364,660	OTHER	3,444,917
TOTAL	19,422,411	TOTAL	47,922,434

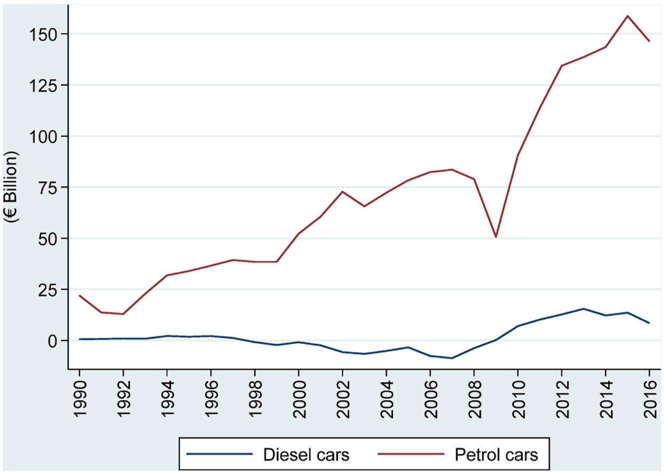

Fig. 6. EU trade balance in cars with the Rest of the World. Source: Comext.

Fulton, 2013). Both diesel and petrol cars for import and export flows show a clear increase in average size, being somewhat more moderate in the case of EU imported petrol cars, while always showing a significant smaller average size in the latter case. Interestingly, exported and imported diesel cars and exported petrol cars show a very similar trend.

The previous figures and table refer to EU trade flows in passenger cars, including both new (the vast majority) and used cars. It is interesting to look at used cars solely, an issue seldom studied in the literature. The main exporters of used cars are Germany, the US and Japan (Fuse et al., 2009), with used imported cars representing a significant share of new registrations in African and Eastern European countries (IEA, 2009). Fig. 10 shows EU exports of used diesel and petrol cars to the Rest of the World. The trend is more cyclical, especially in the case of petrol cars. Around three-quarters of EU exported used cars are petrol powered. The size distribution of EU exported used cars (Fig. 11) is not very different from the general picture (see Fig. 8, which includes both new and used cars, with new cars predominating). However, the role of the large category in used car exports is less predominant, especially in the case of petrol cars. Table 2 shows that the main destinations for EU used diesel cars are Eastern European countries, whereas used petrol cars are exported mainly to both African and Eastern European countries. Therefore, the trade data suggest that EU exports of used cars to emerging and less developed countries has not been noteworthy in terms of large, fuel-intensive cars.

Finally, heading 8703 of the HS and CN classifications includes a residual category for cars with alternative powertrains. Fig. 12 reveals that, in the study period covered in this paper, the role played by cars with engines other than internal combustion engines is very marginal. The share of cars of this type only exceeds 1 percent of the total value of EU imported cars in 2015, this share being somewhat lower for exports.

3. Methodology

I analyse the effects of EU dieselization using a gravity equation, the benchmark empirical model of international trade, extensively reviewed in Head and Mayer (2014), Yotov et al. (2016) and Baier et al. (2018). The starting point is the following specification:

$$X_{ijkt} = \exp[\alpha + \beta'\mathbf{Z_{ijkt}} + \varphi DEU1998_{ijkt}] + u_{ijkt} \quad (1)$$

where i indexes the exporter; j, the importer; k, the product (category of passenger car); and t denotes time. X_{ijkt} is the value of exports from country i to country j of category k cars in year t, α is a constant term, $\mathbf{Z_{ijkt}}$ is a vector of gravity controls, $DEU1998_{ijkt}$ is the dummy of interest, discussed below, and u_{ijkt} is an error term. In principle, the vector of gravity controls, $\mathbf{Z_{ijkt}}$, can include regressors that vary in the i-t or j-t dimensions such as country GDPs, time-invariant bilateral determinants of trade flows such as the distance between countries, time-varying bilateral determinants of trade flows such as membership of the EU, membership of the GATT/WTO, the engagement of both countries in customs unions, preferential trade agreements, etc., and regressors that vary in the i-j-k-t dimensions such as tariffs.

Several best practices are commonly found in the literature. First,

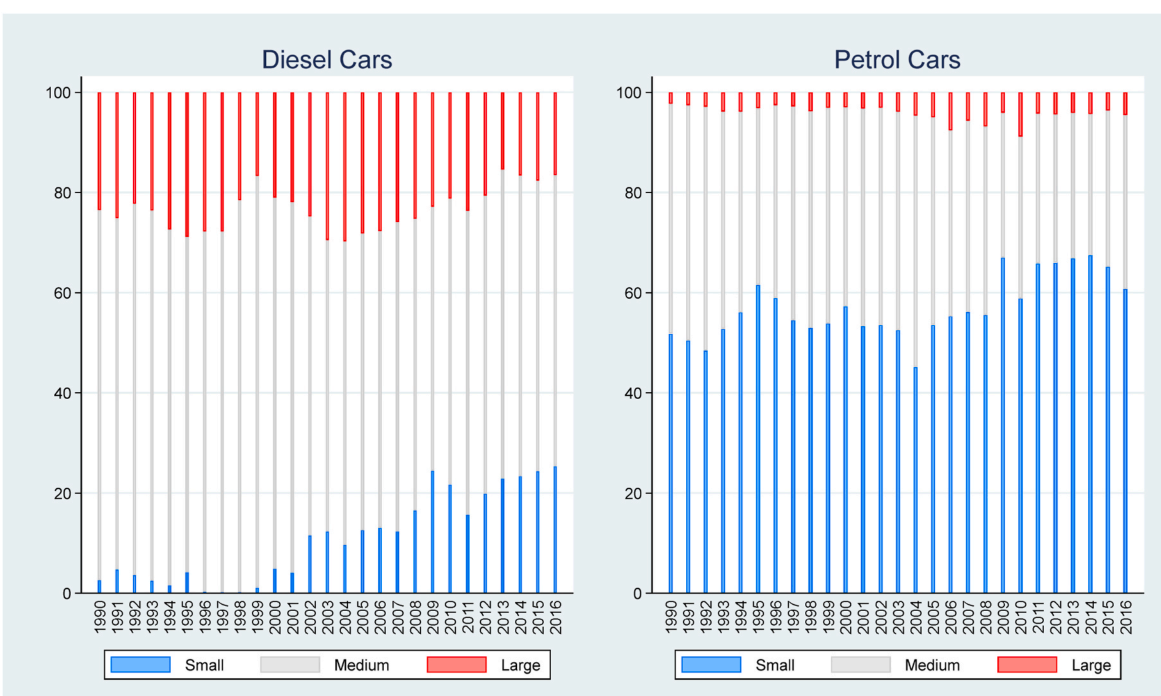

Fig. 7. Size distribution of EU car imports from the Rest of the World. Notes. The width of the columns is proportional to the share in total volume of trade. Source: Comext.

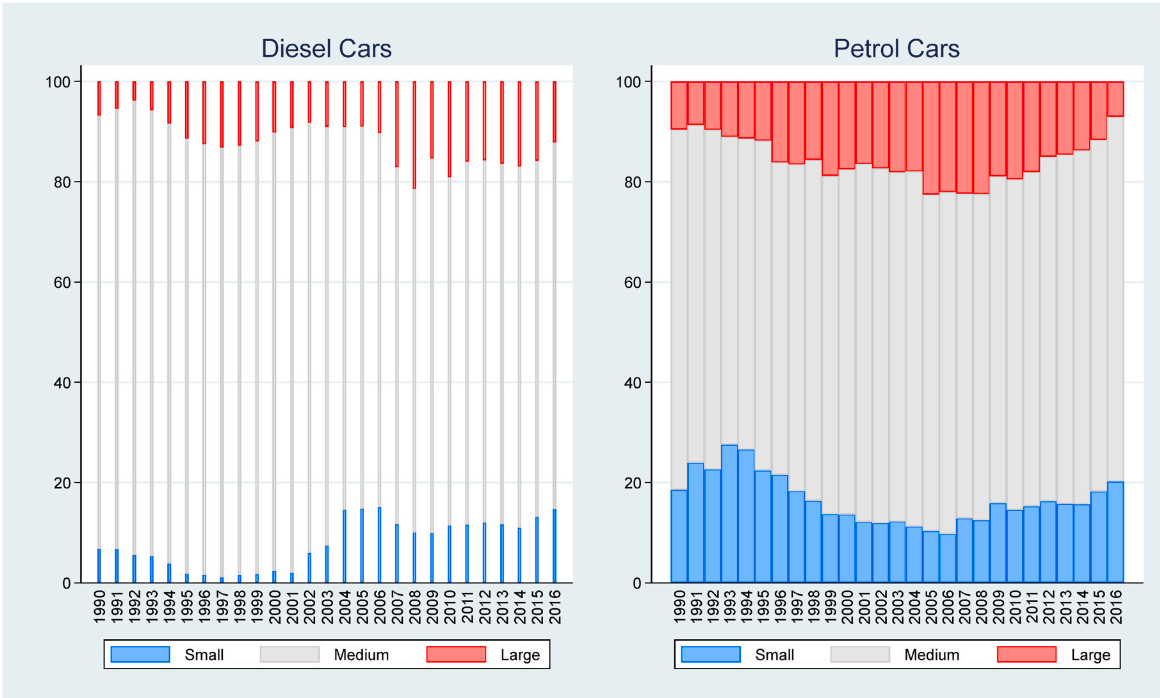

Fig. 8. Size distribution of EU car exports to the Rest of the World. Notes. The width of the columns is proportional to the share in total volume of trade. Source: Comext.

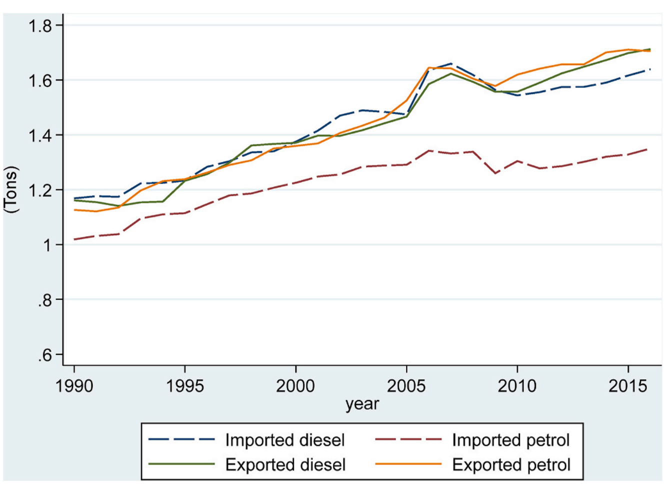

Fig. 9. Average size of EU traded cars with the Rest of the World. Notes. This figure plots the average curb weight for EU imported and exported diesel and petrol cars, measured in tons and computed as the weighted average using trade value weights. Source: Comext.

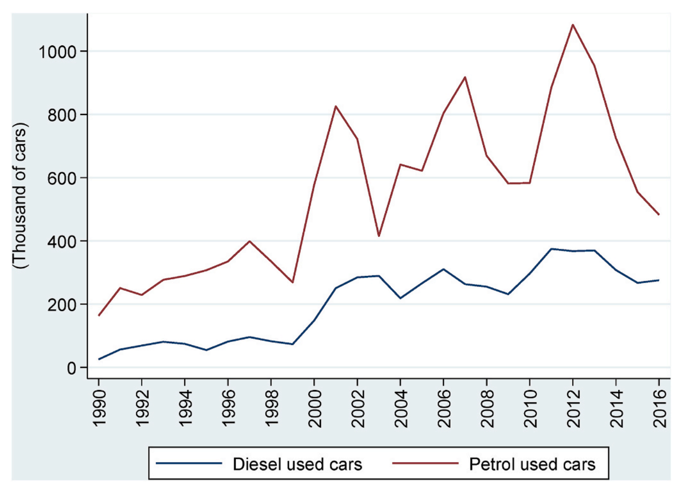

Fig. 10. EU used car exports to the Rest of the World (thousands of cars). Source: Comext.

following Santos Silva and Tenreyro (2006), the regressors enter (1) exponentially to estimate the gravity model using the Poisson Pseudo Maximum Likelihood (PPML) estimator. The PPML estimator accounts for heteroscedasticity in trade data and is able to deal with the information incorporated in zero trade flows. Second, the inward and outward multilateral resistance terms (Anderson and Van Wincoop, 2003) that should be included in the gravity equation can be proxied by exporter-time and importer-time fixed effects (Olivero and Yotov, 2012). The cost of including these fixed effects is that they absorb any regressor that varies in the country-time dimensions, such as country GDPs. Finally, the inclusion of country-pair fixed effects is advisable to control for the endogeneity of trade policy regressors (Baier and Bergstrand, 2007). Since the tariff regressor and the dummies of interest will vary in the k dimension (category of passenger cars), country-pair-product fixed effects will be included. The drawback of including these fixed effects is that the time-invariant bilateral determinants of trade flows are absorbed by the country-pair fixed effects and thus cannot be identified.

Thus, the final specification is as follows:

$$X_{ijkt} = \exp[\alpha + \beta_1 EU\_both_{ijt} + \beta_2 WTO\text{-}GATT_{ijt} + \beta_3 CU_{ijt} + \beta_4 EIA_{ijt} + \beta_5 FTA_{ijt} + + \beta_6 PTA_{ijt} + \beta_7 \ln(1+tariff_{ijkt}) + \varphi DEU1998_{ijkt} + \Omega_{it} + \Psi_{jt} + \Pi_{ijk}] + u_{ijkt} \quad (2)$$

where, beginning with the gravity controls, EU_both_{ijt} is a dummy variable that takes the value of 1 if both i and j are EU countries in year t and 0 otherwise; $WTO\text{-}GATT_{ijt}$ takes the value of 1 if both countries i and j are members of the GATT/WTO in year t and 0 otherwise; CU_{ijt} takes the value of 1 if both i and j are engaged in a customs union in year t and

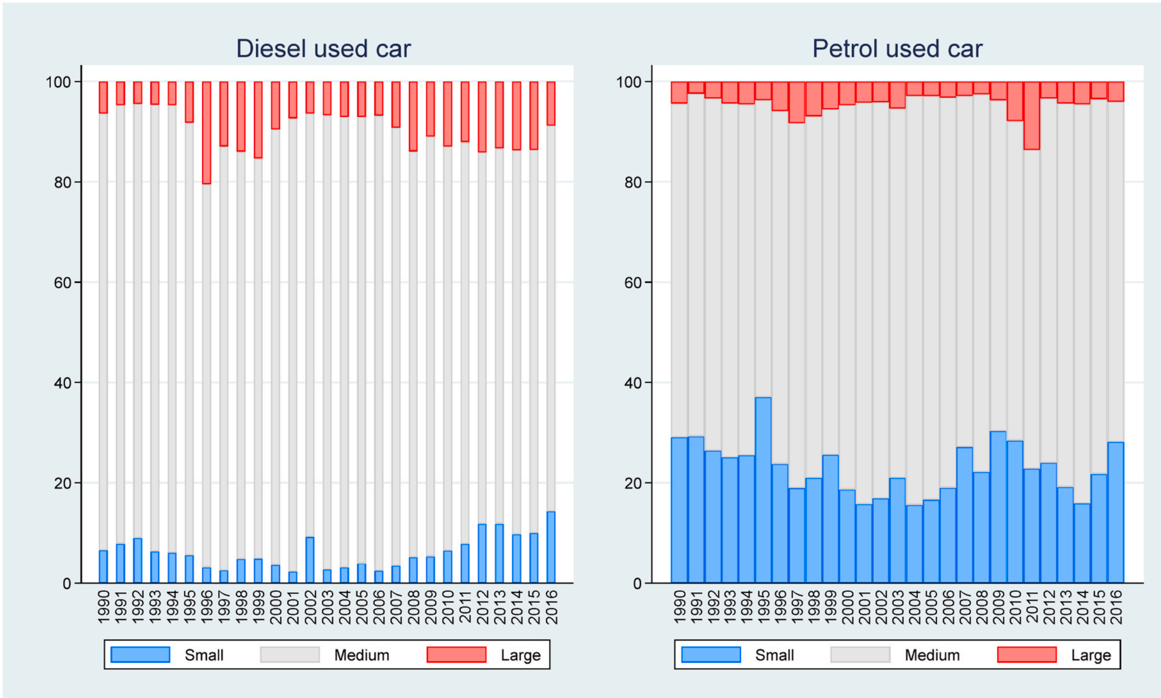

Fig. 11. Size distribution of EU used car exports to the Rest of the World. Notes. The width of the columns is proportional to the share in total volume of used car exports. Source: Comext.

Table 2
Main destinations for EU used car exports, 1990–2016 (number of cars). Source: Comext.

EU Exports (1990–2016)			
Used diesel cars		Used petrol cars	
Belarus	559,794	Benin	1,618,473
Serbia	430,970	Nigeria	1,028,275
Bosnia-Herzegovina	328,118	Russian Fed.	930,797
Russian Fed.	309,251	Kazakstan	867,854
Poland	281,156	Belarus	519,230
Norway	263,044	Poland	495,395
Algeria	259,266	Libya	449,673
Romania	230,665	Niger	407,143
Croatia	174,034	Ghana	362,786
Senegal	131,973	Cameroon	329,058
Switzerland	130,285	Georgia	323,156
Czech Republic	125,954	Togo	316,572
Ukraine	119,605	Tajikistan	311,011
Bulgaria	110,224	Guinea	305,281
Albania	104,614	Lebanon	302,896
OTHER	1,914,881	OTHER	6,327,909
TOTAL	5,473,834	TOTAL	14,895,509

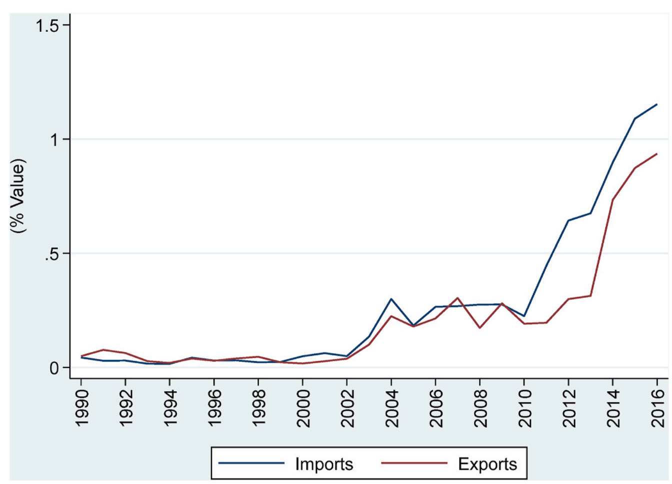

Fig. 12. Share of cars with alternative powertrains (percentage of total value).

0 otherwise; EIA_{ijt} takes the value of 1 if both i and j are engaged in an economic integration agreement in year t and 0 otherwise; FTA_{ijt} takes the value of 1 if both i and j are engaged in a free trade agreement in year t and 0 otherwise; PTA_{ijt} takes the value of 1 if both i and j are engaged in a preferential trade agreement in year t and 0 otherwise; $tariff_{ijkt}$ is the ad valorem tariff; and $DEU1998_{ijkt}$ is the dummy of interest. Finally, Ω_{it}, Ψ_{jt} and Π_{ijk} are fixed effects and u_{ijkt} is the error term.

In gravity equation (2), X_{ijkt} represents international trade in cars between any two countries in the world. The variable of interest, $DEU1998_{ijkt}$, aims to control for the effect of dieselization in EU countries' car trade flows, i.e. how it is reflected in EU countries' car imports and exports. To this end, $DEU1998_{ijkt}$ takes the value of 1 if several conditions are met (0 otherwise). First, the trade flow comprises diesel cars. Second, following the literature (Fontaras and Samaras, 2007; Cames and Helmers, 2013), 1998 is used as the reference year for analysing the effects of dieselization. And third, at least one EU country has to be involved in the trade flow as importer or exporter, including the cases where both the importer and exporter are EU countries. Precisely for this last condition, there are different ways of defining this dummy depending on the type of trade flow to be controlled for, including its decomposition into more specific, complementary dummies. These alternative definitions of $DEU1998_{ijkt}$, with slightly different names to differentiate between them, are explained in turn. The first option has the more general definition. $DEU1998(any)_{ijkt}$ is a dummy variable that takes a value of 1 if an EU country is involved in diesel car trade as an exporter or importer in a trade flow with any other country (i.e. EU or non-EU) in year 1998 and afterwards, and 0 otherwise. This dummy can be split into two complementary dummies, $DEU1998(intra)_{ijkt}$ and $DEU1998(extra)_{ijkt}$, to be included simultaneously. $DEU1998(intra)_{ijkt}$ takes a value of 1 if k is a diesel car and both the exporter, i, and the importer, *j*, are EU countries in year 1998 and afterwards and 0 otherwise; whereas $DEU1998(extra)_{ijkt}$ takes the value of 1 when either the exporter or the importer is a non-EU country and 0 otherwise, thus controlling for diesel car trade flows between EU and non-EU countries. Finally, the latter dummy can be further split depending on the type of flow. $DEU1998(extra\text{-}exporter)_{ijkt}$ takes the value of 1 for the trade flows in diesel cars in 1998 and afterwards when *i* is a EU country and *j* is a non-EU country and 0 otherwise. Similarly, $DEU1998(extra\text{-}importer)_{ijkt}$ takes the value of 1 when a EU country is the importer and a non-EU country is the exporter, and 0 otherwise. These two more specific dummies have to be included with $DEU1998(intra)_{ijkt}$ in the same gravity regression.

The data sources for gravity estimations are as follows. Nominal bilateral trade flows were obtained from COMTRADE (see Section 2 and Appendix A). COMTRADE data are available in the HS classification since 1988, and the sample period (1988–2008) is fixed with a twenty-one-year window around 1998, the reference year for EU dieselization. The product dimension, *k*, comprises 8 categories of cars (6-digit HS codes), including four categories of petrol car, three categories of diesel car and a residual category for "other cars" (electric, hybrid, etc.) (see Appendix A for further details.). The tariff data were obtained from UNCTAD's TRAINS database.[7] The gravity indicator variables were obtained from the Dynamic Gravity dataset (see Gurevich and Herman, 2018). The sample comprises 100 exporters and 165 importers. Countries with rather sporadic data or without available data prior to 1998 are excluded. Table B1 in Appendix B lists the countries in the sample, while Table B2 shows the descriptive statistics for the variables used in the estimations.

4. Results

Table 3 provides the empirical results of estimating Equation (2) with the different alternatives for the dummy of interest. The estimated coefficients for the gravity controls are very similar across estimations. Some of these estimates are rather imprecise. The estimates on customs union and free trade areas are negative, but not statistically significant, except in one case in which they are only marginally significant. These results can be related to the overlapping nature of the gravity indicator variables included in the regressions. The coefficient estimates for the tariff regressor are negative, but also not statistically significant. The estimates on all the dummies of interest, proxying the effects of dieselization on EU trade, are highly statistically significant and have the expected positive sign. The estimate on $DEU1998(any)_{ijkt}$ shown in column (1) is 1.141; this result would indicate that, comparing the period 1998–2008 with the period 1998–1997, EU trade in diesel cars with any country grew 213% ($e^{1.141} = 3.129$). Furthermore, the results shown in column (2) indicate that the effect of $DEU1998(intra)_{ijkt}$ is slightly larger than that of $DEU1998(extra)_{ijkt}$. Thus, dieselization would have a somewhat greater effect on intra-EU trade flows. However, this conclusion is qualified when $DEU1998(extra)_{ijkt}$ is split into $DEU1998(extra\text{-}importer)_{ijkt}$ and $DEU1998(extra\text{-}exporter)_{ijkt}$. The results in column (3) of Table 3 show that the largest effect of dieselization would be on EU imports of diesel cars from third countries, which show a growth of 254% ($e^{1.264} = 3.539$), clearly a larger effect than that for EU exports to the Rest of the World, which show a growth of 93%. The results obtained from Table 3 are essentially in line with the general conclusions of Section 2.2. EU trade flows corroborate that dieselization has been mostly a European phenomenon, but that it has also been fed more by imports from third countries than by exports of diesel cars to the Rest of the World.

The dummies of interest included in the regressions in Table 3 do not distinguish by size of diesel cars. Table 4 investigates whether the conclusions vary when the dummies are defined by diesel car size, using the same size categories as in Section 2.2. For the sake of brevity, only the regressions in columns (1) and (3) of Table 3 are re-run. Thus, there are six regressions results in Table 4, where the dummies of interest maintain the same underlying logic as before, but are defined for each size category. For instance, in the small diesel cars regression in column (1) of Table 4, $DEU1998(any)_{ijkt}$ takes the value of 1 if an EU country is involved in small diesel car trade flow with any other country. In the regression in column (2), $DEU1998(intra)_{ijkt}$, $DEU1998(extra\text{-}importer)_{ijkt}$ and $DEU1998(extra\text{-}exporter)_{ijkt}$ are also defined for small diesel cars. Columns (3)–(4) and (5)–(6) repeat the regressions with the dummies defined for medium and large diesel cars, respectively. Comparing these results with the benchmark results in Table 3, dieselization would have more noticeable effects in terms of small and large diesel cars, especially in intra-EU trade flows. The estimate on $DEU1998(intra)_{ijkt}$ for small diesel cars is the largest, 2.230. This means that there was an 830%

Table 3
Main regression results.

	(1)	(2)	(3)
EUijt	0.476* (0.254)	0.425 (0.281)	0.368 (0.235)
WTO-GATTijt	0.290 (0.281)	0.298 (0.280)	0.316 (0.295)
CUijt	−0.171 (0.290)	−0.162 (0.291)	−0.156 (0.298)
EIAijt	0.232** (0.113)	0.242** (0.116)	0.255** (0.112)
FTAijt	−0.295 (0.183)	−0.300 (0.185)	−0.309* (0.184)
PTAijt	0.524*** (0.174)	0.523*** (0.176)	0.519*** (0.180)
ln(1+tariffijkt)	−0.616 (0.434)	−0.622 (0.436)	−0.634 (0.437)
DEU1998(any)ijkt	1.141*** (0.136)		
DEU1998(intra)ijkt		1.164*** (0.173)	1.157*** (0.170)
DEU1998(extra)ijkt		1.049*** (0.0894)	
DEU1998(extra-importer)ijkt			1.264*** (0.124)
DEU1998(extra-exporter)ijkt			0.659*** (0.155)
Observations	344,618	344,618	344,618
Pseudo R2	0.968	0.968	0.968

Notes. The dependent variable is X_{ijkt}, the value of exports from country *i* to country *j* of category *k* cars in year *t*. All regressions include exporter-time, importer-time and exporter-importer-product fixed effects. Three-way (exporter, importer and product) clustered standard errors are shown in parentheses below the coefficient estimates. *, ** and *** denote significance at the 10, 5 and 1 per cent level, respectively.

[7] See https://trains.unctad.org/[Accessed 30 September 2021].

Table 4
Additional regression results.

	(1)	(2)	(3)	(4)	(5)	(6)
	SMALL	SMALL	MEDIUM	MEDIUM	LARGE	LARGE
EUijt	0.406* (0.219)	0.311 (0.230)	0.307 (0.249)	0.311 (0.263)	0.260 (0.265)	0.215 (0.261)
WTO-GATTijt	0.327 (0.311)	0.332 (0.314)	0.285 (0.282)	0.288 (0.286)	0.327 (0.317)	0.337 (0.320)
CUijt	−0.227 (0.271)	−0.158 (0.288)	−0.0508 (0.303)	−0.0351 (0.310)	−0.0736 (0.311)	−0.0747 (0.311)
EIAijt	0.286*** (0.0979)	0.296*** (0.0961)	0.259*** (0.0962)	0.255** (0.102)	0.301*** (0.103)	0.306*** (0.101)
FTAijt	−0.327* (0.191)	−0.327* (0.196)	−0.309 (0.189)	−0.305 (0.190)	−0.324* (0.194)	−0.329* (0.196)
PTAijt	0.534*** (0.179)	0.527*** (0.187)	0.514*** (0.183)	0.508*** (0.182)	0.517** (0.201)	0.516*** (0.200)
ln(1+tariffijkt)	−0.697 (0.463)	−0.699 (0.466)	−0.637 (0.451)	−0.634 (0.441)	−0.701 (0.469)	−0.700 (0.470)
DEU1998(any)ijkt	2.021*** (0.202)		0.813*** (0.191)		1.210*** (0.295)	
DEU1998(intra)ijkt		2.230*** (0.235)		0.775*** (0.214)		1.581*** (0.286)
DEU1998(extra-importer)ijkt		0.960*** (0.336)		1.228*** (0.181)		0.785** (0.320)
DEU1998(extra-exporter)ijkt		1.313*** (0.187)		0.609*** (0.110)		0.564*** (0.173)
Observations	344,618	344,618	344,618	344,618	344,618	344,618
Pseudo R2	0.966	0.966	0.966	0.967	0.966	0.966

Notes. The dependent variable is X_{ijkt}, the value of exports from country *i* to country *j* of category *k* cars in year *t*. All regressions include exporter-time, importer-time and exporter-importer-product fixed effects. Three-way (exporter, importer and product) clustered standard errors are shown in parentheses below the coefficient estimates. *, ** and *** denote significance at the 10, 5 and 1 per cent level, respectively.

($e^{2.230} = 9.299$) increase in traded small diesel cars in the period 1998–2008 compared to the period 1988–1997. It should be borne in mind that trade in small diesel cars was fairly marginal in the period 1988–1997. For large cars, the estimate on $DEU1998(intra)_{ijkt}$ is 1.581, representing an increase of 386%. The most relevant size category, medium diesel cars, showed a more modest increase in intra-EU trade flows, 117%, mainly due to the fact that this category of diesel car already played a significant role in the trade flows of the former period. In extra-EU trade, the effect of $DEU1998(extra\text{-}importer)_{ijkt}$ predominates over the effect of $DEU1998(extra\text{-}exporter)_{ijkt}$ for medium and large diesel cars, a result in line with the descriptive analysis in Section 2.2, whereas the latter predominates for small diesel cars. The smallest effect of dieselization would be on exports of large diesel cars from EU countries to third countries.

5. Conclusions and policy implications

The European dieselization phenomenon commenced in the mid-to late 1990s with the steady increase in the diesel share in new passenger car registrations. It is usually associated with the voluntary agreements signed by the European Commission and the automobile industry within the context of the first EU strategy to reduce CO2 emissions from passenger cars. In exchange for technological efforts made to reduce CO2 emissions from new car registrations that in the end did not help in lowering total emissions, the industry obtained lenient CO2 targets and emissions standards and preferential tax treatment for diesel cars. It can be said that diesel fuel efficiency was a key element of this strategy, and technological efforts by manufacturers further improved CO2 and tailpipe emissions from diesel (and petrol) cars. However, the literature is unanimous in concluding that the reduction in emissions has been insufficient, largely due to the rebound effects incentivized by the drivers of the dieselization phenomenon (e.g. through preferential fuel taxation). Besides, when it became clear that the dieselization strategy to reduce emissions had run its course, the conclusive evidence regarding the divergence between emissions during certification and in real-world use, together with the Dieselgate scandal, led to the beginning of the end of the European diesel car boom.

Focussing on EU international trade in passenger cars, I have attempted to contribute to the literature on dieselization by analysing EU countries' export and import car flows with other EU and non-EU countries. The more relevant insights from the descriptive analysis and the gravity estimation results are as follows. First, the EU dieselization process can be tracked by looking at the trade flows in petrol and diesel cars. Second, trade data confirm that dieselization is an intra-EU phenomenon; i.e. the bulk of EU diesel imports and exports occur between EU partners. However, diesel imports from other countries such as Japan and Korea are also worth mentioning. Gravity estimation results show that EU dieselization had a clear effect on import flows from non-EU countries. Third, the external competitiveness of the EU car industry is, by far, based on petrol car exports. EU dieselization has also been exported, but to a limited extent. Fourth, the size distribution of EU imports evidences the importance of large diesel cars and small petrol cars. The size distribution of diesel and petrol car exports is more similar, with a somewhat clearer predominance of medium-sized cars. Gravity estimation results also show that the smallest effect of dieselization is on large diesel car exports to third countries. Fifth, the analysis of the average size of EU traded cars reflects previous findings in the literature regarding the steady increase in car size. The increase in average exported diesel, imported diesel and exported petrol cars is quite similar, whereas the evolution of the average size of EU imported petrol cars shows a more moderate increase and a smaller average size. Finally, Comext trade data allow the analysis of EU trade flows in used cars. EU exports in used cars are seen to play a somewhat minor role for large cars. Petrol cars are also predominant, being mainly exported to African and Eastern European countries, whereas Eastern European countries are the main destinations of EU exports of used diesel cars.

Trade data also show that EU dieselization did not have a widespread effect through exports, although the phenomenon was also fed by imports from countries such as Japan, a country where diesel cars play a minor role. These facts point to the lack of cooperation and coordination in environmental policies for passenger cars between countries, as well as the isolation of the EU strategy underlined in part of the literature (Hooftman et al., 2018). More international coordination and harmonization of emissions regulations would be desirable, especially between the EU and the US due to their role as leaders in environmental regulations (Rodriguez and Posada, 2019). In fact, the discarded Transatlantic Trade and Investment Partnership (TTIP) may have been an opportunity to achieve common ground in environmental regulation (Holzer and Cottier, 2015; Pelkmans et al., 2015).

The analysis of EU trade in cars carried out in this paper also contributes to the interpretation of past decisions and their consequences, and may have implications for policy. Besides technological improvements, the fact that the EU's initial strategy concerning CO2 emissions also considered their reduction "by changes in the market, and in particular by a shift towards smaller and fuel-efficient cars ('downsizing')" (EC, 1998, p. 3; emphasis in the original) is usually overlooked. However, these market changes were loosely committed to fiscal measures and fuel-economy labelling. The increase in average size car, underlined in the literature and also corroborated by EU trade flows, clearly shows that this lax intention was rapidly surpassed by the facts.

To prevent the countervailing effect of car upsizing and other rebound effects, an appropriate combination of standards, fuel and registrations taxes and subsidies for the adoption of clean technologies also appears to be necessary (Ajanovic et al., 2012; Ajanovic and Haas, 2012; Santos, 2017; Yang et al., 2018). However, the evident failure to downsize car buying intentions suggests that other stricter measures, such as the regulation of sales and use of large cars, could be necessary (Anable and Goodwin, 2019). In general, environmental policies for passenger cars should not only strive for efficiency improvements, demand management policies to confront car dependence are also required (Sorrell, 2015; Creutzig et al., 2018; Mattioli et al., 2020; Lamb et al., 2021). Urgent reductions in global warming emissions will not be met without lowering the demand for passenger mobility.

The EU has adopted the 2050 climate neutrality objective with the European Green Deal, enshrined in legislation with the European Climate Law. In the new EU strategy for road transport, demand management policies will have much more importance, with a specific strategy for accelerating the shift to sustainable and smart mobility (EC, 2020b). However, the regulation on CO2 emissions standards for new passenger cars (and light commercial vehicles) is still considered the cornerstone for reducing total CO2 emissions from this sector. A new strengthened CO2 emission standard for 2030 (a 55% reduction of the target in 2021) has been proposed by the European Commission (EC, 2021). The objective is to accelerate the deployment of zero-emission vehicles. A key element in this strategy is the role to be played by low-emission vehicles such as PHEVs. On the one side, plug-in hybrids are necessary in the transition to climate neutrality, especially when the deployment of charging infrastructure is still limited. On the other side, the dieselization experience warns us of the major inertia inherent in shaping incentives, and a clear-cut schedule would be desirable. In a prospective scenario analysis for the UK, Brand et al. (2020) show that, in addition to lowering the demand for mobility, an early phasing out of conventional fuel vehicles including PHEVs is needed to achieve large reductions in carbon emissions. The European Commission's proposal points in this direction, including a de facto ban on any type of internal combustion engines by introducing a zero-emissions requirement by 2035. This proposal will mean the definitive phasing out of conventional diesel and petrol cars, 'mild' hybrids and gas propelled cars, as well as PHEVs.

Finally, although the dieselization phenomenon profoundly marked the evolution of the EU car industry, its substantial trade surplus with third countries is completely based on petrol cars. This fact is overlooked when it is stated that dieselization put the EU automotive industry's competitiveness at stake. Although the developments of the industry have obviously focussed on conventional powertrains, it should not be poorly positioned for the global electric vehicle race due to its long-standing experience in manufacturing, its large internal market and diversified portfolio of R&D projects and patents (Fredriksson et al., 2018). With the new strategy for road transport, the EU also seeks to foster leadership by the automotive industry in zero-emission technologies (EC, 2021). By developing a leading market for clean vehicles, EU climate policy can be green industrial policy, generating a positive expansion of global supply of zero-emission technologies (Rodrik, 2014). Furthermore, this potential leadership would help manufacturers to fully adapt to the coming sustainable mobility scenario with zero-emission vehicles, more public transport and green mobility, as well as lower demand for travel and a decreased role for the private car. The threat of catastrophic climate change urges the automotive industry to get on board once and for all for clean and sustainable mobility.

Author statement

Ignacio del Rosal: Conceptualization, Methodology, Writing – original draft preparation, Visualization, Investigation, Formal analysis, Validation, Writing- Reviewing and Editing.

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Declaration of competing interest

None.

APPENDIX

Appendix A. Data Sources

Two trade data sources have been used in this paper:

- United Nations' Commodity Trade Statistics Database (COMTRADE) (https://comtrade.un.org/), available online via the World Integrated Trade Solution (WITS) website, maintained by the World Bank (https://wits.worldbank.org/default.aspx?lang=en).
- Eurostat's Comext database (see Eurostat, 2020, and https://ec.europa.eu/eurostat/web/international-trade-in-goods/data/focus-on-comext), available for bulk download at https://ec.europa.eu/eurostat/data/bulkdownload.

COMTRADE is the trade database used for the gravity equation estimation, given the fact it contains world-wide coverage. Trade data are provided according to the international 6-digit Harmonized System (HS) product classification. The HS is updated every 5-years, but heading 8703 (comprising passenger cars) did not change during the period analysed in this paper. COMTRADE data provided in the HS classification is available since 1988, so the 1988 HS version is used to download the data for the entire study period. Heading 8703 comprises nine 6-digit categories of passenger cars, but code 870,310 (comprising snow vehicles, golf cars and similar vehicles) has been discarded. The remaining eight codes comprise petrol and diesel cars classified according to cylinder capacity, and a code for other vehicles (electric, hybrid, etc.). Table A1 shows the eight 6-digit HS codes comprising passenger cars considered in the analysis.

Table A1

HS categories of passenger cars included in the gravity equation estimation. Source: WITS (https://wits.worldbank.org/default.aspx?lang=en)

6-digit HS code	Description
870,321	Petrol cars with a cylinder capacity not exceeding 1000 cc
870,322	Petrol cars with a cylinder capacity exceeding 1000 cc but not exceeding 1500 cc

(*continued on next page*)

Table A1 (*continued*)

6-digit HS code	Description
870,323	Petrol cars with a cylinder capacity exceeding 1500 cc but not exceeding 3000 cc
870,324	Petrol cars with a cylinder capacity exceeding 3000 cc
870,331	Diesel cars with a cylinder capacity not exceeding 1500 cc
870,332	Diesel cars with a cylinder capacity exceeding 1500 cc but not exceeding 2500 cc
870,333	Diesel cars with a cylinder capacity exceeding 2500 cc
870,390	Other

The descriptive analysis in Section 2.2 relies mainly on Comext data. Comext data are reported according to the 8-digit Combined Nomenclature (CN), a EU product classification based on the HS. Thus, the CN classification adds two more digits to the 6-digit HS codes shown in Table A1, distinguishing between new and used cars and including specific codes for petrol and diesel motor caravans. Generally speaking, the 8-digit CN classification changes constantly, but the codes under heading 8703 are quite stable over the study period. Two easily-trackable, simple code changes that occurred in 1996–1997 and 1999–2000 are noted.

Details about the HS and CN product classifications can be found in the Eurostat's metadata server RAMON (https://ec.europa.eu/eurostat/ramon/index.cfm?TargetUrl=DSP_PUB_WELC).

Both COMTRADE and Comext trade data come from customs records and are expressed in value and volume (units and weight). COMTRADE bilateral trade flows in current dollars are used for the gravity equation estimation. Specifically, export flows in free-on-board (FOB) value are taken as the reference. For the descriptive analysis in Section 2.2, Comext trade data measured in current euros, units of cars and weight in metric tons are used. The fact that the trade data come from customs records means that value figures are always more reliable, while units and weight figures are noisier due to mis-recording or measurement errors. Thus, Comext data measured in units and weight have to be screened in order to purge clear outliers. Simple interpolation has been used for this purpose.

UNCTAD's Trade Analysis Information System (TRAINS) database (https://trains.unctad.org/) provides tariff data at the 6-digit HS level. This data is also available on the World Bank's WITS website (https://wits.worldbank.org/default.aspx?lang=en).

The gravity indicator variables used in the estimations come from the Dynamic Gravity dataset (see Gurevich and Herman, 2018, for details), available via the Gravity Portal of the United States International Trade Commission (https://www.usitc.gov/data/gravity/dgd.htm). The indicator variable WTO-GATTijt used in the estimations is the combination of the variables member_gatt_joint and member_wto_joint of the Dynamic Gravity dataset.

Appendix B

Table B1
List of countries in the gravity equation estimations. Source: COMTRADE.

Albania, Algeria, Andorra, Angola, Antigua and Barbuda, Argentina, Armenia, Australia, Austria, Azerbaijan, Bahamas, Bahrain, Bangladesh, Barbados, Belarus, Belgium-Luxembourg, Belize, Benin, Bermuda, Bhutan, Bolivia, Bosnia and Herzegovina, Brazil, Brunei, Bulgaria, Burkina, Faso, Burundi, Cambodia, Cameroon, Canada, Cape Verde, Central African Republic, Chad, Chile, China, Colombia, Congo Rep., Costa Rica, Cote d'Ivoire, Croatia, Cuba, Cyprus, Czech Republic, Denmark, Djibouti, Dominica, Dominican Republic, Ecuador, Egypt Arab Rep., El Salvador, Equatorial Guinea, Eritrea, Estonia, Ethiopia, Fiji, Finland, France, French Polynesia, Gabon, Gambia, Georgia, Germany, Ghana, Greece, Grenada, Guatemala, Guinea, Guinea-Bissau, Guyana, Haiti, Honduras, Hong Kong, Hungary, Iceland, India, Indonesia, Iran Islamic Rep., Ireland, Israel, Italy, Jamaica, Japan, Jordan, Kazakhstan, Kenya, Korea, Rep., Kuwait, Kyrgyz Republic, Lao PDR, Latvia, Lebanon, Libya, Lithuania, Macao, Macedonia FYR, Madagascar, Malawi, Malaysia, Maldives, Mali, Malta, Mauritania, Mauritius, Mexico, Moldova, Mongolia, Montserrat, Morocco, Mozambique, Myanmar, Nepal, Netherlands, New Zealand, Nicaragua, Niger, Nigeria, Norway, Oman, Pakistan, Palau, Panama, Papua New Guinea, Paraguay, Peru, Philippines, Poland, Portugal, Qatar, Romania, Russian Federation, Rwanda, Saudi Arabia, Senegal, Seychelles, Sierra Leone, Singapore, Slovak Republic, Slovenia, South Africa, Spain, Sri Lanka, St. Kitts and Nevis, St. Lucia, St. Vincent and the Grenadines, Suriname, Sweden, Sudan, Switzerland, Tanzania, Thailand, Togo, Trinidad and Tobago, Tunisia, Turkey, Uganda, Ukraine, United Arab Emirates, United Kingdom, United States, Uruguay, Uzbekistan, Vanuatu, Venezuela, Vietnam, Yemen, Zambia, Zimbabwe.

Table B2
Descriptive statistics. Sources: COMTRADE, TRAINS, Dynamic Gravity dataset.

Variable	Observations	Mean	Std. Dev.	Min.	Max.
X_{ijkt} ($1000)	208,589	26647.2	346500.3	0	3.12E+07
EU_{ijt}	208,589	0.1525	0.3595	0	1
$WTO\text{-}GATT_{ijt}$	208,589	0.9089	0.2877	0	1
CU_{ijt}	208,589	0.1846	0.3879	0	1
EIA_{ijt}	208,589	0.2451	0.4301	0	1
FTA_{ijt}	208,589	0.3336	0.4715	0	1
PTA_{ijt}	208,589	0.3948	0.4888	0	1
$\ln(1+tariff_{ijkt})$	208,589	0.1191	0.1554	0	1.5405
$DEU1998(any)_{ijkt}$	208,589	0.2040	0.4030	0	1
$DEU1998(intra)_{ijkt}$	208,589	0.0462	0.2099	0	1
$DEU1998(extra)_{ijkt}$	208,589	0.1579	0.3646	0	1
$DEU1998(extra\text{-}importer)_{ijkt}$	208,589	0.0460	0.2095	0	1
$DEU1998(extra\text{-}exporter)_{ijkt}$	208,589	0.1118	0.3152	0	1
$DEU1998(any)_{ijkt}$ (Small)	208,589	0.0413	0.1990	0	1

(*continued on next page*)

Table B2 (*continued*)

Variable	Observations	Mean	Std. Dev.	Min.	Max.
DEU1998(intra)$_{ijkt}$ (Small)	208,589	0.0142	0.1185	0	1
DEU1998(extra-importer)$_{ijkt}$ (Small)	208,589	0.0090	0.0945	0	1
DEU1998(extra-exporter)$_{ijkt}$ (Small)	208,589	0.0180	0.1331	0	1
DEU1998(any)$_{ijkt}$ (Medium)	208,589	0.0890	0.2848	0	1
DEU1998(intra)$_{ijkt}$ (Medium)	208,589	0.0171	0.1296	0	1
DEU1998(extra-importer)$_{ijkt}$ (Medium)	208,589	0.0214	0.1448	0	1
DEU1998(extra-exporter)$_{ijkt}$ (Medium)	208,589	0.0505	0.2190	0	1
DEU1998(any)$_{ijkt}$ (Large)	208,589	0.0737	0.2613	0	1
DEU1998(intra)$_{ijkt}$ (Large)	208,589	0.0148	0.1209	0	1
DEU1998(extra-importer)$_{ijkt}$ (Large)	208,589	0.0156	0.1238	0	1
DEU1998(extra-exporter)$_{ijkt}$ (Large)	208,589	0.0433	0.2035	0	1

References

ACEA (European Automobile Association), 2019a. CO2-based motor vehicle taxes in the EU. https://www.acea.be/uploads/publications/CO2_tax_overview_2018.pdf.

ACEA (European Manufacturers Automobile Association), 2019b. ACEA tax guide. https://www.acea.be/uploads/news_documents/ACEA_Tax_Guide_2019.pdf.

Ajanovic, A., Dahl, C., Schipper, L., 2012a. Modelling transport (energy) demand and policies - an introduction. Energy Pol. 41, iii–xiv. https://doi.org/10.1016/j.enpol.2011.12.033.

Ajanovic, A., Haas, R., 2012. The role of efficiency improvements vs. price effects for modeling passenger car transport demand and energy demand-Lessons from European countries. Energy Pol. 41, 36–46. https://doi.org/10.1016/j.enpol.2011.03.086.

Ajanovic, A., Schipper, L., Haas, R., 2012b. The impact of more efficient but larger new passenger cars on energy consumption in EU-15 countries. Energy 48, 346–355. https://doi.org/10.1016/j.energy.2012.05.039.

Ajanovic, A., Haas, R., Wirl, F., 2016. Reducing CO2 emissions of cars in the EU: analyzing the underlying mechanisms of standards, registration taxes and fuel taxes. Energy Effic 9, 925–937. https://doi.org/10.1007/s12053-015-9397-4.

Anable, J., Goodwin, P., 2019. Transport & mobility. In: Eyre, N., Killip, G. (Eds.), Shifting the Focus: Energy Demand in a Net-Zero Carbon UK. Centre for Research into Energy Demand Solutions, Oxford, pp. 47–60.

Anderson, J.E., Van Wincoop, E., 2003. Gravity with gravitas: a solution to the border puzzle. Am. Econ. Rev. 93, 170–192. https://doi.org/10.1257/000282803321455214.

Baier, S.L., Bergstrand, J.H., 2007. Do free trade agreements actually increase members' international trade? J. Int. Econ. 71, 72–95. https://doi.org/10.1016/j.jinteco.2006.02.005.

Baier, S.L., Kerr, A., Yotov, Y.V., 2018. Gravity, distance, and international trade. In: Blonigen, B.A., Wilson, W.W. (Eds.), Handbook of International Trade and Transportation. Edward Elgar, Cheltenham (UK), pp. 15–78.

Beise, M., Rennings, K., 2005. Lead markets and regulation: a framework for analyzing the international diffusion of environmental innovations. Ecol. Econ. 52, 5–17. https://doi.org/10.1016/j.ecolecon.2004.06.007.

Berggren, C., Magnusson, T., 2012. Reducing automotive emissions-The potentials of combustion engine technologies and the power of policy. Energy Pol. 41, 636–643. https://doi.org/10.1016/j.enpol.2011.11.025.

Brand, C., Anable, J., Morton, C., 2019. Lifestyle, efficiency and limits: modelling transport energy and emissions using a socio-technical approach. Energy Effic 12, 187–207. https://doi.org/10.1007/s12053-018-9678-9.

Brand, C., Anable, J., Ketsopoulou, I., Watson, J., 2020. Road to zero or road to nowhere? Disrupting transport and energy in a zero carbon world. Energy Pol. 139, 111334 https://doi.org/10.1016/j.enpol.2020.111334.

Burguillo-Cuesta, M., García-Inés, M.J., Romero-Jordan, D., 2011. Does dieselization favour a cleaner transport? evidence from EU-15. Transp. Rev. 31, 571–589. https://doi.org/10.1080/01441647.2011.566378.

Cames, M., Helmers, E., 2013. Critical evaluation of the European diesel car boom - global comparison, environmental effects and various national strategies. Environ. Sci. Eur. 25, 1–22. https://doi.org/10.1186/2190-4715-25-15.

Clerides, S., Zachariadis, T., 2008. The effect of standards and fuel prices on automobile fuel economy: an international analysis. Energy Econ. 30, 2657–2672. https://doi.org/10.1016/j.eneco.2008.06.001.

Creutzig, F., Roy, J., Lamb, W.F., Azevedo, I.M.L., Bruine De Bruin, W., Dalkmann, H., Edelenbosch, O.Y., Geels, F.W., Grubler, A., Hepburn, C., Hertwich, E.G., Khosla, R., Mattauch, L., Minx, J.C., Ramakrishnan, A., Rao, N.D., Steinberger, J.K., Tavoni, M., Ürge-Vorsatz, D., Weber, E.U., 2018. Towards demand-side solutions for mitigating climate change. Nat. Clim. Chang. 8, 268–271. https://doi.org/10.1038/s41558-018-0121-1.

Cuenot, F., 2009. CO2 emissions from new cars and vehicle weight in Europe; How the EU regulation could have been avoided and how to reach it? Energy Pol. 37, 3832–3842. https://doi.org/10.1016/j.enpol.2009.07.036.

De Borger, B., Mulalic, I., Rouwendal, J., 2016. Measuring the rebound effect with micro data: a first difference approach. J. Environ. Econ. Manag. 79, 1–17. https://doi.org/10.1016/j.jeem.2016.04.002.

Degraeuwe, B., Weiss, M., 2017. Does the New European Driving Cycle (NEDC) really fail to capture the NOX emissions of diesel cars in Europe? Environ. Pollut. 222, 234–241. https://doi.org/10.1016/j.envpol.2016.12.050.

EC (European Commission), 1995. A Community Strategy to Reduce C02 Emissions from Passenger Cars and Improve Fuel Economy. Communication from the Commission to the Council and the European Parliament. COM (95) 689 final.

EC (European Commission), 1998. Implementing the Community Strategy to Reduce C02 Emissions from Cars: an Environmental Agreement with the European Automobile Industry. Communication from the Commission to the Council and the European Parliament. COM, p. 495 (final).

EC (European Commission), 1999. Commission Recommendation of 5 February 1999 on the reduction of CO2 emissions from passenger cars (1999/125/EC). Off. J. Eur. Commun. (L 40), 49.

EC (European Commission), 2000a. Commission Recommendation of 13 April 2000 on the reduction of CO2 emissions from passenger cars (JAMA) (2000/304/EC). Off. J. Eur. Commun. (L 100), 57.

EC (European Commission), 2000b. Commission Recommendation of 13 April 2000 on the reduction of CO2 emissions from passenger cars (KAMA) (2000/303/EC). Off. J. Eur. Commun. (L 100), 55.

EC (European Commission), 2005. Implementing the Community Strategy to Reduce CO2 Emissions from Cars: Fifth Annual Communication on the Effectiveness of the Strategy. Communication from the Commission to the Council and the European Parliament. COM, p. 269 (final).

EC (European Commission), 2019. The European Green Deal. Communication from the Commission to the European Parliament. the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. COM, p. 640 (final).

EC (European Commission), 2020a. Stepping up Europe's 2030 Climate Ambition. Investing in a Climate-Neutral Future for the Benefit of Our People. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. COM, p. 562 (final).

EC (European Commission), 2020b. Sustainable and Smart Mobility Strategy – Putting European Transport on Track for the Future. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. COM, p. 789 (final).

EC (European Commission), 2021. Proposal for a Regulation of the European Parliament and of the Council Amending Regulation (EU) 2019/631 as Regards Strengthening the CO2 Emission Performance Standards for New Passenger Cars and New Light Commercial Vehicles in Line with the Union's Increased Climate Ambition. COM, p. 556 (final).

EEA (European Environment Agency), 2016. Explaining road transport emissions. A non-technical guide. https://doi.org/10.2800/71804.

EEA (European Environment Agency), 2017. Monitoring CO2 emissions from new passenger cars and vans in 2016. EEA Report No 19/2017. https://doi.org/10.2800/987976.

EEA (European Environment Agency), 2018. Monitoring CO2 emissions from new passenger cars and vans in 2017 (No. EEA Report No 15/2018). https://doi.org/10.2800/74986.

EEA (European Environment Agency), 2020. Monitoring CO2 emissions from passenger cars and vans in 2018. EEA Report No 02/2020. https://doi.org/10.2800/19757.

EEA (European Environment Agency), 2021a. Annual European Union Greenhouse Gas Inventory 1990–2019 and Inventory Report 2021.

EEA (European Environment Agency), 2021b. CO2 performance of new passenger cars in Europe. https://www.eea.europa.eu/data-and-maps/indicators/average-co2-emissions-from-motor-vehicles-1/assessment.

EEA (European Environment Agency), 2021c. Sharp decrease in CO2 emissions of new cars in 2020. https://www.eea.europa.eu/highlights/sharp-decrease-in-emissions-of.

EFTE (European Federation for Transport and Environment), 2011. Fuelling oil demand. What happened to fuel taxation in Europe? European Federation for Transport and Environment (T&E), Brussels, 2011.

EU (European Union), 2020. Statistical Pocketbook 2020. EU Transport in Figures. Publication Office of the European Union, Luxembourg. https://doi.org/10.2832/491038.

Eurostat, 2020. In: User guide on European statistics on international trade in goods, 2020 edition. Publications Office of the European Union, Luxembourg. https://doi.org/10.2785/76978.

Fontaras, G., Samaras, Z., 2007. A quantitative analysis of the European Automakers' voluntary commitment to reduce CO2 emissions from new passenger cars based on independent experimental data. Energy Pol. 35, 2239–2248. https://doi.org/10.1016/j.enpol.2006.07.012.

Fontaras, G., Zacharof, N.G., Ciuffo, B., 2017. Fuel consumption and CO2 emissions from passenger cars in Europe – laboratory versus real-world emissions. Prog. Energy Combust. Sci. 60, 97–131. https://doi.org/10.1016/j.pecs.2016.12.004.

Fredriksson, G., Roth, A., Tagliapietra, S., Veugelers, R., 2018. Is the European automotive industry ready for the global electric vehicle revolution? Bruegel Policy Contribution (26).

Fuse, M., Kosaka, H., Kashima, S., 2009. Estimation of world trade for used automobiles. J. Mater. Cycles Waste Manag. 11, 348–357. https://doi.org/10.1007/s10163-009-0263-3.

Greening, L.A., Greene, D.L., Difiglio, C., 2000. Energy efficiency and consumption - the rebound effect - a survey. Energy Pol. 28, 389–401. https://doi.org/10.1016/S0301-4215(00)00021-5.

Gulbrandsen, L.H., Christensen, A.R., 2014. EU legislation to reduce carbon emissions from cars: intergovernmental or supranational policy making? Rev. Pol. Res. 31, 503–528. https://doi.org/10.1111/ropr.12100.

Gurevich, T., Herman, P., 2018. The Dynamic Gravity Dataset : 1948 – 2016, US International Trade Commission, Economic Working Paper Series No. 2018– 02– A (No. 2018– 02– A), Economic Working Paper Seires.

Head, K., Mayer, T., 2014. Gravity equations: workhorse,Toolkit, and cookbook. In: Gopinath, G., Helpman, E., Rogoff, K. (Eds.), Handbook of International Economics. Elsevier B.V., pp. 131–195. https://doi.org/10.1016/B978-0-444-54314-1.00003-3

Helmers, E., Leitão, J., Tietge, U., Butler, T., 2019. CO2-equivalent emissions from European passenger vehicles in the years 1995–2015 based on real-world use: assessing the climate benefit of the European "diesel boom. Atmos. Environ. 198, 122–132. https://doi.org/10.1016/j.atmosenv.2018.10.039.

Holzer, K., Cottier, T., 2015. Addressing climate change under preferential trade agreements: towards alignment of carbon standards under the Transatlantic Trade and Investment Partnership. Global Environ. Change 35, 514–522. https://doi.org/10.1016/j.gloenvcha.2015.06.006.

Hooftman, N., Messagie, M., Van Mierlo, J., Coosemans, T., 2018. A review of the European passenger car regulations – real driving emissions vs local air quality. Renew. Sustain. Energy Rev. 86, 1–21. https://doi.org/10.1016/j.rser.2018.01.012.

ICCT (International Council of Clean Transportation), 2018. Changes to the Motor Vehicle Type-Approval System in the European Union. International Council of Clean Transportation Report.

IEA (International Energy Agency), 2009. Transport Energy and CO2 : Moving towards Sustainability. IEA/OECD. https://doi.org/10.1787/9789264073173-en.

Ivanova, D., Barrett, J., Wiedenhofer, D., Macura, B., Callaghan, M., Creutzig, F., 2020. Quantifying the potential for climate change mitigation of consumption options. Environ. Res. Lett. 15 https://doi.org/10.1088/1748-9326/ab8589.

Kalinowska, D., Keser, K., Kunert, U., 2009. CO2 based taxation on cars is rising in Europe. DIW Berlin Wkly. Rep. 5, 159–170.

Klier, T., Linn, J., 2016. The effect of vehicle fuel economy standards on technology adoption. J. Publ. Econ. 133, 41–63. https://doi.org/10.1016/j.jpubeco.2015.11.002.

Lamb, W.F., Wiedmann, T., Pongratz, J., Andrew, R., Crippa, M., Olivier, J.G.J., Wiedenhofer, D., Mattioli, G., Khourdajie, A. Al, House, J., Pachauri, S., Figueroa, M., Saheb, Y., Slade, R., Hubacek, K., Sun, L., Ribeiro, S.K., Khennas, S., De La Rue Du Can, S., Chapungu, L., Davis, S.J., Bashmakov, I., Dai, H., Dhakal, S., Tan, X., Geng, Y., Gu, B., Minx, J., 2021. A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018. Environ. Res. Lett. 16 https://doi.org/10.1088/1748-9326/abee4e.

Matiaske, W., Menges, R., Spiess, M., 2012. Modifying the rebound: it depends! Explaining mobility behavior on the basis of the German socio-economic panel. Energy Pol. 41, 29–35. https://doi.org/10.1016/j.enpol.2010.11.044.

Mattioli, G., Roberts, C., Steinberger, J.K., Brown, A., 2020. The political economy of car dependence: a systems of provision approach. Energy Res. Soc. Sci. 66, 101486 https://doi.org/10.1016/j.erss.2020.101486.

Mayeres, I., Proost, S., 2013. The taxation of diesel cars in Belgium - revisited. Energy Pol. 54, 33–41. https://doi.org/10.1016/j.enpol.2011.11.069.

Minjares, R., Blumberg, K., Posada Sanchez, F., 2013. Alignment of policies to maximize the climate benefits of diesel vehicles through control of particulate matter and black carbon emissions. Energy Pol. 54, 54–61. https://doi.org/10.1016/j.enpol.2012.09.053.

Mulholland, E., Miller, J., Braun, C., Jin, L., Rodríguez, F., 2021. Quantifying the Long-Term Air Quality and Health Benefits from Euro 7/VII Standards in Europe. The International Council of Clean Transportation. ICCT Briefing June 2021.

Olivero, M.P., Yotov, Y.V., 2012. Dynamic gravity: endogenous country size and asset accumulation. Can. J. Econ. 45, 64–92. https://doi.org/10.1111/j.1540-5982.2011.01687.x.

Pelkmans, J., Lee, T.M., Mustilli, F., Cernat, L., Norman-López, A., Tucci, A., Goyens, M., Auffrets, L., Kolev, G., Matthes, J., 2015. TTIP: political and economic rationale and implications. Intereconomics 50, 312–343. https://doi.org/10.1007/s10272-015-0557-8.

Pye, S., Usher, W., Strachan, N., 2014. The uncertain but critical role of demand reduction in meeting long-term energy decarbonisation targets. Energy Pol. 73, 575–586. https://doi.org/10.1016/j.enpol.2014.05.025.

Rodríguez, F., Posada, F., 2019. Future Heavy-Duty Emission Standards. An Opportunity for International Harmonization. The International Council of Clean Transportation. White Paper November 2019.

Rodrik, D., 2014. Green industrial policy. Oxf. Rev. Econ. Pol. 30, 469–491. https://doi.org/10.1093/oxrep/gru025.

Santos, G., 2017. Road fuel taxes in Europe: do they internalize road transport externalities? Transport Pol. 53, 120–134. https://doi.org/10.1016/j.tranpol.2016.09.009.

Santos Silva, J.M.C., Tenreyro, S., 2006. The log of gravity. Rev. Econ. Stat. 88, 641–658.

Schipper, L., 2011. Automobile use, fuel economy and CO2 emissions in industrialized countries: encouraging trends through 2008? Transport Pol. 18, 358–372. https://doi.org/10.1016/j.tranpol.2010.10.011.

Schipper, L., Fulton, L., 2013. Dazzled by diesel? The impact on carbon dioxide emissions of the shift to diesels in Europe through 2009. Energy Pol. 54, 3–10. https://doi.org/10.1016/j.enpol.2012.11.013.

Schipper, L., Marie-Lilliu, C., Fulton, L.M., 2002. Diesels in Europe: analysis of characteristics, usage patterns, energy savings and Co_2 emission implications. J. Transport Econ. Pol. 36, 305–340.

Sims, R., Schaeffer, R., Creutzig, F., Cruz-Núñez, X., D'Agosto, M., Dimitriu, D., Figueroa Meza, M.J., Fulton, L., Kobayashi, S., Lah, O., McKinnon, A., Newman, P., Ouyang, M., Schauer, J.J., Sperling, D., G, T., Z, J, 2014. Transport. In: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C., T, C.M. (Eds.), Climate Change 2014 Mitigation of Climate Change. Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Skeete, J.P., 2017. Examining the role of policy design and policy interaction in EU automotive emissions performance gaps. Energy Pol. 104, 373–381. https://doi.org/10.1016/j.enpol.2017.02.018.

Sorrell, S., 2015. Reducing energy demand: a review of issues, challenges and approaches. Renew. Sustain. Energy Rev. 47, 74–82. https://doi.org/10.1016/j.rser.2015.03.002.

Sorrell, S., Dimitropoulos, J., Sommerville, M., 2009. Empirical estimates of the direct rebound effect: a review. Energy Pol. 37, 1356–1371. https://doi.org/10.1016/j.enpol.2008.11.026.

Sterner, T., 2007. Fuel taxes: an important instrument for climate policy. Energy Pol. 35, 3194–3202. https://doi.org/10.1016/j.enpol.2006.10.025.

Tietge, U., Mock, P., German, J., Bandivadekar, A., Ligterink, N., 2017. From Laboratory to Road: A 2017 Update of Official and "Real-World" Fuel Consumption and CO2 Values for Passenger Cars in Europe. The International Council of Clean Transportation. White Paper November 2017.

UN (United Nations), 1992. United Nations framework convention on climate change. https://unfccc.int/files/essential_background/background_publications_htmlpdf/application/pdf/conveng.pdf.

UN (United Nations), 1998. Kyoto protocol to the united Nations framework convention on climate change. https://unfccc.int/sites/default/files/resource/docs/cop3/l07a01.pdf.

UN (United Nations), 2015. Paris agreement. United Nations framework convention on climate change. https://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf.

Wallington, T.J., Lambert, C.K., Ruona, W.C., 2013. Diesel vehicles and sustainable mobility in the U.S. Energy Pol. 54, 47–53. https://doi.org/10.1016/j.enpol.2011.11.068.

Wappelhorst, A.S., Tietge, U., Bieker, G., Mock, P., 2021. Europe's CO2 Emission Performance Standards for New Passenger Cars: Lessons from 2020 and Future Prospects. The International Council of Clean Transportation. Working Paper 2021-32.

Williams, M., Minjares, R., 2016. A Technical Summary of Euro 6/VI Vehicle Emission Standards. The International Council of Clean Transportation. Briefing Paper.

Winkler, S.L., Anderson, J.E., Garza, L., Ruona, W.C., Vogt, R., Wallington, T.J., 2018. Vehicle criteria pollutant (PM, NOx, CO, HCs) emissions: how low should we go? Clim. Atmos. Sci. 1 https://doi.org/10.1038/s41612-018-0037-5.

Yang, Z., Mock, P., German, J., Bandivadekar, A., Lah, O., 2018. On a pathway to de-carbonization – a comparison of new passenger car CO2 emission standards and taxation measures in the G20 countries. Transport. Res. Trans. Environ. 64, 53–69. https://doi.org/10.1016/j.trd.2017.06.022.

Yotov, Y.V., Piermartini, R., Monteiro, J.-A., Larch, M., 2016. An Advanced Guide to Trade Policy Analysis: the Structural Gravity Model. World Trade Organization/ United Nations. https://doi.org/10.30875/abc0167e-en.

Zachariadis, T., 2013. Gasoline, diesel and climate policy implications-Insights from the recent evolution of new car sales in Germany. Energy Pol. 54, 23–32. https://doi.org/10.1016/j.enpol.2011.11.075.

Zachariadis, T., 2016. After "dieselgate": regulations or economic incentives for a successful environmental policy? Atmos. Environ. 138, 1–3. https://doi.org/10.1016/j.atmosenv.2016.04.045.