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Anna Alberini and Colin Vance[1]

Competing Forces in the German New Car Market: How do they Affect Diesel, PHEV, and BEV sales?

Abstract

With more than 3 million new passenger cars sold every year, Germany's automobile industry is a major player on the European car market, and one seen as an important arena for achieving climate protection targets. Using high-resolution car registration data from each state in Germany between January 2015 to March 2020, we estimate reduced-form panel data models to identify the effects of three flagship policies aimed at reducing transport emissions from cars: diesel bans, rebates for battery vehicles, and subsidies for charging station projects. The models show that the policies have significant effects on the sales of specific powertrains. But policy simulations that incorporate estimates of lifecycle CO2-emissions reveal that they have only negligible effects on emission reductions and are costly. Rebates on the purchase of a battery-electric or plug-in hybrids result in a cost per ton of reduced CO2-emissions of over €1000. Even the most optimistic scenarios result in a cost per ton of CO2-reduced by subsidies for the construction of charging stations of at least €400. These figures are very large when compared with the cost of abatement implicit in the price of allowances on the European Emissions Trading System, with important implications on cross-sectoral trading, such as that envisioned in the European Union's Fit-for-55 program.

JEL-Codes: H23, Q48, Q54, R41

Keywords: New car sales; CO2-emissions; German Bundesländer; policy simulation

October 2023

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1 Anna Alberini, University of Maryland, College Park; Colin Vance, RWI and Constructor University. *- This research was supported by an EXPRO grant from the Czech Science Foundation (grant #19-26812X) and by the German Federal Ministry of Education and Research (BMBF) within the Kopernikus Project Ariadne (grant #03SFK5C0). Declaration of interests: None. We are grateful to the participants of seminars at the Climate Economics Chair, Universite de Paris Dauphine, and Charles University, Prague, and attendees of the International Energy Workshop, Freiburg, for their helpful comments.* *- All correspondence to: Colin Vance, RWI, Hohenzollernstr. 1-3, 45128 Essen, Germany, e-mail: colin.vance@rwi-essen.de*

1 Introduction

The transport sector has long been a renegade in Europe's efforts to reduce CO_2 emissions and local air pollutants. Over the past three decades, European countries have introduced a variety of demand-side and technological policy measures to reduce the sector's growing environmental footprint, including fuel efficiency labels, emissions standards, and CO_2 taxes, but to little avail. Even as total greenhouse gas emissions in Europe have decreased by nearly 25% since 1990, those from transportation are on the rise, increasing by almost 30% (European Commission, 2020).

As the largest car market in Europe, with over three million new cars sold every year, Germany has managed to buck this trend. Since 1990, the country reduced its greenhouse gas emissions from transportation by about 9.5% (Umweltbundesamt, 2022), notwithstanding the absence of evident changes in driving habits (Alberini et al., 2022). In fact, until the COVID pandemic, car mileage in Germany was relatively stable, increasing by about 1% between 2016 and 2019 (KBA, 2022). In this paper, we examine an alternate source of changes in emissions from the road transport sector, namely, changes in the composition of the new car fleet. Drawing on a panel dataset of new car sales at the Bundesland (state) level from 2015 to early 2020, we focus specifically on the role of local and federal policy measures in determining new car registrations.

Legislation from the European Union (EU) has obliged Germany's automakers to meet fleetwide emissions targets, initially set at 120g CO_2/km in 2015 and reduced to 95 g CO_2/km in 2020. Consequently, the average CO_2 emissions rate of new cars sold in Germany declined at a fast rate until approximately 2016, then leveled off and even slightly increased as the share of diesel vehicles plummeted. Some of these "missing" diesel cars appear to have been replaced for the most part by conventional gasoline vehicles. The share of hybrids, plug-in hybrids and EVs have been growing, but, at least until COVID hit, in a less than proportional fashion.

Germany has also implemented policies at the national level to reduce emissions, including an annual car circulation tax that penalizes engines with higher CO_2 emissions rate per km and diesel engines (Alberini and Horvath, 2021; Klier and Linn, 2015). Our focus in this paper is on measures targeted specifically at electric- and diesel cars. Since 2016, the German government has pursued a two-pronged strategy to promote electric vehicles (EVs), extending rebates to car buyers and subsidies to firms for the construction of charging stations. In addition, some municipalities in Germany have adopted or have been considering the adoption of diesel vehicle bans out of concern for local pollution problems, a trend that emerged after the Volkswagen "Dieselgate" scandal. Our econometric model exploits cross-sectional and temporal variation in these three measures to examine their effectiveness in shaping new car sales and, in the case of rebates and infrastructure subsidies, to assess their contribution to reducing CO_2 emissions.

Several studies have investigated the impact of rebates and infrastructure subsidies on EV uptake in different countries, generally finding positive and economically significant effects of both measures. Among the handful of studies that have investigated the measures jointly, a common conclusion is that subsidies for infrastructure are more cost-effective per EV than rebates for EV purchases. Li et al. (2017) find that subsidizing charging stations is more than twice as effective as subsidizing consumer purchases in the U.S.. Springel (2021) reaches a similar finding based on a structural equation model with Norwegian data, but she qualifies it by noting that the relation eventually inverts as government spending increases, because the marginal impact of infrastructure subsidies tapers off faster. Li et al.'s (2022) analysis of the Chinese market shows that investing in charging stations is nearly four times as effective as subsidizing consumer purchases in promoting EVs. A simulation analysis of the U.S. market by Cole et al. (2021) that evaluates different financial incentives corroborates these econometric results, pointing to the higher cost-effectiveness of charging infrastructure.

Deploying reduced-form estimating equations that include a rich set of fixed effects to control for unobserved heterogeneity over vehicles, geographical regions, and time, our analysis adds to this evidence by calculating cost effectiveness in the German market. To this end, we undertake an auxiliary analysis of the lifecycle CO_2 emissions in the German new car market, which include those generated in the manufacturing of the vehicle, plus those associated with its use (driving), minus those from recycling the metal and parts at the end of the car's life. Together with the econometric estimates, we use these lifecycle figures to arrive at the cost effectiveness of the measures, both in terms of EVs sold as well as the more climate-relevant metric of reduced tons of CO_2.

Several insights emerge from this analysis. Descriptively, we uncover an important role for "transition" technologies, particularly conventional hybrid vehicles, which, alongside a decline in diesels, appeared to have gained equal or larger shares than all-electrics and plug-in hybrids, despite the emphasis and incentives put on the latter by the government and automakers. Our econometric model shows that the decline in diesel sales is associated with the proposed or actual diesel bans in certain cities, even though the diesel bans would only affect existing cars but not new ones. This suggests that expectations about possible future regulations or production phaseouts, or perceived signals that one technology might be undesirable, play an important role in shaping the fleet and its emissions rates. The model also shows that rebates for battery vehicles and federal funding to charging station projects have significant effects on the sales of specific powertrains.

Even so, our policy simulations suggest that the absolute effects on lifetime emissions are small and come at a high cost, exceeding €1000 per ton of reduced CO_2 in the case of the EV rebate. Our most optimistic estimates of the cost per ton of CO_2 reduced by funding charging stations fall in the range between €400 and €1000 per ton. These figures clearly exceed—by one or even two orders of magnitude—the price per allowance in the EU Emissions Trading System, whose maximum price reached €105 per ton in February 2023.

The remainder of the paper is organized as follows. Section 2 presents the database of car sales. Section 3 describes the three policies under investigation—diesel bans, rebates, and infrastructure subsidies. Section 4 outlines the econometric methodology used to identify their effects. Section 5 presents the results and section 6 concludes.

2 Car Sales and Characteristics of the German Fleet

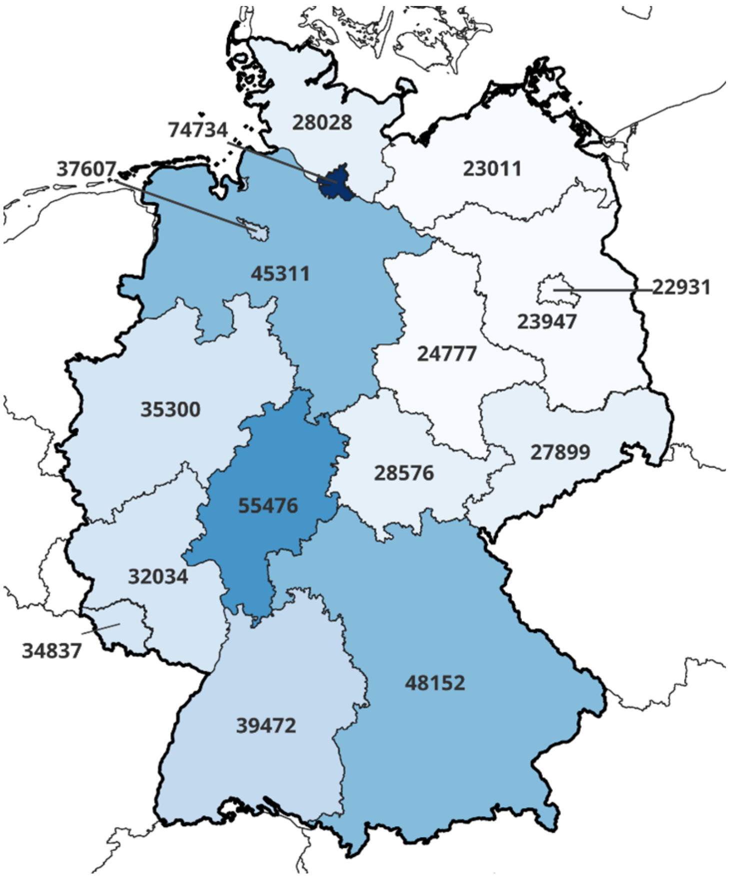
At over 3 million new passenger vehicles sold every year and a passenger car fleet of over 47 million, Germany is the largest car market in Europe. Historically, consumer preferences for large, powerful and fast vehicles have resulted in a fleet with CO_2 emissions rates higher than those of most other European countries. The CO_2 emissions rates of new cars sold in Germany have fallen with the CO_2 emissions regulations promulgated by the EU in 2011, but, as documented below, this decline bottomed out in 2016 and the trend reversed thereafter.

We have data acquired from IHS-Markit on the monthly number of registrations (the closest proxy to sales[1]) for each individual type of passenger vehicle sold in each Bundesland in Germany in each month from January 2015 to March 2020. The data aggregate private and company cars. An individual type of vehicle is defined as the combination of make, model, version and trim, year designed (or year with major redesign), body type, number of doors and seats, type of fuel, engine size, horsepower, number of cylinders, whether turbocharged, dimensions, weight and payload, transmission, number of gears, drivetrain (front, rear, or all-wheel), and axle configuration. The dataset contains additional information for each type of car on the fuel economy (city, highway and combined), the euro standard, the CO_2 emissions rate (in grams/km), and the test procedure employed to determine the emissions rate (NEDC or WLTP).

Figure 1 shows vehicle sales per million residents for the year 2015, which shows substantial heterogeneity across Germany's 16 states. We attribute this heterogeneity to the differences in population density, wealth, and presence of businesses across Bundesländer (our dataset does not distinguish between company cars and cars purchased by private individuals). Nationwide sales of cars (excluding LCVs registered

[1] In the remainder of this paper, we use the terms "registrations" and "sales" interchangeably, even though our data are the registration counts.

Figure 1: Car sales per million residents in 2015



as passenger cars, and cars that run on natural gas, LPG, ethanol, and hydrogen) are displayed in Figure 2. Sales are seasonal, but appear to fluctuate around a stable long-term trend.

Figure 3 compares the shares of the different powertrains in 2015 and 2019, the last complete year of our study period. The information summarized in the figure is striking. First, the share of diesel cars dropped from 46% to 33%, and that of gasoline cars rose, although not quite as much, from 52% to 60%. Second, the shares of hybrids, plug-in hybrids and all electric vehicles are rising, but remain still extremely small, with hybrids accounting for 4%, and plug-in hybrids combined with all-electrics for 3% of the sales in 2019. This is in sharp contrast with Norway, where in 2019 electric vehicles represented 55.9% of all new registrations and 12% of the fleet, and the Netherlands, where the respective shares are 15.1% and 2.5% (Baldursson et al., 2021). In Germany, all-electric cars and plug-in hybrids represented only 0.64% and 0.59% of the fleet in 2020 (see www.eafo.eu).

Figure 2: Monthly car sales in Germany (no LCVs)

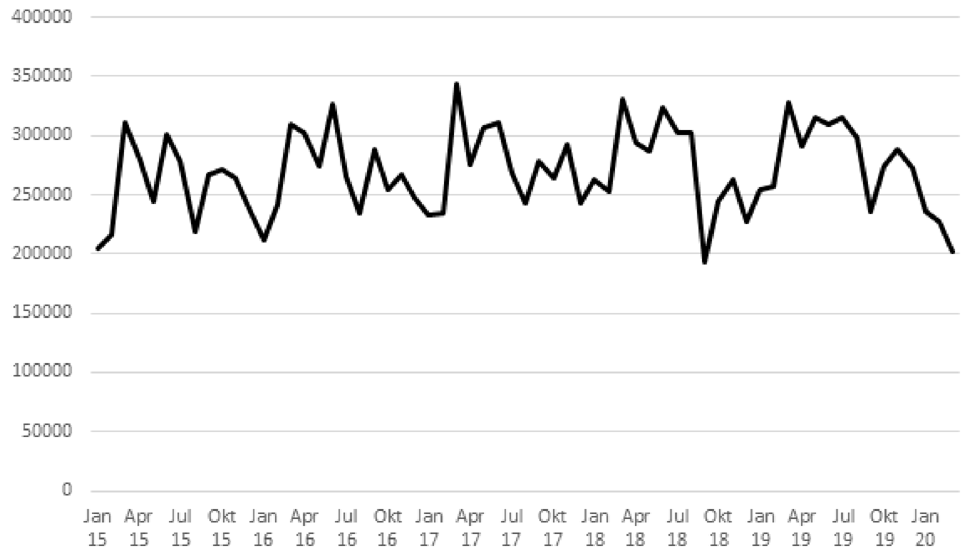


Figure 4 displays how these changes occurred over time. The share of diesel cars out of new car sales was about 50% at the beginning of our study period. It started declining at the end of 2015, and continued to do so over our study period, although it appears to have stabilized to about 30% by the spring of 2018. Where did these "missing" diesel cars go? The figure shows that they appear to have been replaced almost exclusively by gasoline cars until early 2018, when the share of gasoline cars started dropping, and in part by hybrids, plug-in hybrids and electric cars thereafter. Panel B of Figure 4 shows that the number of hybrid, plug-in hybrid and electric car units sold were similar. To illustrate, in the first quarter of 2020, a total of 661,786 passenger cars (excluding LCVs and cars powered by natural gas, LPG, or hydrogen) were sold in Germany. Of these, 193,575 (29.25%) were diesel, 365,478 (55.23%) gasoline, 34,737 (5.25%) gasoline HEVs, 15,864 (2.40%) diesel HEVs, 23,260 (3.51%) gasoline PHEVs, 3,039 (0.46%) diesel PHEVs, and 25,810 (3.90%) all-electrics.

Given these trends, how were the average CO_2 emissions rates of new car sales affected? Figure 5 displays the sales-weighted average CO_2 emissions rates over our study period. Their evolution over time follows closely that of the shares of diesel, gasoline and other fuels: They were falling until October 2015, then rose. The solid line in Figure 5 represents the "legal" CO_2 emissions, i.e., those used to compute the circulation tax, namely the NEDC CO_2 emissions rates until August 2018, and WLTP

Figure 3: Share of sales by type of fuel

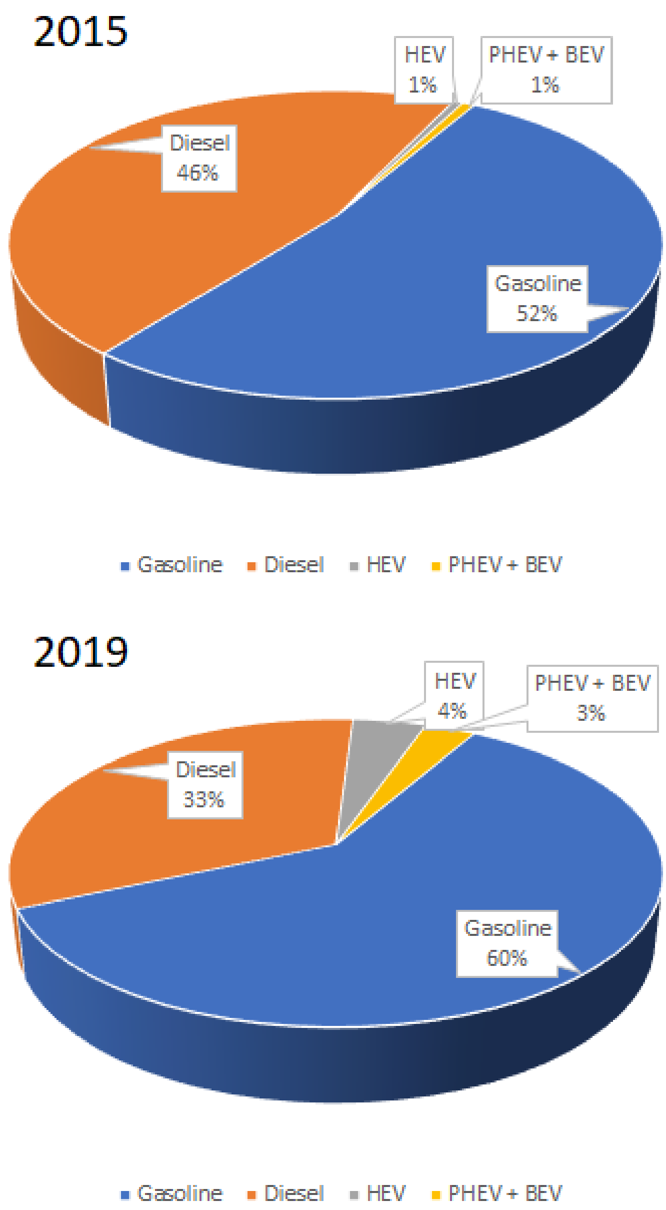


Figure 4: Sales by type of fuel technology

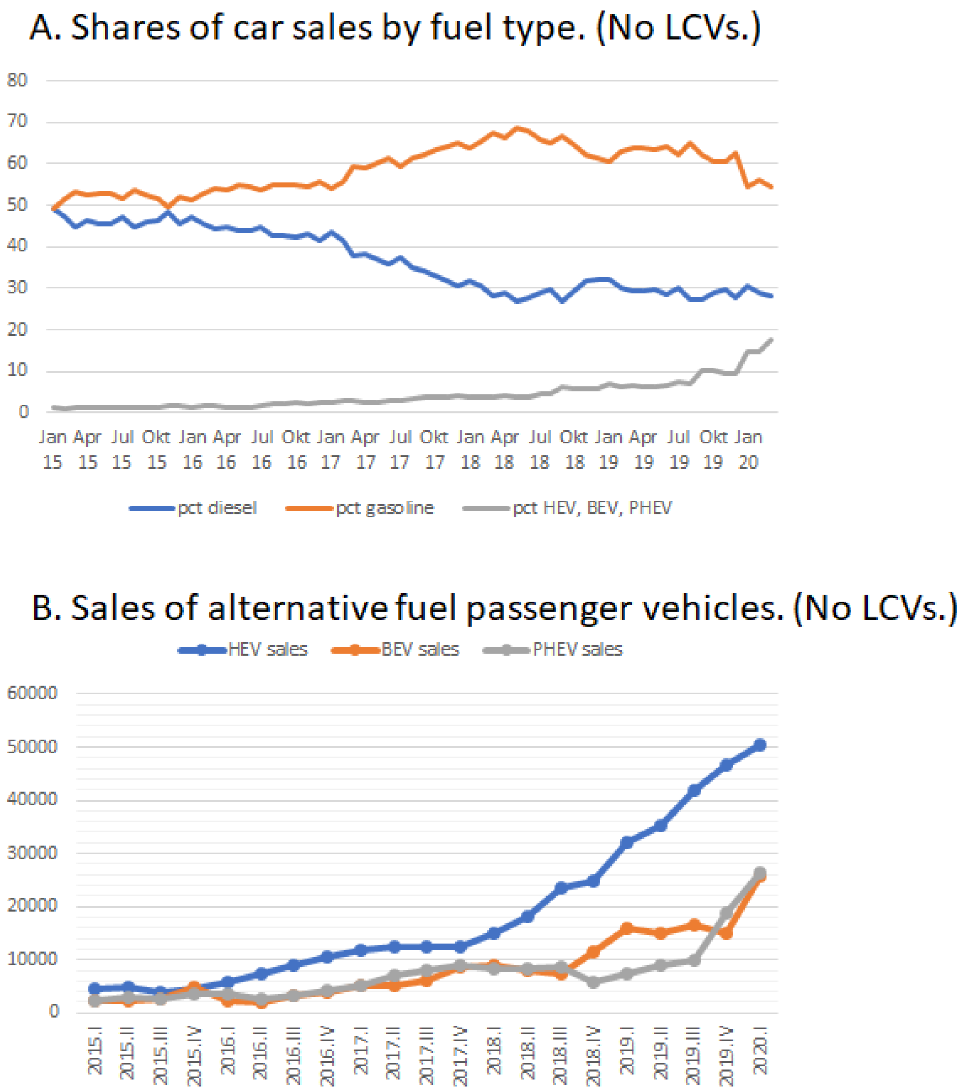
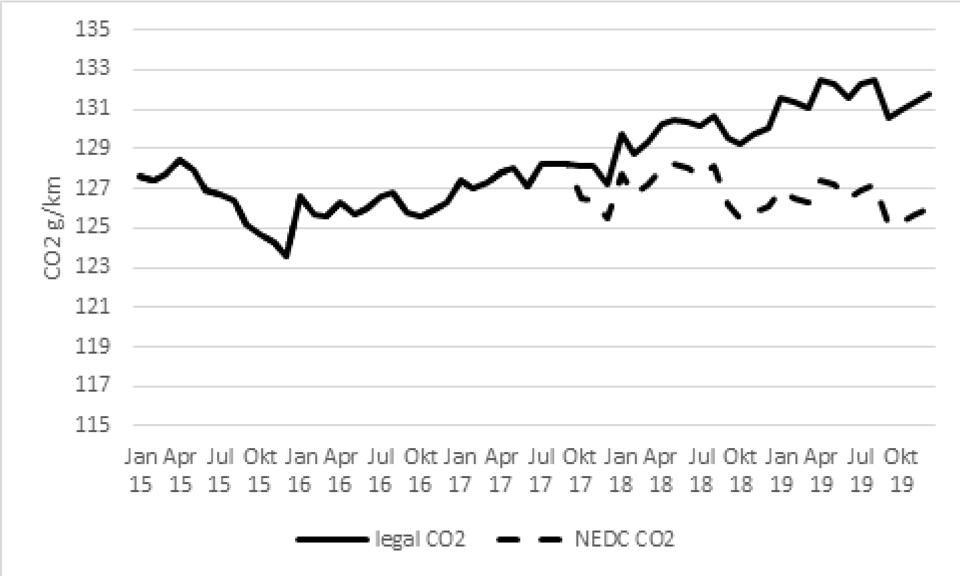


Figure 5: Sales-weighted average emissions rate, Jan 2015-Dec 2019

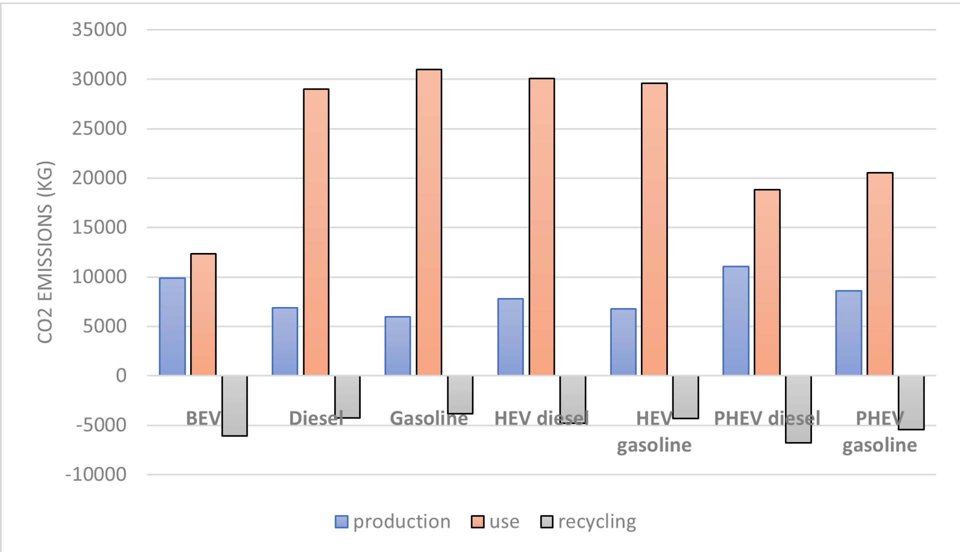


emissions rates (when available) from Sept. 2018. The dashed line refers throughout to the NEDC emissions: They appear to be in slight decline since the end of 2017, presumably as the result of increasing shares of hybrids, plug-in hybrids and battery electric cars.

Emissions rates from driving, of course, explain only part of the climate impact of new vehicles. A more comprehensive indicator, and one that will be central to the policy simulations undertaken below, is the lifecycle emissions of cars, namely the sum of the emissions created during the vehicle's production process, its use, and disposal and recycling at the end of its life. Production emissions are generally assumed to be proportional to the weight of the vehicle (to capture the emissions embodied in steel) and to the size of the battery (in kWh) for all-electrics and hybrids (to account for the procurement of materials and the manufacturing of the batteries). Use emissions are from the consumption of gasoline and diesel, and from the generation of the electricity that charges the batteries of BEVs and PHEVs. The emissions from disposal and recycling are generally negative, since reusing parts and metal eliminates the need for processing virgin materials. We follow the procedure detailed in Buberger et al. (2022) to calculate the lifecycle emissions of vehicles sold in Germany, assuming that each kWh of electricity generated in Germany contains 401 grams of CO_2, that cars are driven 14,000 km/year and that the lifetime of a car is 12 years.

Figure 6 summarizes the lifecycle emissions of new cars available for sale in Germany in 2019 and 2020, showing that all-electrics have the lowest overall lifecycle emissions, followed by plug-in hybrids. Despite greater emissions associated with procuring raw materials for the battery and manufacturing the battery itself, battery vehicles have an overall lower lifetime emissions profile, even in Germany, where, notwithstanding the so-called "Energiewende" (energy transition), a considerable share of electricity generation is done using natural gas and lignite. The figure additionally shows that the share of total emissions accounted for by production is highest for all-electrics, which also boast the lowest use emissions. By contrast, the largest share of the emissions from gasoline and diesel cars comes from driving them.

Figure 6: Lifecycle CO_2 emissions (in kg) by type of car available for sale in the German car market in 2019 and 2020.I. Not sales-weighted.Own calculations based on Buberger et al. (2022)



3 The Policy Context

We are interested in the effect of diesel bans, rebates offered to car buyers upon purchasing an all-electric or plug-in hybrid, and federal subsidies for the construction of publicly accessible charging stations.

3.1 Dieselgate and Diesel Bans

The so-called "Dieselgate" scandal broke out in the US in September 2015, when the US Environmental Protection Agency issued a notice of violation of the Clean Air Act to German automaker Volkswagen (VW) Group. A number of VW vehicles had been found to be equipped with "defeat device" software capable of detecting when the vehicle was subject to the federal emissions tests, and of misreporting the true emissions and fuel economy of the vehicle.

The first consequences of "Dieselgate"—which triggered lawsuits, recalls and government orders over a long period of time—were experienced in Germany around April 2016. Starting in 2017, a number of metropolitan areas in Germany began considering the possibility of banning older diesel vehicles (vintages up to and including euro 5) from accessing the city boundaries and/or circulating inside the city, on the grounds of their contribution to local air pollution problems. There was considerable coverage in the national media in the spring of 2018. However, not all of the discussions resulted into actual proposals, and not all proposed bans were actually adopted.

By the end of our study period, diesel bans were considered or at least mentioned in the media in a total of 39 cities. The bans were adopted in 4 cities (Berlin, Hamburg, Darmstadt, Stuttgart), and were adopted but subsequently repealed in 3 (Mainz, Essen, Gelsenkirchen). We consolidated information on the total population living in areas with considered or actual diesel bans over our study period, displayed in Figure 7. The share of the population affected as of the end of our study period is displayed in Table 1. This table clearly shows that some Bundesländer did not consider or adopt diesel bans. In others, like Hamburg and Berlin, all of the residents are potentially affected, and in the remainder the actual or potential share affected ranged between 2 and 25%.

The decline in the shares of diesel vehicles documented nationwide (see Figure 3 and Figure 4) appears to have occurred at different rates in the various Bundesländer. Figure 8 plots the decline in percentage points from the beginning to the end of the study period (which ranges from 12% to just under 25%) in the different Bundesländer

Figure 7: Population affected by Proposed or Actual Diesel Bans

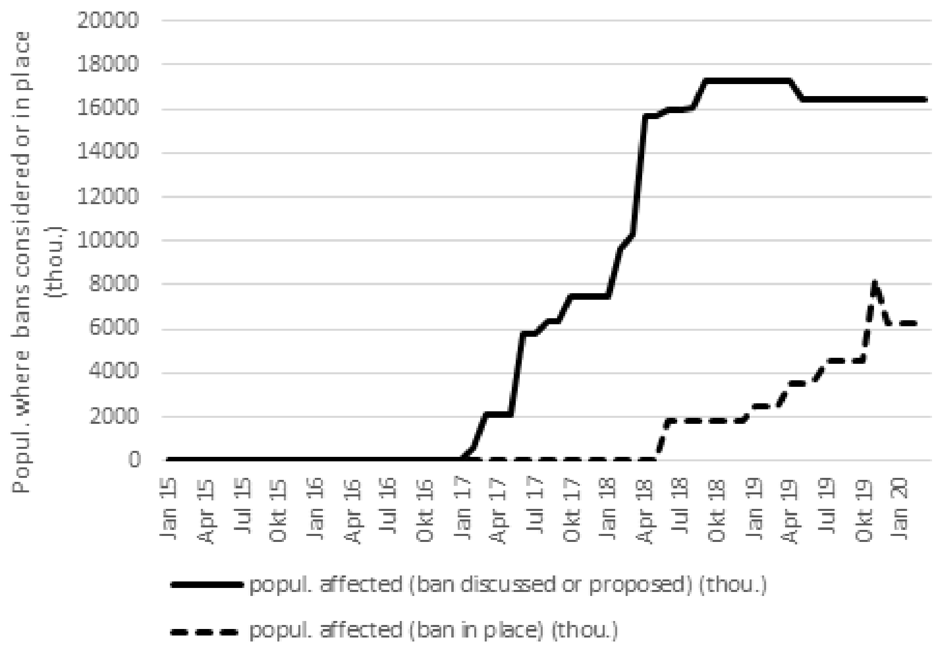
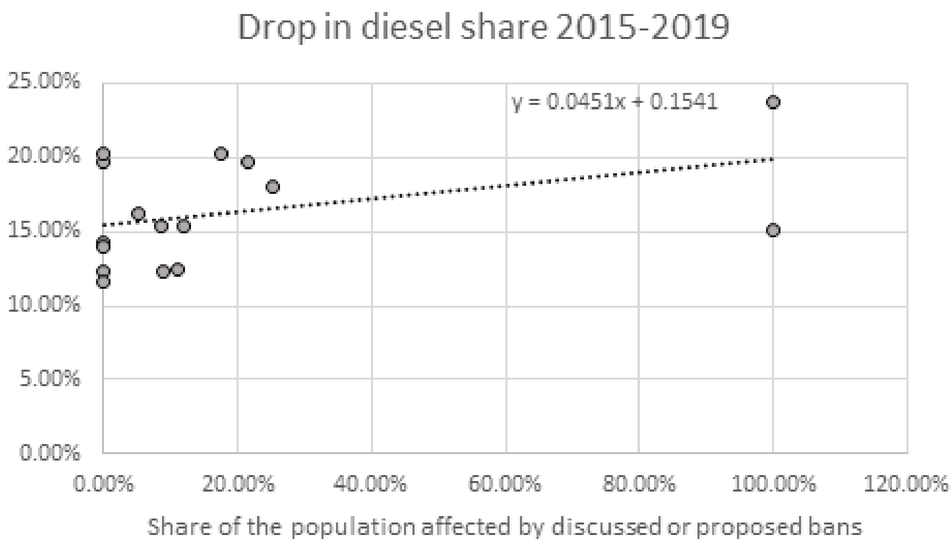


Table 1: Share of the population in each Bundesland that lives in area with proposed diesel bans and actual diesel bans

Bundesland	Share of the population w/ proposed bans	Share of the population w/ bans in place
Baden-Württemberg	12.10%	5.71%
Bayern	17.67%	0%
Berlin	100.00%	100.00%
Brandenburg	0%	0%
Bremen	0%	0%
Hamburg	100%	100%
Hessen	21.51%	2.52%
Mecklenburg-Vorpommern	0%	0%
Niedersachsen	8.83%	0%
Nordrhein-Westfalen	25.38%	0%
Rheinland-Pfalz	5.30%	0%
Saarland	0.00%	0%
Sachsen	0.00%	0%
Sachsen-Anhalt	10.90%	0%
Schleswig-Holstein	8.50%	0%
Thüringen	0.00%	0%

against the share of the Bundesland population affected by proposed or actual diesel bans, showing two key pieces of evidence. First, all Bundesländer experienced a decline in their diesel shares, irrespective of whether diesel bans were under consideration or in place. Second, the extent of the decline appears to be positively associated with the share of the Bundesland population that is or would be affected by the bans. This variation bodes well for the econometric models described in the next section.

Figure 8: Relation between share of diesel car sales and diesel bans



It bears emphasizing that the diesel bans do not cover new diesel vehicles. By the time the diesel bans were being considered, proposed, discussed, adopted or even dis-adopted, manufacturers had long turned to making vehicles that meet the euro 6 standards, and hence are not covered by the bans. However, consumers and companies may have reacted to the signal that diesel is no longer desirable, or to expectations that diesel vehicles—new or otherwise—might be banned completely in the future, phased out of production, and/or become untradable in the used car market.[2]

3.2 Promotion of EVs: Rebates and Infrastructure Subsidies

Starting in July 2016, the German government allocated €1.2 billon to subsidize the purchase of electric vehicles. Rebates of €4000 and €3000 were offered for "pure" battery electric vehicles (BEVs) and plug-in hybrid vehicles (PHEVs), respectively. In

[2]Driving bans are not new to Germany or other European countries. Wolff (2014) examines the role of banning vehicles that do not meet certain emissions requirements from entering cities in Germany in 2005-2008. He finds that the ambient concentrations of particulate matters did decline significantly in the cities that adopted the bans compared to cities with similar baseline pollution levels that chose other control measures. He also finds evidence that the bans may have increased the shares of low-emitting vehicles.

November 2019, these figures were increased by 50% for BEVs and PHEVs priced up to €40,000, and by 25% for BEVs and PHEVs priced between €40,000 and €65,000.[3]

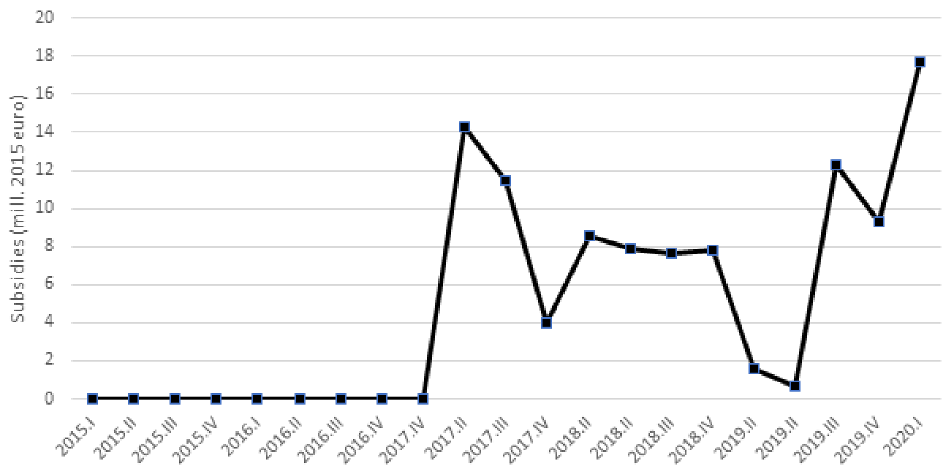
In parallel, the government has promoted the expansion of public charging infrastructure, recognizing that "range anxiety" is a major barrier to EV uptake. Between 2017 and March 2020, about €300 million (2015 euro) was allocated to establish publicly accessible charging stations. The Federal Ministry for Digital Affairs and Transport (BMDV) administers the funding, providing up to a maximum of €20,000 per charging point and a maximum of €100,000 for the grid connection per location.

Figure 9 plots the total federal funding to the establishment of charging stations over our study period. Subsidies were issued starting with the second quarter of 2017 and display considerable variation from one quarter to the next. We aggregate the funding to the Bundesland level, finding considerable variation across Bundesländer in any given period as well. A regression of the Bundesland-level funding in each quarter on a measure of the stock of charging stations available at the time (the density of fast charging stations per 100,000 residents present in the previous quarter) results in an R-square of 0.25, showing that funding and existing infrastructure are correlated, but that there is enough independent variation in the former that can be exploited to identify its effect on new car sales. In sum, we take advantage of the variation over time and across Bundesländer to see how funding affected the composition by fuel type of the new car sales.

As a control variable, in our regressions below we include the stock of public charging infrastructure using data from the German federal Bundesnetzagentur. We measure the charging infrastructure as the number of publicly accessible normal (up to 22 kW) and fast (more than 22 kW) charging points, respectively, available in each Bundesland in each month of our study period. Charging columns (or charging stations, Ladesstationen) can be lined up along street curbs, or placed in shopping malls and the parking lot of supermarkets, or in dedicated facilities. Each charging column can feed from one to at most four cars. Each of these "outlets" in a charging column is a

[3]PHEVs must meet the additional requirement that the range of the electric battery is at least 40 km, or that the emissions rate is less than 50 g CO2/km.

Figure 9: Federal funding awarded to charging infrastructure (mill. 2015 euro)

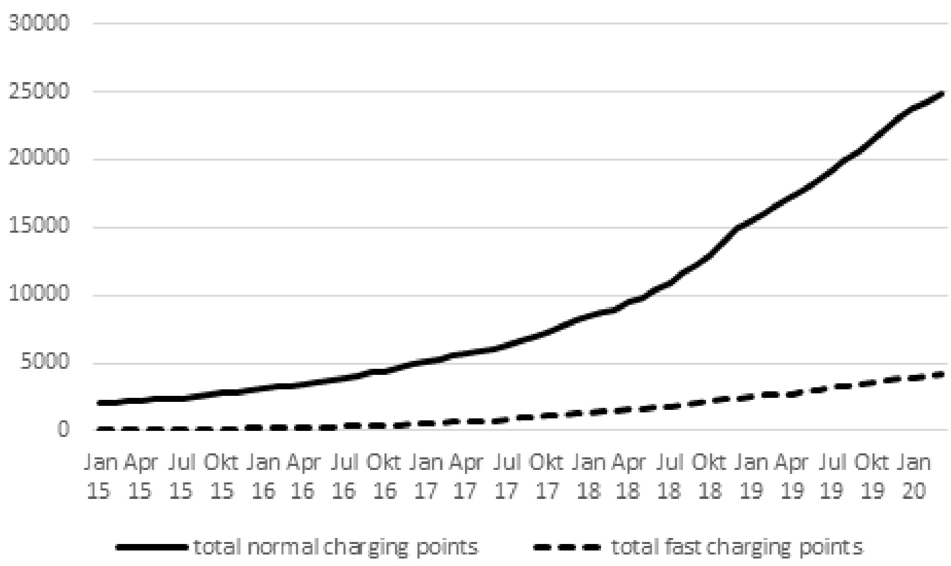


charging point.

The growth in the number of public charging points in Germany is displayed in Figure 10. At the end of 2015 there were 3015 normal and 201 fast publicly accessible charging points. By the of the first quarter of 2020, these figures had grown to 24,866 and 4,159, respectively. The Bundesnetzagentur reports that the density of charging points in Germany, as measured by the number of charging points per plug-in hybrid or electric car, compares well with the recommendations and goals of the European Union (Bundesregierung, 2020). Specifically, as of August 2020, there were some 220,000 electric vehicles circulating in Germany and 21,100 charging points, which means about 0.10 charging points per electric vehicle (or 10.42 electric vehicles per charging point), which corresponds roughly to the European Commission's recommended minimum of one charging point to 10 EVs.

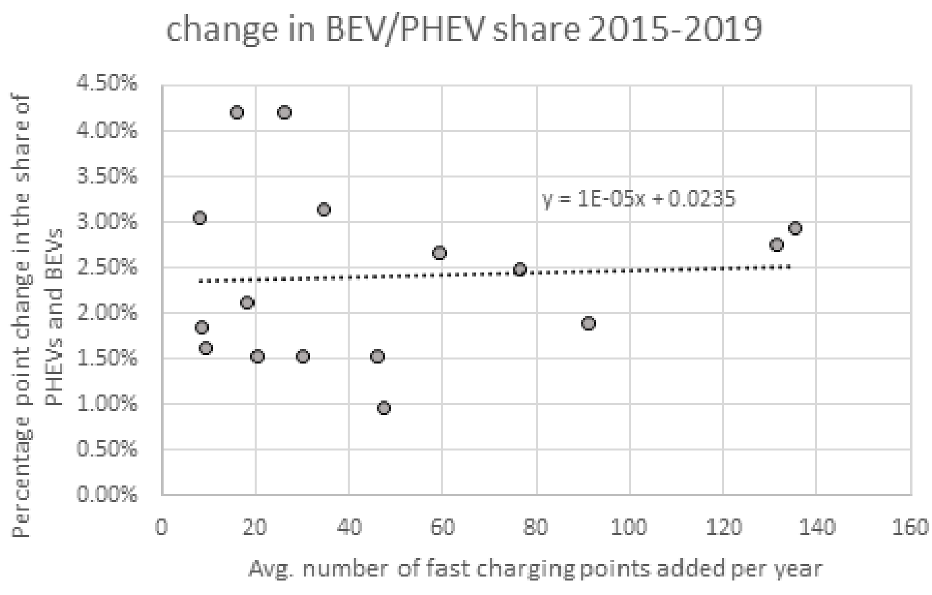
Figure 11 suggests that the growth rate in battery vehicles over our study period is positively correlated with the overall growth in the charging infrastructure. As a final point, we note that while range anxiety and the high prices of the battery vehicles serve as a deterrent to the adoption of battery vehicles, their fuel cost per kilometer is lower than that of conventional cars. During our study period, at an average of €0.047/km, all-electric vehicles are the cheapest to drive, followed by diesel cars (€0.059/km), diesel PHEVs (€0.065/km), gasoline HEVs (€0.068/km), diesel HEVs (€0.0706/km),

Figure 10: Charging infrastructure in Germany



gasoline PHEVs (€0.072/km), and finally gasoline cars (€0.079/km).[4]

Figure 11: Change in the share of battery vehicles and additions to the stock of fast charging points by Bundesland from 2015 to 2019



[4]Between 2015 and the first quarter of 2020, the price of gasoline and diesel fluctuated within a narrow band (no more than €0.30/liter).

4 The Model

In this paper attention is restricted to passenger cars, so we exclude from our analyses light-duty commercial vehicles that were registered as passenger cars. We also exclude cars powered by natural gas, LPG, and hydrogen or fuel cell, which account for less than 0.3% of all sales. We aggregate the sales to the quarter level. All of the independent variables in the econometric model described below are the quarterly averages of the original monthly data.

Following Berry (1994), we start with a random utility model of the representative consumer, which posits that the indirect utility that he or she receives from new vehicle j is

$$V_j = -\alpha * P_j + x_j \beta \tag{1}$$

where P denotes the price of the vehicle, x is a vector of vehicle attributes, α is the marginal utility of money and β the marginal utilities of the attributes of the vehicle. On appending an error term that is i.i.d. type I extreme value distribution, and on allowing for the "out of market good" (namely the possibility of no car purchase, or of purchasing a used car), the probability that the consumer purchases new vehicle k is

$$Pr(k) = exp(w_k \gamma)/[1 + \sum_j exp(w_j \gamma)] \tag{2}$$

where w contains P and x, and γ contains -α and β. Since the sales of vehicle k are equal to the total number of sales multiplied by vehicle k's share (namely, equation 2), it is easy to show that

$$lnSales_k - lnSales_{OOMG} = w_k \gamma \tag{3}$$

Appending an error term and moving the log sales of the out-of-market good, labeled with the subscript OOMG, to the right-hand side renders equation 3 a log-linear regression model. Information about the population and/or a number of fixed effects are often used in practice to capture the "sales" of the "out of market good." In the Berry model, the car attributes are regarded as exogenous but price is endogenous (as automakers can set it so as to influence their market shares), which means that it must be instrumented (Berry et al., 1995).

Our dataset documents the sales of an individual type of vehicle in the Bundesland over time. We fit a model based on (3), with two amendments. First, we remove the price (as our dataset only contains a national manufacturer suggested retail price that does not change for a given vehicle across regions or over time) from the right-hand of equation 3, letting the car attributes capture its effect. Second, we enter policy variables interacted with selected car attributes. This preserves the RUM foundation of the model, and the fact that its empirical counterpart is a conditional logit.

Our estimating equation is thus:

$$lnSales_{ibt} = Z_{ibt}\delta + X_{ibt}\eta + \alpha_{ib} + \tau_{mt} + \lambda_{bt} + \epsilon_{ibt} \tag{4}$$

where i denotes the individual vehicle (here defined as the combination of make-model, version, trim, engine size, horsepower, drivetrain (two- or four-wheel drive), transmission, body type, weight, euro standard), b is the Bundesland, t is quarter and year, and m is the make-model (e.g., Audi A3). Z is a vector of policy variables, interacted with the relevant vehicle attributes, X is a vector of control variables (e.g., the existing charging infrastructure interacted with battery vehicles), and the remainder are fixed effects.

α_{ib} is vehicle-by-Bundesland fixed effect meant to capture the size of each Bundesland's market and taste. For example, the residents of a region may prefer a certain make and model because it suits the local terrain and roads well, or because this make has factories and employs many people in the Bundesland. Wealth, public transportation and other factors may also make some locations more car-ownership oriented than others.

The make-model-by-time fixed effects (τ_{mt}) capture automaker shocks, technological advances and responses to the EU-wide regulations, plus the nationwide popularity of that particular make-model in that quarter and year. The Bundesland-by-time effects (λ_{bt}) account for the entire regional car market in each period. The δ (and τ) coefficients are identified from the variation within the very same car in a Bundesland over time, nationally within a given time period, and across a Bundesland within a given time period.

Many models of car demand include the price of fuel or the fuel cost per km driven, which depends on the price of fuel and the fuel economy of the vehicle. Such variables are generally found to be determinants of market shares—in the US (Klier and Linn, 2015; Busse et al., 2013) as well as in Germany (Alberini and Horvath, 2021). We omit them from equation 4, as they are completely collinear with the car-by-Bundesland fixed effects and the time fixed effects.[5] Similar considerations apply to another source of driver costs capable of shaping car sales, namely the annual circulation tax (Alberini and Horvath, 2021).[6]

We capture the effect of diesel bans by interacting the share of the population living in a Bundesland that would be affected by actual or proposed diesel bans at time t with a dummy denoting whether the vehicle has a diesel engine (or is a diesel hybrid or plug-in hybrid). Equation 4 further includes the log of the rebate that would apply to vehicle i, which is zero if the vehicle is an ICE. The rebate amounts vary across models and over time if i is an all-electric or plug-in hybrid, and effectively changes the purchase price.

We posit that car buyers base their decision to purchase a battery vehicle vis-à-vis an ICE on the grounds of the existing as well expected future charging station network. We measure the existing charging station network in the Bundesland as the density of fast charging points per million residents. To mitigate the possible endogeneity of the

[5]We collected daily gasoline prices from all of the gas stations in Germany from Tankkoenig (URL here), and formed Bundesland-specific monthly averages. There is very little variation across Bundesland in any given month, so the fuel km per cost is completely absorbed into the vehicle-by-Bundesland and the Bundesland-by-time or make-model-by-time fixed effects.

[6]The annual circulation tax depends on the car's engine size, fuel, and CO2 emissions rates. These remain constant for a vehicle over time, unless in September 2018 the emissions rate of a vehicle changed as a result of switching from the NEDC to the WLTP test procedure (Alberini and Horvath, 2021). Again, this means that the effect of the circulation tax would be subsumed into the car fixed effects and the make-model-by-time fixed effects.

charging station network with car sales, we enter in the model the previous quarter's fast charging station density. We further posit that consumers assume that the future growth of the charging station network depends on the federal funding presently allocated to charging station projects in the Bundesland. Both the previous quarter's charging station density and this quarter's federal funding to charging stations are interacted with a dummy denoting that the vehicle is an all-electric or a plug-in hybrid.

We cannot rule out measures in individual municipalities and Bundeslaender that prioritize battery vehicles and support the charging infrastructure. We hope to capture the presence of such programs with Bundesland-by-time fixed effects—with the caveat that such effects may be strongly correlated with other terms included in the regression, such as the diesel bans and the stock of charging infrastructure (although these variables are entered in the model as interactions with a diesel vehicle dummy and a battery vehicle dummy, respectively). We therefore experiment with variations on equation 4 with and without such Bundesland-by-time fixed effects.

We use the estimated coefficients from the regression along with our calculations of lifecycle CO_2 emissions to assess the effect of the policies on car sales, their cost-effectiveness per ton of CO_2 emissions reduced, and their cost effectiveness at inducing the sale of a battery vehicle, holding the total car sales in the Bundesland in each period (S_{bt}) fixed. This means that the sales of vehicle k if policy vector Z is modified to Z' (for example by eliminating the rebates, the diesel bans, or the funding to the charging station network) is:

$$S'_{kbt} = S_{bt} * \frac{exp(\boldsymbol{Z}'_{kbt}\delta + \boldsymbol{X}_{ibt}\boldsymbol{\eta} + \alpha_{kb} + \tau_{mt} + \lambda_{bt})}{\sum_i exp(\boldsymbol{Z}'_{ibt}\delta + \boldsymbol{X}_{ibt}\boldsymbol{\eta} + \alpha_{ib} + \tau_{mt} + \lambda_{bt})} \tag{5}$$

Equation 5 follows from conditioning the analysis to new car sales, and, as based on a conditional logit model, accounts for substitution between different types of vehicles.[7] It also shows that the Bundesland-by-time fixed effects drop out, implying

[7]The share of a specific mode, conditional on a new car purchase (as opposed to the out-of-market good) is $exp(\boldsymbol{Z}'_{kbt}\delta + \boldsymbol{X}_{kbt}\boldsymbol{\eta} + \alpha_{kb} + \tau_{mt} + \lambda_{bt})/(1 + \sum_i exp(\boldsymbol{Z}'_{ibt}\delta + \boldsymbol{X}_{kbt}\boldsymbol{\eta} + \alpha_{kb} + \tau_{mt} + \lambda_{bt}))$, divided by $\sum_i exp(\boldsymbol{Z}'_{ibt}\delta + \boldsymbol{X}_{kbt}\boldsymbol{\eta} + \alpha_{kb} + \tau_{mt} + \lambda_{bt})/(1 + \sum_i exp(\boldsymbol{Z}'_{ibt}\delta + \boldsymbol{X}_{kbt}\boldsymbol{\eta} + \alpha_{kb} + \tau_{mt} + \lambda_{bt}))$, yielding expression (5).

that any differences in the predicted number of car sales across specifications with and without the Bundesland-by-time fixed effects are solely due to differences in the estimates of the δs (and ηs) and the other fixed effects.

In sum, we fit a reduced-form regression motivated by an underlying RUM. To capture unobserved heterogeneity and mitigate endogeneity, the regression includes a rich set of fixed effects that effectively renders it a difference-in-difference-in-difference model, characterized by the three two-way interactions between the two groups a car falls in (make-model and Bundesland) and time. We assume that the policy variables are, conditional on the fixed effects, as good as randomly assigned.[8] Effectively, since our policy simulations hold the total number of cars sold the same, we are examining how the sales would be redistributed across different types of cars.

5 Results

5.1 Regression estimates

Table 2 reports the results from fitting least squares to four alternate specifications of equation 4. Specification (A) assumes that, conditional on the fixed effects, the policy variables adequately capture the existing programs. Bundesland-by-time fixed effects are therefore omitted. Specification (B) is similar, but simplifies the make-model-by-time effects to make-by-time fixed effects. Specification (C) includes the full set of fixed effects; specification (D) likewise includes all of the fixed effects but omits the interaction of the stock of charging stations with a battery vehicle indicator.

The signs of the coefficients are consistent across specifications, and the R squares are 0.70 or more, indicating a good model fit. The sales of diesel cars respond negatively to the intensity of the proposed diesel bans, measured as the share of the Bundesland population that is affected by actual or proposed bans. Model (A) in the first column indicates that a one percentage point increase in the share of the affected pop-

[8]We recognize that these substitution patterns are those prescribed by the conditional logit model: In other words, they impose the independence of irrelevant alternatives.

Table 2: Regression results. Standard errors clustered at the exact variant-Bundesland level

	Specific. (A)	Specific. (B)	Specific. (C)	Specific. (D)
Diesel *X* share of pop. affected by proposed bans	-0.1882*** (-0.0132)	-0.1993*** (-0.0133)	-0.3780*** (-0.0159)	-0.3814*** (-0.0159)
Log rebate	0.0263*** (-0.0047)	0.0438*** (-0.0043)	0.0232*** (-0.0046)	0.0305*** (-0.0045)
Battery *X* funding from federal government	0.0172* (-0.0094)	0.0286** (-0.0095)	0.0226*** (-0.0094)	0.0433*** (-0.0094)
Battery *X* density of fast charging points	Yes	Yes	Yes	No
Exact variant *X* Bundesland	Yes	Yes	Yes	Yes
Bundesland *X* quarter- year	No	No	Yes	Yes
Make-model *X* quarter- year	Yes	No	Yes	Yes
Make *X* quarter-year	No	Yes	No	No
R-square	0.7353	0.7056	0.7371	0.7363
Nobs	1,512,637	1,513,037	1,512,637	1,594,541

Note: Robust standard errors are in parentheses. ***, ** and * denote statistical significance at the 1 %, 5 % and 10 % level, respectively.

ulation is associated with an 0.188% decrease in diesel sales. This implies that if 100% of the population in the Bundesland were covered by a diesel ban, there would be a 10% fall in diesel car sales, all else the same.

Likewise, the rebate, the density of fast charging stations and the federal funding issued to charging stations in that quarter have a significant effect on plug-in hybrid and electric car sales. The model predicts that if the rebate on the purchase of battery vehicle had stayed at the level in place before the 50% increase in November 2019, the sales of PHEVs and BEVs would have been 9.5% lower in the fourth quarter of 2019, and 4.16% lower in the first quarter of 2020. The model further predicts that a one-million 2015 euro increase in federal funding to charging stations infrastructure in the Bundesland raises all-electric and plug-in hybrid sales by 1.7%.

While the coefficient estimates are uniformly statistically significant across specifications (A)-(D), their magnitude can vary dramatically. For example, the coefficient on the diesel ban term is twice as large in (C) and (D) as it is in (A) and (B). The coefficient on the electric vehicle rebate increases by over two-thirds from (A) to (B), and that on the federal funding to charging stations doubles when the charging network term is omitted, as is the case in specification (D) compared to (C). Do these large changes in the coefficients imply large differences in the effects on the composition of the car fleet and associated CO_2 emissions that we ascribe to the policies?

5.2 What are the Effect of the Policies?

We use the estimated coefficients from the models in table 2 and the conditional logit model (equations 3 and 4) to predict the number of sales of each type of car if each of the three policies had not been imposed, holding the total car sales in each Bundesland and quarter the same as the actual. We then multiply these figures by the lifecycle emissions factors summarized in Figure 5 to estimate the change in CO_2 emissions.

Table 3 and Table 4, which show predictions from specifications (A) and (B), agree that a decline (by 66-70,000 units, or just under 2%) in the sales of diesel cars can be attributed to the actual or proposed diesel bans. However, over 95% of these missing diesel sales would be replaced by gasoline car sales, and the growth in electric vehicles would be too modest to make a dent on the emissions. The net result is a very small increase of about 0.03% in CO_2 emissions. The story changes when model (D) is used (Table 5), predicting a twice as strong decline in diesel sales. In this case, we see a modest decline in CO_2 emissions, but again the magnitude is very small, about 0.05%.[9]

All models credit the rebate program with an increase in BEV and PHEV sales. Relative to a counterfactual scenario with no rebate and total car sales held fixed, the effect ranges from a 23% (specification (A)) to a 43% (specification (D)) increase in sales, which translates into reductions in lifetime CO_2 emissions from new the cars sold by 719 to 1194 tons. The effectiveness of the rebate program on climate protection is thus very limited, since it accounts for 0.2 - 0.3% of lifetime emissions.

Nevertheless, these absolute reductions compare favorably with those of the fed-

[9]Neither the raw data nor our models indicate that Volkswagen's diesel car sales were penalized by the diesel bans more heavily than those of other manufacturers. Specification (D) in table 2 predicts that between 2017 and the first quarter of 2020, Volkswagen lost 3.31% of its diesel sales, while its competitors lost 3.63% of their diesel sales. See Bachmann et al. (2023) for an analysis of the substitution across German and non-German makes and away from diesel following the Dieselgate scandal in the US.

Table 3: Summary of policy effects based on specification (A) in table 2

		diesel sales	gasoline sales	HEV gasoline sales	HEV diesel diesel	PHEV gasoline sales	PHEV diesel sales	BEV sales	lifetime CO2 emissions
Diesel ban (since 2017.II)	Δ	-66.234	63.343	2929	-2365	1114.13	-293	1505	86
	%Δ	-1.78	0.93	1.11	-2.66	1.04	-2.64	1.07	0.03
Rebate (since 2016.III)	Δ	-17.640	-33.116	-1454	-547.85	21.995	2178	28.585	-819
	%Δ	-0.41	-0.42	-0.5	-0.6266	23.54	23.34	23.92	-0.21
20% more fast chargers	Δ	-5752	-10.621	-551	-267.49	6894	816	9482	-264
	%Δ	-0.09	-0.11	-0.17	-0.303	5.34	6.74	5.96	-0.16
Federal funding (since 2017.I)	Δ	-1542	-2802	-141	-60.92	1936	214	2393	-67
	%Δ	-0.03	-0.03	-0.04	-0.069	1.52	1.8	1.53	-0.01

Table 4: Summary of policy effects based on specification (B) in table 2

		diesel sales	gasoline sales	HEV gasoline sales	HEV diesel diesel	PHEV gasoline sales	PHEV diesel sales	BEV sales	lifetime CO2 emissions
Diesel ban (since 2017.II)	Δ	-70,616	67,622	3043	-2471	1224.00	-318	1515	87
	%Δ	-1.89	1	1.18	-2.81	1.11	-2.79	1.14	0.03
Rebate (since 2016.III)	Δ	-27,200	-50,748	-2175	-809	35,261	3448	42,224	-1195
	%Δ	-0.62	-0.65	-0.76	-0.93	42	41.95	43.02	-0.31
20% more fast chargers	Δ	-6169	-11,298	-576	-270	7673	880	9759	-279
	%Δ	-0.1	-0.11	-0.19	-0.31	5.87	7.24	6.37	-0.06
Federal funding (since 2017.I)	Δ	-2467	-4485	-217	-91	3280	348	3632	-106
	%Δ	-0.074	-0.07	-0.09	-0.11	3.18	3.34	2.87	-0.03

Table 5: Summary of policy effects based on specification (D) in table 2

		diesel sales	gasoline sales	HEV gasoline sales	HEV diesel diesel	PHEV gasoline sales	PHEV diesel sales	BEV sales	lifetime CO2 emissions
Diesel ban (since 2017.II)	Δ	-135,453	129,651	6017	-4884	2242	-599	3027	-173
	%Δ	-3.58	1.92	2.28	-5.27	2.12	-5.25	2.19	-0.05
Rebate (since 2016.III)	Δ	-16,180	-30,264	-1099	-330	20299	1434	26,140	-719
	%Δ	-0.42	-0.44	-0.49	-0.6	27.9	27.64	28.13	-0.22
20% more (since 2017.I)	Δ	-3785	-6878	-342	-145	4776	532	5842	-165
	%Δ	-0.11	-0.11	-0.13	-0.17	4.87	5.32	4.47	-0.05

eral subsidies for charging stations, which reduce emissions by 67 to 265 tons of CO_2 relative to a zero-subsidy scenario. Both the rebate and the subsidies for infrastructure appear to attract sales away from ICEs, the former to a stronger extent than the latter. Sales of diesel and gasoline cars decrease by upwards of 0.44% under the rebate, compared with only 0.11% under the subsidy. The increase in PHEVs and BEVs under the subsidy is at most about 5% (according to specification (D)), and is thus much more modest than the increase attained from the rebate (23%-43%, with specification (D) estimating it to be approximately 27%).

Table 6 suggests a strong degree of heterogeneity across Germany in the effect of the federal funding program, with Baden-Württemberg and Bayern experiencing the strongest percentage growth in battery vehicles. We suspect this result to be due to the interaction between the funding and the better developed existing charging station network, as shown by the policy simulation summarized in column (B) of table 6.

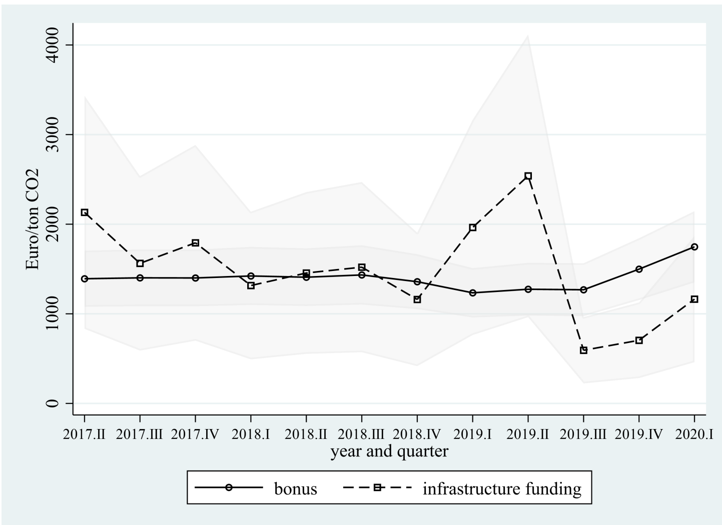
Table 6: Geographical variation in the effect of infrastructure and/or infrastructure funding in 2019: % change effect on sales of BEVs and PHEVs

Bundesland	(A) The federal funding to charging infrastructure (model (D) of table 2)	(B) Increasing charging infrastructure by 20% (model (C) of table 2)
Baden-Württemberg	7.66%	12.61%
Bayern	5.38%	13.70%
Berlin	0.37%	1.69%
Brandenburg	1.77%	2.08%
Bremen	0.16%	0.88%
Hamburg	0.27%	3.99%
Hessen	1.66%	5.46%
Mecklenburg-Vorp	0.10%	1.09%
Niedersachsen	2.48%	10.25%
Nordrhein-Westfalen	2.10%	7.74%
Rheinland-Pfalz	1.65%	6.56%
Saarland	0.48%	0.64%
Sachsen	1.49%	3.63%
Sachsen-Anhalt	0.23%	2.34%
Schleswig-Holstein	0.75%	3.93%
Thüringen	1.15%	3.21%

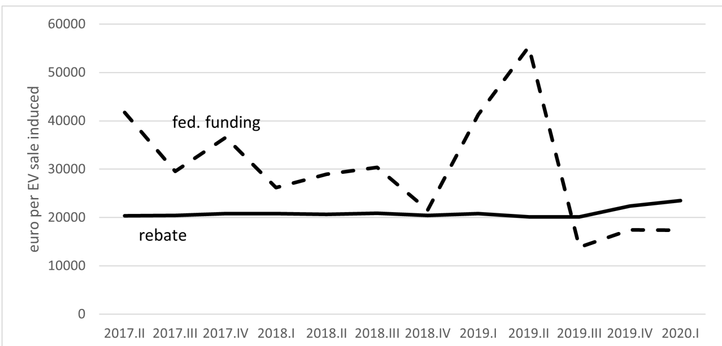
The scope of the programs in terms of electric vehicle sales induced and CO_2 emissions reductions saved is one thing; their cost-effectiveness per electric vehicle sale induced and per ton of CO_2 emissions reduction another. We compute the latter two using the results from specifications (A), (B) and (D), respectively, and display them in Figures 12-14. Attention is restricted to the period from the second quarter of 2017 (2017.II) to the first quarter of 2020 (2020.I), because that is the period when both the rebate policy and the infrastructure subsidies are in place. Standard errors are calculated using a bootstrap with 300 draws.

Figure 12a shows the profiles of the cost per ton of CO_2 reduced by the rebate and infrastructure subsidy from specification (A). The profile for the rebate is relatively flat and stays between €1400 and €1500 for most of 2017.II to 2019.III, rising above €1500/ton only when the rebate was increased by 50% for qualifying battery vehicles at the end of 2019. By contrast, the cost-effectiveness of the infrastructure subsidy bounces up and down following the funding amounts, with the point estimate reaching a high of €2500/ton in 2019.II and a low of €600/ton in the following quarter. The 95% confidence intervals of the two profiles overlap over most of the study period.

Figure 12: Cost-effectiveness of rebate v. federal funding to charging infrastructure. Based on specification (A) in table 2. All figures in 2015 euro. The thin dashed lines represent the 95% confidence interval around the cost (bootstrapped with 300 replications.



((a)) Cost per ton of CO2 reduced



((b)) Cost per EV sale induced

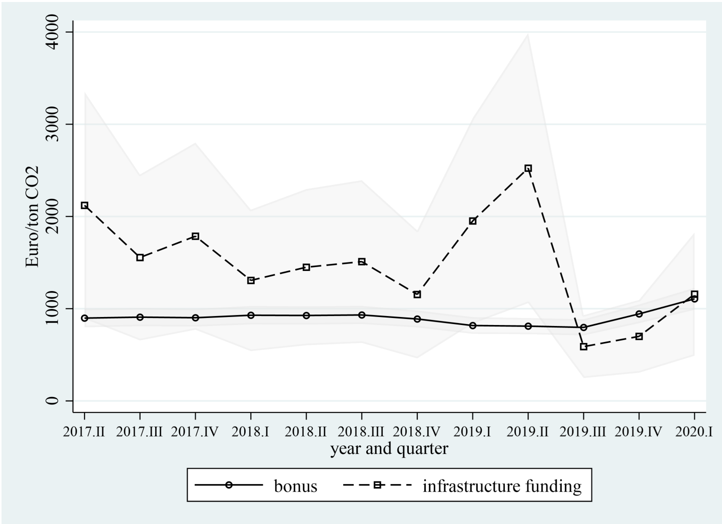
The cost per battery vehicle sale induced in panel (B) follows a similar pattern, and is generally more favorable for the rebate program (€20,000 per vehicle) than for the charging station funding program, where it even exceeds €50,000 per battery vehicle sale induced. When the cost per battery car sale induced by the infrastructure subsidy dips below that of the rebate, it is between €14,000 and €15,000 (2015 euro). We omit the 95% confidence intervals around the cost-effectiveness figures; those for infrastructure funding are exceptionally wide, due to the imprecision with which the coefficient on this variable is estimated in the model.

Figure 13 is based on specification (B) and displays similar patterns, but presents somewhat more favorable cost-effectiveness figures for the rebate, with the cost per ton of CO_2 emissions reduced just under €1000 for much of the policy period. While the confidence interval of this profile is tighter than in specification (A), its overlap with that of the infrastructure subsidy again prevents us from making definitive statements as to which program is more cost-effective. The costs per battery vehicle sale induced are likewise lower than in Figure 12, staying under €15,000 per vehicle for the rebate program and for the most part below €25,000 per vehicle for the federal infrastructure funding program.

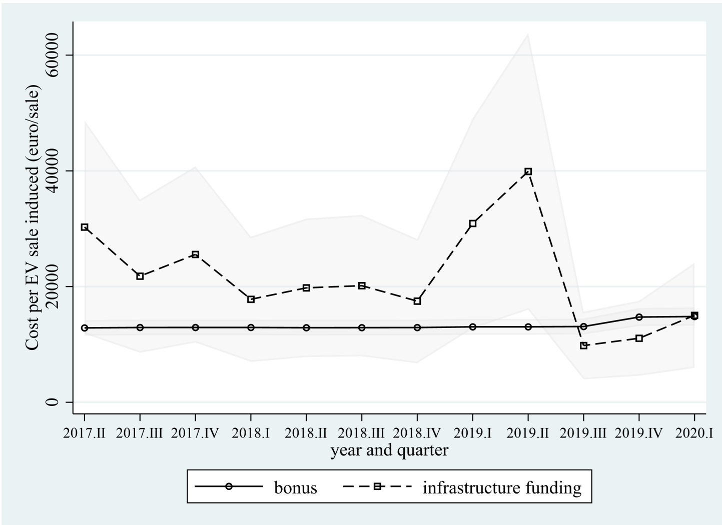
The relative performance of the two programs is reversed in Figure 14, which is based on specification (D) in table 2. The cost per ton of CO_2 reduced by the rebate is again stable at about €1200 until the third quarter of 2019, when it rises to about €1500. Save for the peak in the second quarter of 2019 when funding was exceptionally low, the profile of the infrastructure subsidy is generally just under €1000, dipping below €500 in 2019.III. The cost per battery vehicle sale induced is stable between €17,000 and just over €20,000 for the rebate program, but generally lower than €15,000 and even just under €6000 for the infrastructure subsidy. (All euro figures are in 2015 euro.)

In sum, calculations based on alternate specifications of the econometric model generally result in estimates of the cost per ton of CO_2 reduced and battery vehicle sales induced that are stable over time and similar across specifications for the rebate. Their counterparts for the infrastructure subsidy vary much more widely over the

Figure 13: Cost-effectiveness of rebate v. federal funding to charging infrastructure. Based on specification (B) in table 2. All figures in 2015 euro. The shaded areas represent the 95% confidence interval around the cost (bootstrapped with 300 replications.



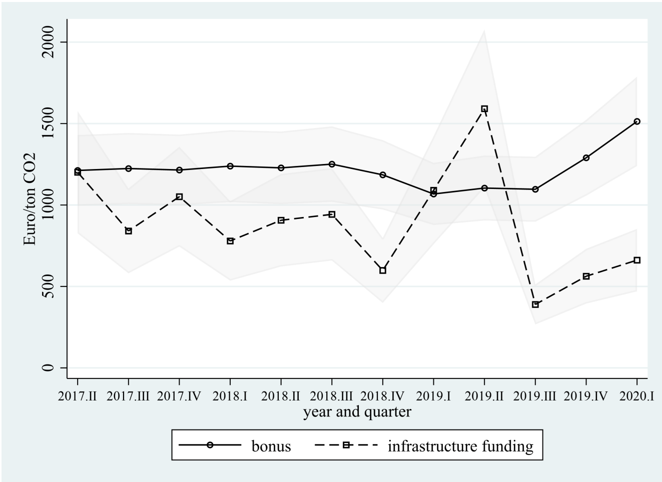
((a)) Cost per ton of CO2 reduced



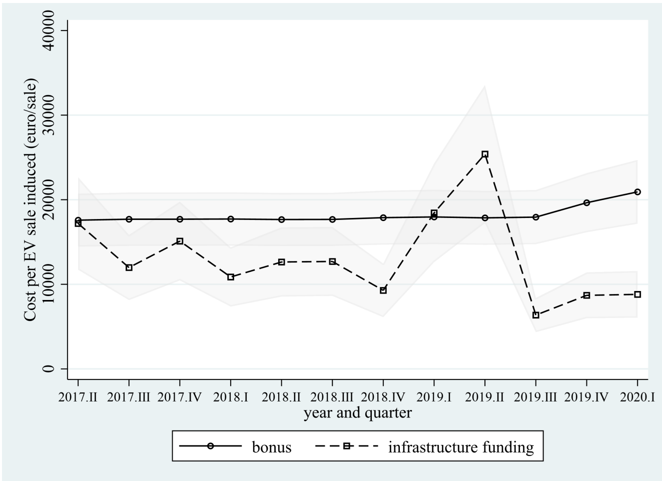
((b)) Cost per EV sale induced

policy period and across specifications. One thing is clear: The cost per ton of CO_2 reduced is high compared to other policies such as the cap-and-trade market established by the European Trading System, which achieved a 41% decrease in emissions in the sectors covered by the system—notably excluding transportation—at a certificate price that never topped €105 per ton. It is also clear that of the different policies examined in this paper, the rebate is the one that delivers consistently the largest absolute emissions reductions. Those attributable to the infrastructure subsidy are one order of magnitude smaller.

Figure 14: Cost-effectiveness of rebate v. federal funding to charging infrastructure. Based on specification (D) in table 2. All figures in 2015 euro. The shaded areas represent the 95% confidence interval around the cost (bootstrapped with 300 replications.



((a)) Cost per ton of CO2 reduced



((b)) Cost per EV sale induced

6 Conclusion

Using high-resolution data about the sales of new cars in each Bundesland in Germany from January 2014 to March 2020, we have examined the role of proposed and actual diesel driving bans, subsidies for the construction of public charging infrastructure, and consumer rebates for BEVs and PHEVs, in shaping the composition of the new car fleet. We have documented a decline in the share of diesel car sales during our study period. The "missing" diesel cars appear to be replaced mostly by gasoline cars (at least until the beginning of 2018) and only in part by hybrids, plug-in hybrids and all-electrics. The latter have eroded somewhat the share of gasoline cars since 2018, but their numbers are still too small during our study period to result in meaningful reductions in the annual CO_2 emissions from new cars.

Importantly, our data show that during our study period, "transition technologies" like conventional hybrids accounted for equal or even larger shares than the highly touted PHEVs and BEVs, suggesting that they should not be neglected, at least in the short- to medium-run, by governments seeking to de-carbonize the fleet. Both the data and the results from our econometric models suggest that expectations about future restrictions on certain types of vehicles, or perceptions that a technology is no longer desirable, may shape car sales and the fleet.

In this regard, the models show that new car sales do respond to local diesel driving bans and charging infrastructure, as well as to nationwide programs, namely the incentives offered to battery vehicles and federal funding to charging station projects. We have used the estimated coefficients on these variables, along with estimated life-cycle CO_2 emissions, to conduct policy simulations to assess how these policies have affected new car sales and the per unit cost of emissions reductions. While the effect on the sales of specific types of cars are in some cases substantial, with the rebate increasing sales of BEVs by 43%, the effect on the CO_2 emissions that can be expected each year from driving the new cars is small, usually less than 1%. Correspondingly, the cost of each ton of CO_2 emissions removed is high, generally above €1000 per ton, although whether the cost-effectiveness is better for the rebate or infrastructure subsidy is not possible to discern given the overlap of the confidence intervals.

Table 7 anchors our estimates with the handful of other studies that have investigated the cost-effectiveness of EV promotional measures. Our estimates of the rebate cost per EV sale induced are in the ballpark of, but lower than, those computed by Springel (2021) for earlier years in Norway. One major difference between Springel's figures and ours is that she examines only BEVs, while we lump together BEVs and PHEVs. In addition, contrasting with other studies that allow for the comparison, we cannot unequivocally conclude that infrastructure subsidies are most cost-effective than rebates. While this conclusion holds on average for Model D, it should be kept in mind that the simulated differences yielded by this and the other models are statistically insignificant over most quarters of the data. Last, it is of interest to note that our estimate of the cost per per EV sale, which is on the order of €20,000 (or $21,600), is closely aligned with that of Sheldon et al. (2023) for the US market. By contrast, our estimate of the cost per ton of CO_2 reduced, at roughly €1000, is the highest among the handful of other estimates from the literature.

Table 7: Cost-effectiveness of policies in terms of cost per sale of vehicles induced or reduced CO2 emissions

Author(s)	Location	Year(s)	Rebate: cost per EC sale induced	Infrastr funding: cost per EV sale induced	Rebate: cost per ton CO2 reduced	notes
Chandra et al. (2010)	Canada	1989-2006			$195	HEV, not BEV or PHEV
Li et al., (2017)	US	2011-2013	$5,022	$2,920-$3,452		
Sheldon and Dua (2019)	US	2015	$35,601			$16,000 if targeted at poor people
Springel (2021)	Norway	up to 2015	$25,000	$8,700		BEV only (no PHEV)
Xing et al. (2021)	US	2010-2014	$6,630		$795	
Li et al., (2022)	China	2015-2018	€13,300	€ 3,717		
Sheldon et al., (2023)	US	2017	$20,000		$399	BEV only

In terms of absolute changes, rebates for the purchase of battery vehicles result in greater CO_2 emissions reductions than the actual level of subsidies for charging station projects and changes in the stock of charging infrastructure. Taken together, these findings confirm that it is neither easy nor inexpensive to secure CO_2 emissions reductions in the transportation and passenger car sectors.

In concluding, we note that our models are reduced-form equations with a rich set of fixed effects meant to mitigate possible biases of the estimates due to unaccounted-for confounders, thereby supporting a causal interpretation of the coefficient estimates on the policy variables. That they indicate little in terms of emissions reduction and at unfavorable cost-effectiveness is a finding with important implications for future measures to reduce the transport sector's persistently high carbon footprint.

The EU has recently set on a regulatory path, approving a measure that would require all new cars and vans registered in the EU to be zero-emission as of 2035. Germany, Italy, Poland and the Czech Republic, have, however, recently requested and obtained (on March 28, 2023) an exception to this rule that would allow ICE cars to be produced and sold after 2035, as long as they run exclusively on e-fuels. E-fuels are obtained by extracting carbon dioxide directly from the air and combining them with hydrogen to produce synthetic gasoline or diesel, which are carbon-neutral as long as the energy used in the various stages of the process is renewable. In other words, technological solutions for road transport are being explored as alternatives to the complete electrification of the road fleet.

Germany, meanwhile, has introduced a tax of €25/metric ton of CO_2-equivalent on emissions in the transport and building sectors in 2021, which will transition to an auction system in 2026. Ultimately, the German system could serve as a blueprint for the expansion of cross-sector emissions trading at the EU-level, as envisioned in the EU's Fit-for-55 Program, although at this time this issue remains in flux (Clean Energy Wire, 2023). The Fit-for-55 program, provisionally agreed upon by Member States at the close of 2022, foresees a separate emission trading system in Europe that would cover the building and road transport sector. The current policy framework thus includes both regulatory and price-based measures at the European level, calling into question the value added of national measures that subsidize the transition to zero-emission cars. Not only are such measures potentially costly, as demonstrated in our analysis of rebates and infrastructure funding, but they may also be rendered redundant by the existence of a European-wide cap on transport emissions coupled with the regulatory requirement of zero-emissions vehicles planned for 2035.

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