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Wolfgang Habla, Vera Huwe and Martin Kesternich

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Coordination: Bernd Hayo • Philipps-University Marburg
School of Business and Economics • Universitätsstraße 24, D-35032 Marburg
Tel: +49-6421-2823091, Fax: +49-6421-2823088, e-mail: hayo@wiwi.uni-marburg.de

BEYOND MONETARY BARRIERS TO ELECTRIC VEHICLE ADOPTION: EVIDENCE FROM OBSERVED USAGE OF PRIVATE AND SHARED CARS[1]

Wolfgang Habla[a], Vera Huwe[a], Martin Kesternich[a,b]

[a] *ZEW – Leibniz Centre for European Economic Research, Mannheim*

[b] *Department of Economics, University of Kassel*

Abstract

We use car-level micro data to provide empirical evidence on the usage of conventional and electric vehicles (EVs) in private and car sharing fleets in Germany. We shed light on both monetary and non-monetary barriers to EV adoption and usage by exploiting the feature that variable costs are identical for shared vehicles but different for private car owners across engine types. While drivers respond to monetary incentives when using conventional cars, this does not hold for EVs. We find that EVs are, on average, driven shorter distances than conventional vehicles, both in terms of annual and single-day mileage, even if costs are identical. We also document that car sharing intensifies the usage of conventional cars but not that of EVs.

Keywords: Electric vehicles, internal combustion engine vehicles, barriers to adoption, cruising range, driving patterns, car sharing, range limitations, range anxiety

JEL Codes: R41, D12, Q50

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1. Introduction

Electric vehicles are considered a key technology for developing future transport systems, particularly due to their ability to reduce local air pollutants, road noise, and carbon emissions (e.g., BMVI, 2019). However, market penetration has not yet taken off. Penetration rates were below 1% of the overall fleet in Germany in 2019. The low adoption rates hint towards remaining challenges on both the producer and the consumer side. For consumers, battery electric vehicles (EVs) differ from vehicles with internal combustion engines (ICEVs) in a number of ways. Apart from slightly different driving characteristics, important differences persist with respect to costs (including purchase, maintenance and running costs) and cruising ranges. While EVs tend to be more expensive with respect to the purchase price than comparable ICEVs (even after deducting the explicit and implicit subsidies granted by many governments), they typically have lower variable costs per km, as electricity usually comes at a lower cost than fossil fuels. Despite recent technological advances, EVs still suffer a disadvantage compared to ICEVs with respect to cruising range due to the lower energy density of batteries compared to fossil fuels. Also, the network of charging stations is currently much less dense than the network of petrol stations. As a result, non-monetary costs, e.g., in terms of trip planning and refueling time, or psychological costs may arise. Furthermore, drivers might suffer from behavioral lock-in effects, cognitive biases or range anxiety. The latter describes the fear that a vehicle has insufficient range to reach the driver's desired destination and thus strands its occupants. It is often presumed that range anxiety constitutes a major barrier to the adoption of EVs, suggesting that EVs and ICEVs may not yet be perceived to provide substitutable services.

In this paper, we focus on the consumer side. We first discuss the monetary incentives for using an EV vs. an ICEV based on the underlying cost structures for two different types of ownership, namely privately owned and shared cars. We also examine potential non-monetary costs related to EV usage. We then confront the resulting predictions with car-level micro data from Germany. To investigate both ownership types, we bring together car-level micro data on privately owned vehicles from the most recent German national travel survey (Mobilität in Deutschland 2017) as well as booking data from Flinkster, the largest stationary car sharing provider in Germany. Together, the two datasets cover two important pillars of individual mobility demand and convey a very detailed picture of the current state of EV use in one of the largest car markets in the world. We provide empirical evidence on how observed usage differs between EVs and ICEVs both for daily and annual usage for both ownership types. The comparative analysis between privately owned and shared vehicles is important for a variety of reasons. First, EV penetration is already substantially higher in the car sharing fleet than in the private car fleet (in our data: 5.3% in the car sharing fleet vs. 0.002% in the private fleet). Secondly, the monetary incentives users face differ in a substantive manner depending on the ownership type. Specifically, driving costs (per km and hour) for car sharing customers are identical across all engine types (electric vs. conventional) within a certain car segment. The identical cost structure offers a unique opportunity to examine EV usage in a setting where no additional monetary barriers to adoption exist in comparison with ICEV usage. This setting enables us to gain new insights on whether usage differences persist beyond monetary incentives. If so, the remaining difference in usage may result from non-monetary barriers, behavioral lock-in effects or preferences. Among the various non-monetary barriers to EV adoption, range anxiety is considered key. Building on observed single-day mileages, we examine whether range anxiety is justified for the trips taken with ICEVs in our sample. Given different EV cruising range assumptions, we investigate which share of the observed single-day trips (and single-booking trips, respectively) made with an ICEV could be completed with an EV without any adaptation required. We discuss potential selection effects relevant for the interpretation of our results in detail.

Our paper stresses the importance of monetary incentives for conventional vehicle choices. Privately owned diesel cars are driven longer distances (both in terms of annual and single-day mileage) than gasoline-powered cars, which is in line with the lower total costs of ownership of diesel cars, while diesel and gasoline cars are used in a similar way when no cost differences for customers exist as in the car sharing setting. This is plausible as both ICEV types offer an identical service. By contrast, EV usage is not in line with financial incentives. Once the higher investment cost for an EV is paid (and thus sunk), variable costs are lower compared to conventional cars. This provides incentives for using an EV at least as much as an ICEV.[2] Our most important finding is that EVs are, on average, driven less than ICEVs, both in terms of single-day and annual mileage. We observe this pattern both among privately owned and shared vehicles. In particular, the higher fraction of high-mileage cars among ICEVs (particularly among diesel cars) compared to EVs drives this result. Altogether, we observe that EVs are

[2] In case EV usage increases in response to a (comparative) decrease in cost, this is typically referred to as "rebound effect" (e.g., Sorrell and Dimitropoulos, 2008). An alternative or complementary explanation could be moral licensing. Moral licensing refers to the case when an individual has shown a morally desirable behaviour and is then more inclined to perform a behaviour that may be deemed socially undesirable (see Merritt et al., 2010, for a review). In our setting, moral licensing implies that an individual who adopted an EV starts driving longer distances and thus cause additional greenhouse gas emissions because they know that the car is less polluting than an ICEV (for a given number of km).

used less than conventional cars, particularly diesel cars, even when operating costs are identical. In a setting of equal costs, choosing an EV rather than an ICEV is likely to be predominantly driven by non-cost attributes including self-image or environmental concerns or a preference for EV driving characteristics (EVs are, e.g., less loud and accelerate faster than ICEVs). These results suggest that differences in purchase costs may not constitute the main impediment to EV adoption. Instead, non-monetary costs, behavioral lock-in effects like status quo bias or range anxiety seem to be more important.

In addition to the above results on vehicle choices and driving patterns, we document that car sharing intensifies car usage for conventional cars only. Shared EVs reveal substantially lower annual mileage than the conventional shared cars. This is the result of both lower average mileage per booking and lower booking frequency in general.

Finally, the large majority of 82% to 92% of ICEV drivers could cover their single-day mileage requirement with an EV without any adaptation required under very conservative EV driving range assumptions, with even higher numbers for more moderate range assumptions. Range anxiety is thus not justified for the majority of distances traveled on a single day, neither for private nor for shared cars. It should be noted that we do not observe the full set of single-day mileage for the private fleet but only a measure of an average day and may thus not be able to capture individual days with particularly high mobility demand (e.g., holiday trips).

By assessing usage differences between EVs and ICEVs both in the private and in a car sharing fleet, this paper contributes to a small but growing literature on the potential of EVs for substituting ICEVs. Pearre et al. (2011) study the potential market share for limited-range EVs. Using high-resolution data on the use of gasoline vehicles in 13 US states, the authors analyze how many single-day trips could be completed with EVs with and without adaptions to the limited driving range of EVs. The main finding is that a significant (but still low) fraction of transportation needs could be covered with EVs without adaptation. For example, if drivers were willing to make adaptions on only two days per year, a 100-mile (approx. 160 km) range car would satisfy the mobility demand of 17% of all drivers. Greaves et al. (2014) hypothetically assess the extent to which current car travel needs can be met with EVs for a sample of motorists in Sydney, assuming a home-based charging set-up. They find that EVs with a range of as low as 60 km would be able to accommodate well over 90% of day-to-day driving. Combining information from travel surveys with high-resolution GPS data, Needell et al. (2016) estimate the energy requirements of personal vehicle trips across the US. They find that existing, affordable EVs could meet the energy requirements of 87% of vehicle-days.

Analyzing driving patterns in Sweden and Germany based on survey data, Jakobsson et al. (2016) conclude that a range of 230 km is required for half of all vehicles, and thus EVs are better suited to serve as second cars in a household. Based on a simulation model with Swiss and Finnish survey data, Melliger et al. (2018) find that 85-90% of all trips could have already been made with EVs in 2016. Using various policy scenarios, they shed light on which percentage of trips could be covered with improved charging infrastructure and improved battery technology. Davis (2019) uses nationally representative data from the United States to analyze differences in the mileage of EVs and ICEVs. He finds that on average EVs are driven considerably fewer miles per year than gasoline-powered vehicles. The difference is highly statistically significant and holds for both all-electric and plug-in hybrid vehicles, for both single- and multiple-vehicle households, and both inside and outside California. Qualitatively, the author discusses potential selection effects that may drive the results. Langbroek et al. (2019) compare travel patterns of shared EVs and ICEVs in a case study on the island of Gotland in Sweden. They find that people renting an EV are on average closer to EV adoption than people renting an ICEV. Furthermore, people who rent an EV are, at the time of rental, associated with more positive attitudes towards EVs, have more knowledge about EVs, and would feel more secure driving an EV. The driving patterns of EVs do not seem to indicate serious limitations regarding driving distance, parking time, and the destinations visited, as compared to the driving patterns of conventional rental cars. Using data on free-floating car sharing services in 12 European and US cities, Sprei et al. (2019) find that rental time is shorter and the number of rentals per car and day are slightly fewer for EVs compared to ICEVs. We contribute to this literature by investigating vehicle choices, driving patterns, and the intensity of car usage both for privately owned and shared cars based on rich micro data from Germany.

This paper is organized as follows. Section 2 discusses the incentives to choose an EV vs. an ICEV based on monetary and non-monetary costs. Section 3 outlines potential selection effects into EV usage, with important implications for the interpretation of our results. We describe the datasets used in Section 4, while Section 5 presents our empirical analyses. Section 6 concludes.

2. The economics of using EVs vs. ICEVs

In order to guide our empirical analysis, we first outline the monetary incentives for using an EV vs. an ICEV. We discuss monetary incentives based on the underlying cost structures inherent in different engine types as well as potential non-monetary costs related to vehicle choice.

When an individual has bought a certain vehicle, the purchase costs should be (close to) sunk[3] and should, theoretically, not influence the owner's mileage decision (though the choice of vehicle does partly depend on expected mileage). What should matter for the decision how far to drive by car are the variable costs per km (and possibly the price of alternative mode choices). The variable costs are typically lower for EVs than for ICEVs, at least when EVs are charged at home or at the workplace.[4] For instance, Sivak and Schoettle (2018) find cost ratios for annual fuel costs of driving a typical gasoline vehicle vs. driving a typical battery electric vehicle in US states of between 1.364 and 3.602, with an average of 2.304. Even if diesel prices are lower than gasoline prices, we thus expect, based on monetary incentives alone, an EV to be used at least as much as an ICEV. Furthermore, it is conceivable that a car owner has taken into consideration the available recharging opportunities as well as the required mileage before making the purchase decision and only chooses an EV if it is considered adequate given the conditions and constraints she faces. Therefore, limited recharging opportunities or range restrictions should not severely constrain mileage choice. Regarding different fuel types (diesel and gasoline), diesel cars are more fuel-efficient than gasoline cars and, in addition, diesel is more heavily subsidized than gasoline in Germany (which is often referred to as "diesel privilege"). As a result, diesel cars are – beyond a certain mileage – cheaper in terms of the total costs of ownership than gasoline-powered vehicles despite higher purchase prices. Based on monetary incentives, we thus expect that diesel cars are driven longer distances than gasoline-powered vehicles.

In contrast to private ownership, a car sharing user can choose between an EV and an ICEV for each trip, given that both types of cars are available at a particular station at the moment of booking. Moreover, the monetary incentives differ for a car sharing customer compared to a private car owner. While different payment types exist for different car sharing fleets, members of the car sharing service for which we have data do not incur fixed costs. Most notably, variable costs are differentiated by vehicle category but not by fuel and engine type. Within each category, costs only depend on the distance traveled and the duration of the booking (for the price list see Table 5 in the Appendix). As a result, these variable costs are identical for EVs and ICEVs within one vehicle category. Considering monetary incentives only, we expect that EVs, if chosen, are driven similar distances as ICEVs.

[3] In reality, investment costs may not be perfectly sunk as kilometres travelled may affect a car's resale value. Also maintenance costs may be related to mileage.

[4] Charging station providers sometimes charge relatively high prices per kWh or even a lump-sum amount, irrespective of how much electricity is actually consumed.

It is important to note that, in addition to monetary costs, the decision to buy or book an EV vs. an ICEV may be influenced by so-called non-monetary costs, in particular psychological or time costs, as well as preferences. Some users might prefer an EV over an ICEV because of its driving features (fast and steady acceleration, low noise levels), its environmental features (no local pollution emissions, possibly lower carbon footprint beyond a certain mileage), or because an EV is associated with a certain self-image and status in terms of being environmentalist or tech-savvy. In line with behavioral lock-in tendencies, other users might prefer more "convenient" or familiar engines and thus ICEVs. They might also incur psychological costs of switching from the conventional to the electric vehicle technology. In addition, psychological or time costs may arise from finding a charging station if none is conveniently located close to home or the workplace (in case of private owners) or in the vicinity of the car sharing station. Finally, individuals might suffer from a status quo bias or (justified or unjustified) range anxiety, particularly when they have never experienced driving an EV before. The latter type of range anxiety could be due to a lack of information on typical cruising ranges. Overall, we expect that EVs are more likely to be chosen for shorter trips than for longer ones if range anxiety is a common concern among users. This example illustrates that the effects of non-monetary costs or other influences, such as range anxiety, may interfere with monetary incentives.

3. Selection Issues

In addition to unobservable non-monetary costs and preferences for a particular engine type, a variety of selection mechanisms may be at work for an individual's decision to choose one type of car over the other. Selection into EV ownership or usage is relevant for the interpretation of our results if it occurs based on characteristics that are directly related to mobility demand. This holds, for instance, if individuals who self-select into EV ownership or usage reveal a different mobility demand than ICEV users per se.[5] As this paper follows a descriptive approach, we cannot fully explore the potential channels on self-selection issues directly. Nevertheless, as selection may confound the comparison of usage patterns, we discuss potential selection issues upfront in detail. In the analysis, we differentiate the sample according to a variety of criteria prone for selection whenever possible.

[5] We cannot account for potential rebound effects.

For private households, there is clearly a non-random selection into (i) car ownership in general, and (ii) EV ownership among car owners. The previous literature has not yet provided conclusive causal evidence on the drivers of EV adoption. For Germany, Plötz et al. (2014) provide suggestive evidence for a relationship between intention to adopt an EV and gender, family size, full-time employment as well as regional type. Besides sociodemographic characteristics, they also identify pro-environmental attitudes and openness to technology as related to the intention to adopt. As an intention-behavior-gap has been well documented (e.g. Sheeran, 2002), intention to adopt may only serve as an indicator of actual adoption. Several of the characteristics identified in the literature are also likely to reveal a direct relation with general mobility demand. For instance, households with strong pro-environmental attitudes may also have lower mobility demand than the overall population.

For car sharing, there is selection into car sharing membership in the first place. We distinguish between two user groups: First, there may be individuals signing up for car sharing who need to move around individually but do not have access to a car, for instance because they travel in a city other than their home town. These individuals are likely to be one-time (or infrequent) users. Secondly, an individual may decide to buy a permanent membership and use car sharing repeatedly, possibly in order to get access to a car without owning a car herself (or owning one car less). Both groups may differ in their mobility demands from the overall population of private car users. Furthermore, as outlined in Section 2, selection into EV usage among car sharing users may be based on preferences for a certain engine type, availability of EVs/ICEVs at the station, and trip characteristics, especially required mileage. Lastly, the availability of EVs or ICEVs at a particular station may be the result of strategic considerations made by the car sharing provider, which could have an impact on the observed usage of different engine types. EVs are likely to be placed in regions in which they are also expected to be used. In particular, the car sharing provider might offer EVs at stations where the average distances traveled during one booking are lower than at other stations or where the population is more likely to make use of EVs. We discuss the impact of these potential sources of selection issues on our empirical findings in Section 5.

4. Data

In the empirical part of this paper, we use car-level micro data from Germany from two different data sources. The data reflect two ownership types, namely privately owned vehicles and vehicles owned by a stationary car sharing provider. Private car data is self-reported while car sharing data is retrieved from booking data. We uniquely identify each car as either electric or conventional. Measures of both single-day and annual mileage are reported or can be calculated based on the available data. In the following, we describe the two datasets in detail.

4.1. Privately owned cars

For privately owned vehicles, we use micro data from the most recent German national travel survey, *Mobilität in Deutschland 2017* (MiD), published by the German Federal Ministry for Transport and Digital Infrastructure (BMVI). The MiD is a large-scale household survey with detailed information on mobility patterns, household characteristics, and vehicles owned.[6] Households report engine and fuel type (gasoline, diesel, gas, electric, hybrid) and annual vehicle mileage for up to three vehicles.[7] We restrict the analysis to gasoline- and diesel-powered conventional cars and battery electric vehicles.[8] The distribution of EVs and ICEVs across households that own at least one car is presented in Table 1.[9] The majority of these households (65.0%) owns one car, mostly an ICEV. Among the EV households, the majority also owns one or more ICEVs.

For the analysis of annual vehicle mileage, we use the data at the car level. We use all vehicles for which engine type and annual vehicle kilometers traveled (VKT) is reported.[10] In total, we observe 204,920 cars owned by 134,053 households with one of the three selected engine or fuel types and annual vehicle kilometers traveled (VKT) reported. 408 vehicles are EVs, which amounts to 0.002% of the observed fleet. The low share of EVs in the sample (0.002%) is slightly below the overall market penetration rate of EVs in Germany in 2019. In order to capture single-day mobility patterns in the MiD, each household is assigned to a record date based on statistical sampling methods. Record dates cover all dates between June 13, 2016, and September 12, 2017, and include both weekdays and weekends. For a subsample of vehicles, record-day mileage is available at the car level. Record-day mileage aggregates the distances

[6] Households are recruited based on the national register of residents as well as landline and mobile phone numbers.
[7] If households own more than three cars, they are only required to report the data for three of their cars, i.e., we do not observe the universe of cars owned by the sample households.
[8] We exclude all gas cars for comparability and all hybrids, as they are not classifiable as either conventional hybrids or plug-in hybrids (PHEVs). We also exclude cars with missing information on engine type.
[9] We exclude all households who own at least one gas-powered or hybrid car or do not report the engine type.
[10] We also use electric, gasoline- or diesel-powered cars of those households which are excluded in Table 1 (due to one (or more) cars with gas or hybrid engine or with no engine type reported in the household's car portfolio).

traveled across all trips taken with the car on the record date.[11] We observe single-day mileage for 6,740 vehicles (distributed across 5,282 households), thereof 16 EVs, 4,282 gasoline-powered cars, and 2,442 diesel cars. Due to the large sample size, reported record-day mileage can be used as a measure of single-day mileage for an average day.

# of EVs # of ICEVs	0	1	2	3+	Sum
0	-	55	8	1	**55**
1	74,365	206	9	0	**74,580**
2	48,006	107	0	0	**48,113**
3+	12,962	0	0	0	**12,962**
Sum	**135,333**	**368**	**17**	**1**	**134,780**

Table 1: Numbers of households with different combinations of ICEVs (gasoline and diesel combined) and EVs (source: MiD 2017)

4.2. Vehicles in car sharing fleet

For shared vehicles, we use booking data from Flinkster, the largest stationary car sharing provider in Germany. The data covers the period from January 01, 2014, to December 31, 2016.[12] Customers and vehicles are uniquely identifiable. [13] For each car, its engine type and the vehicle model are reported. For ICEVs, we can further distinguish between fuel types (diesel and gasoline). We observe 1,727 distinct vehicles, thereof 91 EVs (5.3% of the observed fleet).[14] However, fleet size and composition change over time. We also classify vehicles into three car segments based on model type. All segments include EVs, yet the larger segments offer very limited numbers.[15] At the booking level, we observe the customer, the vehicle booked, start and end time, date, rental station[16], as well as the distance traveled. For annual mileage, we aggregate the distances traveled over all bookings made with a particular vehicle

[11] We exclude cars that have not been used on the record date (0 km) as we are only interested in drivers who actually use their car on the record date as well as cars with missing values for single-day mileage.
[12] Available at https://data.deutschebahn.com/dataset/data-flinkster. Upon request, DB Flinkster indicated that the data covers the universe of bookings made during that period except those made with cars of partner providers, which can also be booked via the DB Flinkster application or booking portal.
[13] We assume here that one customer ID is used by only one individual and not several individuals.
[14] 15 plug-in hybrids (PHEV) are excluded due to lack of comparability with privately owned cars.
[15] Small: Citroen C-Zero (EV) and DS3 (ICEV), Fiat 500 (ICEV), Ford Fiesta and Ka (both ICEVs), Mitsubishi i-MiEV (EV), Opel Corsa (ICEV), Peugeot iOn (EV), Toyota Aygo (ICEV); medium: Nissan Leaf (EV), Ford Focus (ICEV), Mercedes C-Klasse (ICEV), Opel Astra (ICEV), Renault Kangoo (ICEV); large: Ford Transit Custom (ICEV), Mercedes Sprinter and Vito (both ICEVs), Nissan eNV200 (EV), VW T5 (ICEV). Small vehicles: 1,269 ICEVs, 80 EVs; medium vehicles: 368 ICEVs, 9 EVs, large vehicles: 26 ICEVs, 2 EVs.
[16] For stationary car sharing, cars are borrowed and returned at the same rental station.

within one year. Importantly, only 31% of the vehicles are available throughout an entire year.[17] For single-day mileage, we restrict the sample to single-day bookings, i.e., bookings for which the car is borrowed and returned on the same day. At the station level, we group stations according to engine type availability: stations where only EVs are available (EV stations), stations where only ICEVs are available (ICEV stations), and stations with both EVs and ICEVs (mixed stations). Engine type availability at a particular station changes over time for some stations. Importantly, we do not check whether an EV or ICEV was available in the moment of booking but only whether the booking falls into a period when at least one EV or ICEV was available at the station in general.[18] Table 2 summarizes the dataset. In total, we observe 52,467 customers making 479,572 bookings within three years. The number of bookings, customers, EVs and rental stations decreases over time.[19] 31.6 % of all customers are one-time customers.

Year	Bookings	Single-day bookings	Customers	Vehicles	EVs	Stations	Mixed stations	EV stations
2014	182,155	152,285	30,265	1,121	84	75	13	61
2015	161,333	133,876	28,615	922	79	73	11	62
2016	136,084	111,602	26,534	1,006	64	66	10	49

Table 2: Numbers of bookings, customers, vehicles and locations of Flinkster

5. Results

In this section, we analyze both annual and single-day mileage by engine and ownership type. Moreover, we examine which share of ICEVs could complete their single-day mileage with an EV under different cruising range scenarios.

5.1. Annual mileage

Private car fleet. In the private car fleet, there is substantial heterogeneity in annual mileage

[17] Full year availability is inferred from at least one booking made in January and at least one booking made in December of the year in consideration. Note that the subsample of vehicles available throughout an entire year is substantially smaller than the full sample, especially for gasoline-powered cars. We consider the full sample unless noted otherwise.
[18] For each rental station, we assign EV (ICEV) availability to the time period between the first day an EV (ICEV) is booked and the last day an EV (ICEV) is booked at that particular station. At stations where both EVs and ICEVs are offered, the average share of EVs among the provided vehicles is 40%.
[19] As we do not observe bookings made with partner companies, which are also available on the Flinkster booking platform, a decrease in booking frequency only represents a decrease in booking frequency with Flinkster vehicles and not necessarily a decrease in car sharing usage.

both between and within engine types. EVs reveal 8.4% lower average annual mileage than ICEVs, as Figure 1 demonstrates. While the average annual mileage is 13,052 km for EVs, ICEVs are driven 14,243 km. The difference in means is statistically significant at the 1% level (Welch's test, p=0.006). [20] However, the median annual mileage is identical (10,000 km for both EVs and ICEVs). Accordingly, the mileage distribution reveals that the difference in means is driven by a larger share of high-mileage vehicles among the ICEVs than among EVs.

When differentiating ICEVs further by fuel type (Figure 1 right panel), we do not find statistically significant difference in means between EVs and gasoline cars (Welch's p=0.99). Moreover, the distributions of annual mileages are similar, indicating that gasoline cars are indeed used similarly as EVs, which is in strong contrast to what we would expect based on the monetary incentives. By contrast, diesel-powered cars exhibit significantly higher annual mileage than EVs (and thus also than gasoline cars), both in terms of means (Welch's p=0.00) and medians. As EVs typically have lower variable costs than diesel cars, the fact that diesel cars are still the preferred choice for high mileages indicates that other impediments to EV adoption exist for high-mileage demand individuals. Range anxiety is likely to be a major concern if a large share of trips is high-mileage. Among ICEVs, the data confirms that diesel cars are used more intensely than gasoline vehicles, which is in line with behavior based on monetary incentives.

To provide suggestive evidence on potential selection effects, we differentiate our analysis by the number of cars in a household. While an analysis keeping the number of cars fixed clearly cannot fully circumvent potential selection effects (e.g., due to unknown household preferences), we focus on single-car households as the group for which mobility demand can plausibly be assumed to be more similar on average, irrespective of engine type. Comparing EVs and ICEVs for single-vehicle households, we do not observe a statistically significant difference in annual mileage between vehicles of different engine types (Welch's p=0.47). Yet, differences exist in multi-vehicle households (Welch's p=0.00, cf. Figure 9 in the Appendix). In these households, which constitute the majority in our sample (cf. Table 1), EVs seem to be more likely to be used as second (or third) car and are thus driven less than the first car. This finding is in line with, e.g., Jensen and Mabit (2017).

[20] We use Welch's t-test because it is more reliable for testing two samples with unequal variances and/or sample sizes than Student's t-test.

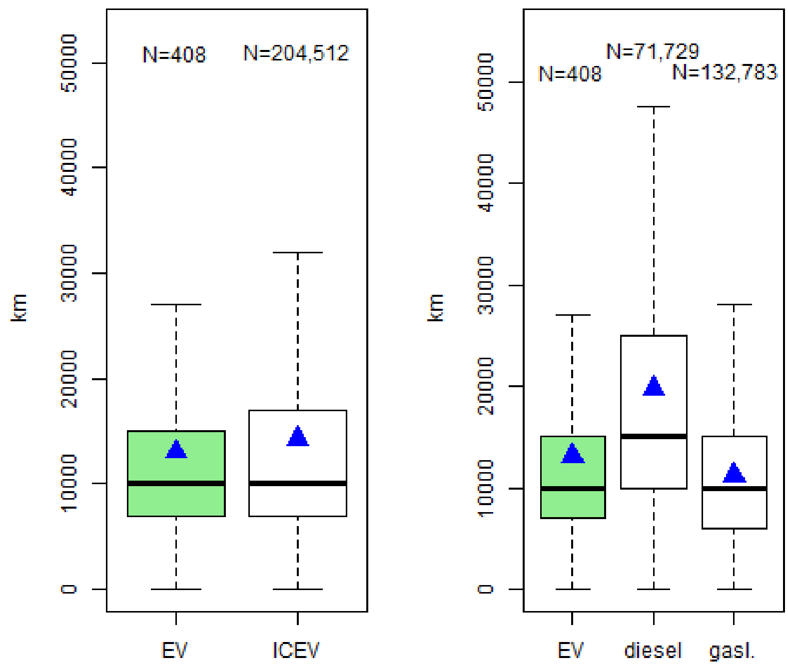

Figure 1: Boxplots of annual mileage for EVs and ICEVs in the MiD, excluding outliers (the triangle indicates the mean, the bold black line the median)

Car sharing fleet. For the car sharing fleet, we also find that EVs are, on average, driven less than ICEVs (Welch's p=0.00; see Figure 2). Average annual EV mileage amounts to a mere 23% of average annual ICEV mileage. The difference is thus substantially more pronounced than for private car ownership and prevails not only with respect to diesel cars but also with respect to gasoline cars (both p=0.00; see Figure 2 right panel).

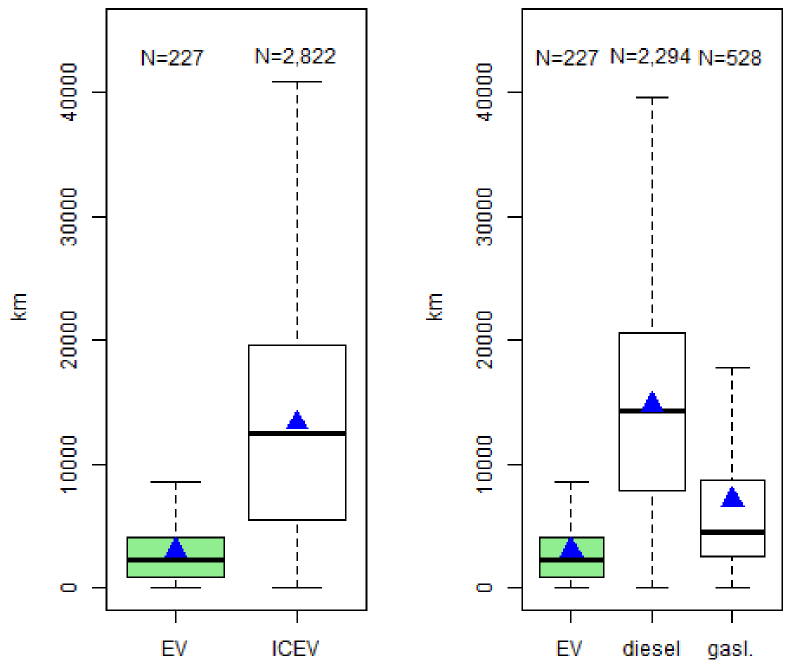

Figure 2: Boxplots for annual mileage of EVs and ICEVs in car sharing fleet, excluding outliers

Lower annual mileage for shared EVs might result both from lower mileage per booking and/or from lower usage intensity as reflected by the booking frequency per car. Both channels are going to be examined in Section 5.2. Thirdly, the difference may partly result from differences in the length of availability of vehicles of different engine and fuel types. Figure 3 plots the distribution of annual mileages for vehicles that have been available throughout an entire year only. For all engine and fuel types, the average annual mileage is substantially higher than before, indicating that the substantial share of vehicles that is not available throughout an entire year drives down the observed travel distances at the annual level. The general pattern is, however, very robust. The difference in means between EVs and ICEVs is even more pronounced for vehicles available throughout an entire year, while diesel and gasoline-cars are used almost identically (in terms of the mean).

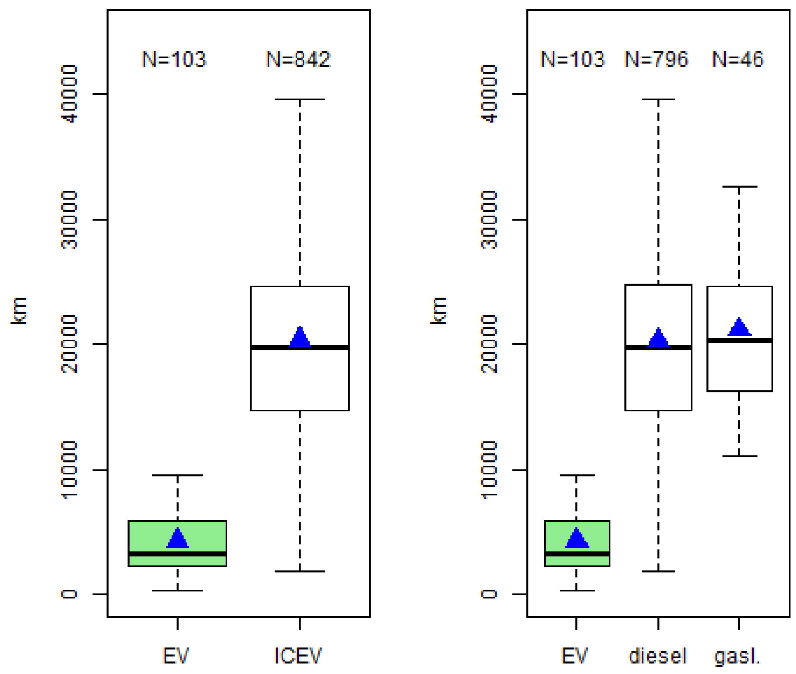

Figure 3: Boxplots for annual mileage of EVs and ICEVs available throughout an entire year in car sharing fleet, excluding outliers

As mentioned earlier, EV or ICEV availability at a station may be strategically chosen by the car sharing provider. Thus, station-specific effects could drive the difference in annual mileage between EVs and ICEVs. We address this concern by only comparing the mileage of EVs and ICEVs at rental stations where both types of cars are hypothetically available on the day of the booking. We find a very similar picture as before (Figure 4), although the difference between EVs and gasoline cars is much smaller now, though still statistically significant (Welch's p=0.06).

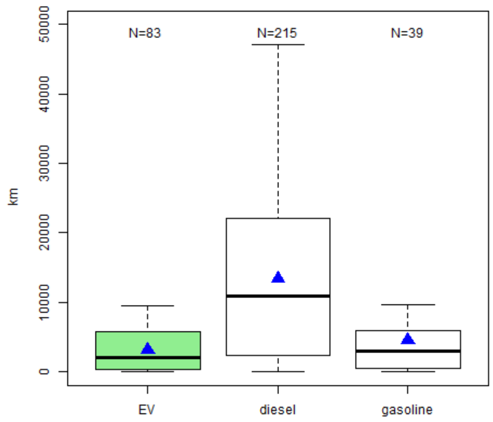

Figure 4: Boxplots for annual mileage of EVs and ICEVs in car sharing fleet at stations where both EVs and ICEVs are available on the day of booking, excluding outliers

We can also compare annual mileage of privately owned and shared vehicles. We restrict the car sharing data to vehicles that were available throughout an entire year (cf. Table 6 in Appendix for summary statistics of the sub-sample). We find that conventional cars reveal substantially higher average mileage when shared compared to private ownership (Welch's $p=0.00$ for gasoline, $p=0.06$ for diesel). By contrast, EVs are driven significantly fewer kilometers per year when shared (Welch's $p=0.00$). These results suggest that car sharing achieves an intensification of car usage only for ICEVs. This observation should, however, be treated with caution as we cannot infer about the large majority of car sharing vehicles which are not available throughout the entire year.

Summarizing our observations on annual driving patterns, we formulate our first result as follows:

Result 1 (annual mileage): *In the aggregate, EVs exhibit lower average annual mileage than ICEVs both in the private and in the car sharing fleet. The difference in means is driven by a higher share of high-mileage cars among ICEVs, particularly among diesel cars. Diesel cars are driven much longer annual distances than EVs, irrespective of ownership type. By contrast, differences between gasoline cars and EVs can only be observed in the car sharing setting. Car sharing intensifies car usage for conventional cars only.*

5.2 Single-day mileage

It is important to not only compare mileage at the annual level but also at the daily level because EV adoption may be hindered if an EV's mileage is insufficient to cover the required mileage at the trip level. As recharging opportunities are expected to be available overnight (e.g., at home or at public charging stations nearby), we focus on single-day mobility demand.

Private car fleet. Among privately owned vehicles, EVs are, on average, driven 45.95 km per day, while ICEVs are driven slightly longer distances (50.13 km, Figure 5). Again, diesel cars show a substantial number of high-mileage trips. We refrain from a more formal statistical test due to the very low number of EVs in the sample (N=16).

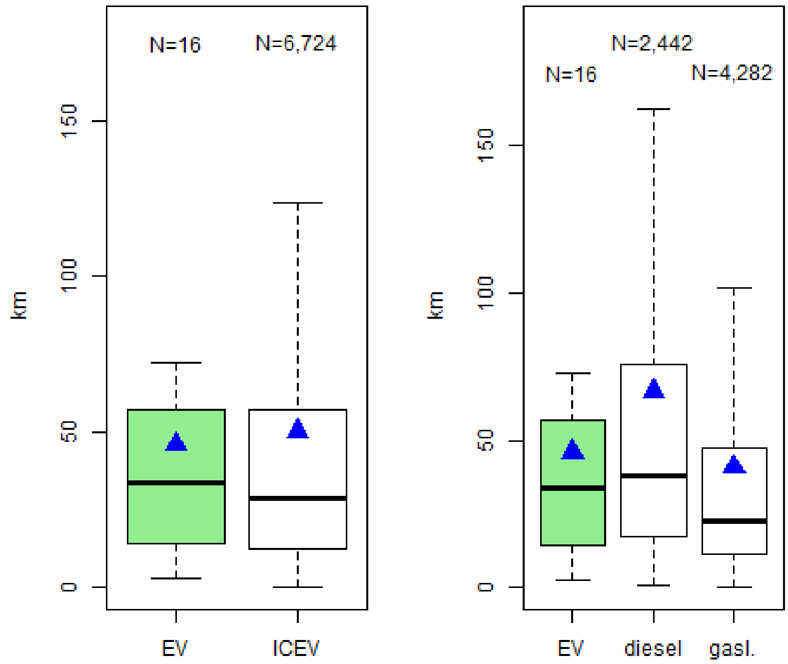

Figure 5: Boxplots for single-day mileage of private EVs and ICEVs, excluding outliers

Car sharing fleet. Despite being offered at equal costs, differences in single-day mileage exist for both ICEV types compared to EV usage (Figure 6 right panel). Again, the difference in means is driven by high-mileage cars, while the medians are more similar across engine and fuel types. Strikingly, the distribution of mileage is more similar for gasoline-powered and diesel cars in the car sharing fleet compared to the private car fleet. This is in line with expectations based on monetary incentives, since diesel cars do not have a cost advantage for the user in this setting.

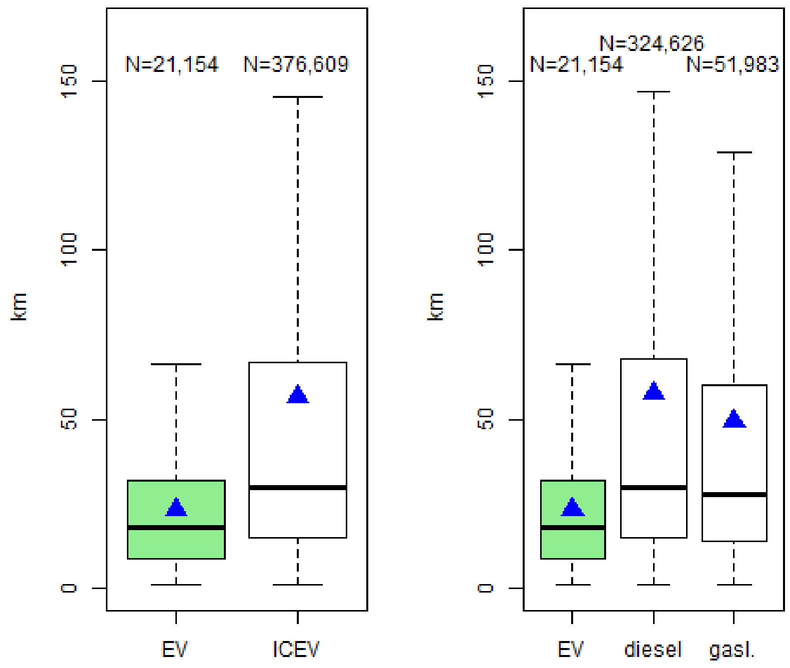

Figure 6: Boxplots for single-day mileage of EVs and ICEVs in car sharing fleet, excluding outliers

In the following, we further differentiate our analysis by user type, station type, and car segment in order to shed light on potential selection effects. We first split the sample accordingly and present the respective distribution of single-day mileage. In a second step, we investigate the relationship between fuel type and single-day mileage econometrically by means of a linear regression while controlling for car segment and both user and station type.

First, one-time customers may differ from frequent users. As before, single-day travel distances are, on average, significantly lower for EVs both among single- and multiple-booking users as compared to ICEVs (both Welch's p=0.00, cf. Figure 7 left panel). This may reflect that individuals select into EV or ICEV choice based on the mileage required for their trip. Importantly, both EVs and ICEVs exhibit higher average distances traveled among one-time customers than among multiple-booking customers (one-time customers ICEVs 78.3 km, EVs 33.2 km, multiple-booking customers ICEVs 55.5 km and EVs 22.6 km). This result supports the conjecture that one-time users may be systematically different from recurring, long-term users.[21] As a further robustness check, we only use the first booking of multiple-booking customers (Figure 7 right panel). The results are quite robust (average mileage for multiple-booking customers now 52.2 km for ICEVs and 23.3 km for EVs) and thus provide suggestive evidence that multiple-booking users do not change their usage behavior in terms of trip distance over time.

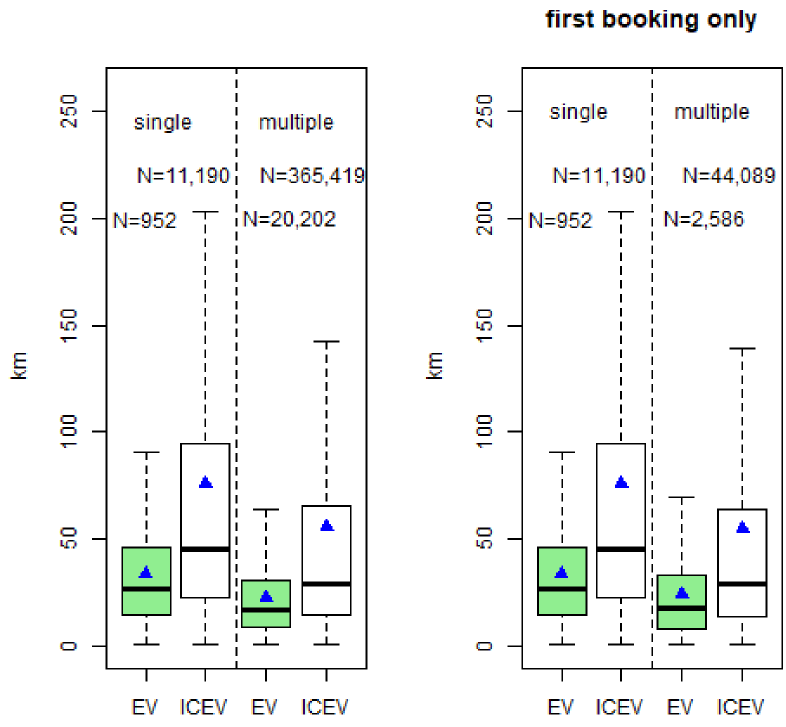

Figure 7: Boxplots for single-day mileage of shared EVs and ICEVs, differentiated by one-time and multiple-booking customers, excluding outliers. Left panel all bookings, right panel first booking only

Next, we compare single-booking distances across station types (cf. Table 7 in the Appendix and Figure 8 for mixed stations only). Again, median mileages are almost identical across engine, fuel, and station types, but EVs reveal lower mean single-day mileage than gasoline and diesel cars. EVs are used for similar single-day distances at EV stations and mixed stations. The same holds true for ICEVs at ICEV stations and mixed stations. Overall, these results

[21] One potential explanation for this could be that many one-time customers book a shared vehicle when there are strikes or bad weather events at Deutsche Bahn (the German railway company) or at local public transit providers in order to get to their final destination, as rental stations of Flinkster (a Deutsche Bahn company) are often close to train stations.

provide little evidence of strategic placement effects of the rental stations by the car sharing provider.

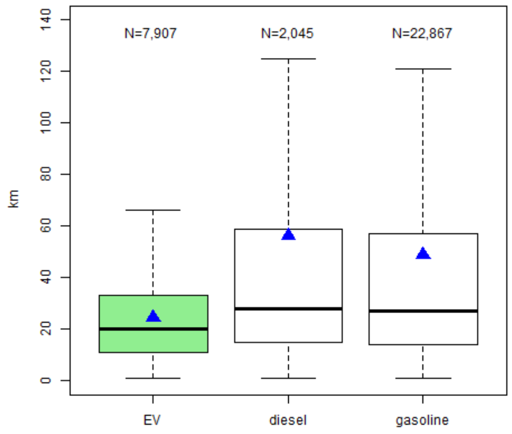

Figure 8: Boxplots for single-day mileage of shared EVs and ICEVs at mixed stations, excluding outliers

Lastly, we differentiate by car segment in order to compare mileages of vehicles of the same or similar size. This is justified on the grounds that vehicles of different segments differ in their variable costs per hour and per km. We find that differences in single-day mileage between EVs and ICEVs prevail within all three vehicle segments (see Figure 10 in the Appendix).

As noted earlier, lower annual mileage of EVs in the car sharing fleet compared to the private fleet can be due to either lower mileage per booking, a lower number of bookings, i.e., a lower usage intensity, or both. For the analysis of booking frequencies, we restrict the sample to cars that were available throughout the entire year. Over all stations and years, EVs are, on average, booked 108 times per year, while ICEVs are booked 261 times. Table 3 summarizes annual booking frequencies at the car level by station type. EV booking frequencies are significantly lower than those of both gasoline and diesel cars (both Welch's $p = 0.00$). In general, gasoline cars reveal the highest average booking frequencies, irrespective of the station type. Interestingly, EVs have a higher booking frequency at mixed stations than at EV stations, while the opposite holds true for ICEVs.

	All stations			EV stations	Mixed stations			ICEV stations	
	EV	Gasoline	Diesel	EV	EV	Gasoline	Diesel	Gasoline	Diesel
Mean	151	360	254	114	131	226	200	350	245
Median	108	341	236	78	109	226	168	336	230
Standard deviation	127	110	117	115	133	177	176	119	117
N	103	46	796	88	42	2	65	46	774

Table 3: Annual booking frequency per car during the whole observation period (cars available all 12 months of a year)

Comparing private and shared cars in terms of single-day mileage, a mixed picture emerges. Privately owned gasoline cars are driven shorter distances than their shared counterparts (Welch's p=0.00). The opposite holds true for diesel cars (Welch's p=0.00).[22]

When controlling for vehicle segment, station and user type simultaneously, we find that single-day mileage is 74% (66%) higher for diesel (gasoline) cars than for EVs (see Table 8 in Appendix). The coefficients are significantly different from zero (both p=0.00) as well as from one another (p=0.00) and are robust across different specifications.[23] This result confirms that diesel cars are driven more than EVs and more than gasoline cars, even when controlling for all available potential confounders.

We summarize our results from this section as follows.

Result 2 (single-day mileage): *For both ownership types, EVs reveal lower single-day mileage on average than ICEVs. Again, a higher share of high-mileage vehicles among ICEVs than among EVs drives the difference. While gasoline cars are driven similarly in the private fleet, they reveal higher mileage in the shared fleet. Diesel cars reveal higher single-day mileage in any case. The results persist when controlling for user type, station type or car segment. Furthermore, EVs are booked less often than ICEVs on average, irrespective of station type.*

[22] We do not formally test for differences between EVs of different ownership type due to the low number of EVs in the private fleet.

[23] With a mean variance inflation factor (vif) of 1.78, multicollinearity does not seem to be major issue in our models.

Overall, the same patterns emerge from Results 1 and 2. When it comes to choosing between different types of ICEVs, car users clearly respond to price incentives. In line with differences in the total cost of ownership, private diesel cars are driven higher annual mileage than gasoline-powered cars. However, the difference decreases substantially once cost differences disappear, i.e., in the car sharing setting.[24] In terms of single-day mileage, diesel and gasoline-powered cars are used even more similarly in the car sharing fleet.

By contrast, observed EV usage patterns are not in line with the predictions based on monetary incentives**.** EVs reveal lower annual and single-day mileage both in the private and shared fleet. While the higher purchase costs may detain private households from EV adoption, substantially lower travel distances of EVs are also observed in the car sharing setting for which costs are identical. Our results suggest that higher purchase costs do not constitute the sole impediment to EV penetration. Shared EVs reveal lower annual mileage not only because they are booked less frequently, but they are also driven lower distances (both compared to shared ICEVs as well as compared to privately owned EVs). An identical cost structure obviously does not suffice to encourage customers to switch from ICEVs to EVs. Two different channels may explain this finding. First, important non-monetary costs might matter for engine type choice in a way that possibly counteracts cost incentives. One can only speculate whether information asymmetries (e.g. unjustified range anxiety), switching or learning costs or status quo bias may lead customers to continue choosing ICEVs rather than EVs. Furthermore, environmental concerns obviously do not push car sharing customers towards using EVs, despite equal costs. Secondly, the results may reflect selection effects, i.e., EVs may be chosen by individuals who reveal lower mobility demand per se. We cannot disentangle the two possible explanations by means of our descriptive analysis.

5.3. Theoretical substitution possibilities between EVs and ICEVs

In this section, we examine whether the difference in usage patterns between EVs and ICEVs could be due to justified range anxiety. In particular, we analyze for which share of ICEVs the observed single-day distance falls within the typical range of an EV. In the analysis, we consider three different range scenarios: i) a conservative scenario with a range of 93 km to cover small and older EVs[25], ii) a range scenario of 330 km that reflects the average range of all EVs sold

[24] However, note that this result does not take into account whether the vehicle has been available throughout the entire year. The share of vehicles available for an entire year differs between gasoline and diesel cars.
[25] Available at: https://www.automobilemag.com/news/electric-vehicle-range-ev-cars-mileage-best-worst/, last accessed on 27/07/2019.

in Germany in 2018[26] under optimal conditions, and iii) an intermediate range of 220 km to account for the case of imperfect weather and adverse operating conditions (cold weather, etc.).[27]

Furthermore, we make two assumptions regarding EV charging opportunities and travel demand, both of which are explicitly conservative to cover the complete set of potential cases of (theoretically possible) EV substitution. First, following Pearre et al. (2011), we assume that EVs are charged once a day, typically at home or at the workplace for privately owned vehicles and at the car sharing station for shared vehicles. We assume that the battery is fully charged before the first trip of the day and that no recharging is being done during the day. This is a conservative assumption that allows us to cover the most extreme case when the car cannot be charged during the course of a day.[28] Second, by using observed single-day travel distances completed with ICEVs, we implicitly assume that drivers do not change their travel demand when switching to an EV. This is again a conservative assumption as adjustments of travel behavior are conceivable when switching to an EV. Such adjustments include, e.g., trip planning (adjustment of travel distance to battery capacity or available charging opportunities), time budget (budgeting of more time during the trip for re-charging), or the choice of the means of transport (switching to trains for longer distances).[29]

Private car fleet. Building on the cumulative distribution function (cf. Figure 11: left panel in Appendix), 82%-92% of all single-day trips made by privately owned ICEVs could be completed with an EV in the most conservative range scenario, depending on the fuel type (Table 4). Given average EV cruising ranges in 2018, range restrictions would not be binding for 97-99% of all ICEV single-day trips under optimal conditions and only negligibly fewer (95%-98%) under suboptimal conditions. Obviously, this share would be even higher for vehicles at the technological frontier. The magnitude of our results is well in line with what the previous literature has established. The average range scenario under optimal conditions is on the upper edge of previous estimates.

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[26] Cf. Horvath & Partners (2019).
[27] We choose 220 km as approximately equidistant from the conservative and the average scenario. This assumption reflects a rather strong impairment of EV range due to weather conditions etc.
[28] However, in reality, car sharing users are provided with cards to recharge their vehicle throughout the trip.
[29] As mentioned earlier, it would also be possible that privately owned EVs are driven longer distances because the lower variable costs per km make it attractive to make additional trips or substitute away from other means of transport.

	Conservative (93 km)	Intermediate (220 km)	Average 2018 (330 km)
Gasoline (privately owned)	92%	98%	99%
Diesel (privately owned)	82%	95%	97%
Gasoline (shared)	86%	98%	99%
Diesel (shared)	83%	96%	99%

Table 4: Percentage of single-day trips made with ICEVs that are below the assumed EV ranges

Car sharing fleet. With respect to shared vehicles, we find that 83%-86% of all single-day ICEV trips could be completed with an EV under the conservative range assumption, depending on the fuel type considered (Table 4, Figure 11: right panel in Appendix). In the case of an EV with 2018 average range and good weather conditions, this share rises to 99%. Again, the loss under suboptimal conditions is negligible. The results are thus almost the same for privately owned and shared vehicles.

We summarize the results of this section as follows.

Result 3 (substitution potential): *The large majority of single-day ICEV trips could be made with an EV without any trip adjustment, irrespective of the cruising range scenario. This result holds both for privately owned and shared vehicles.*

Our analysis provides evidence that cruising range limitations – even though being still perceived as a major obstacle towards the adoption of EV both in private and shared car fleets – affect only a minority of single-day trips. We conclude that either unjustified range anxiety persists for single-day mileage or that few days with higher-than-average mileage requirements, which are not captured by our measure of single-day mileage requirement, impedes EV adoption. This consideration seems most relevant for one-vehicle households who cannot easily switch to an ICEV.

6. Conclusion

In this paper, we document differences in usage patterns between conventional and electric cars for both privately held as well as shared vehicles in Germany. Comparing usage patterns between these ownership types offers the unique opportunity to gain insights into the relative importance of monetary and non-monetary barriers to EV usage. If monetary incentives are identical for different engine types (as is the case for car sharing), differences in usage patterns can be ascribed to non-monetary costs, behavioral lock-in effects, preferences for different engine types, or may additionally or alternatively reflect self-selection.

We find that car users seem to respond to monetary incentives when choosing among conventional cars. Diesel cars are used for longer distances than gasoline cars in the private fleet, which is plausible given that both types of cars have very similar driving features but differ with respect to costs. Differences in usage between these two types of cars disappear for shared vehicles. By contrast, EV usage is clearly not in line with monetary incentives. Our analyses reveal that EVs exhibit lower average distances traveled than conventional cars both at the annual level as well as on a single day, in both fleets. This result stands in contrast to previous findings by, e.g., Davis (2019) and provides evidence that relevant non-monetary barriers exist with respect to EV adoption and usage. Such barriers include psychological and time costs, which may be, among others, related to the lower density of the charging network. Additionally, behavioral lock-in effects may exist. Focusing on range anxiety as one potential barrier, we find that most single-day mobility demands currently satisfied with ICEVs could be met easily with an EV, even under very conservative range assumptions. As a result, range anxiety is not justified for the majority of single-day trips. In light of these results, policy-makers, car manufacturers, and car sharing providers who want to encourage EV adoption may address unjustified range anxiety by providing more information on real-world cruising ranges or by offering opportunities to gain first-hand experience with EVs.

As our measure of single-day mileage for private cars reflects a randomly chosen record day, one may argue that it may not sufficiently capture heterogeneity in mobility demand throughout the year. Many individuals may experience some high-mobility demand days per year on selected days, e.g., when they use their car to go on vacation. It is conceivable that very few high-mobility demand days per year are perceived as a strong barrier to adopting an EV. Among private households, the concern is particularly relevant for one-vehicle households which cannot switch to an ICEV. To circumvent this problem, car manufactures could try to make ICEV rentals over longer time periods (e.g., during a vacation of one or two weeks) or access to long-distance rail transport easily and cheaply available to EV owners, possibly in form of a voucher. Such short-term rentals could also offer an interesting market for car rental companies.

Of course, the increased dispersion of EV charging station availability also helps to resolve the problem. Among car sharing users, individual days with particularly high mobility demand should not pose a problem for EV adoption as a car sharing membership allows users to flexibly choose between different engine types for every single trip (although rentals over a couple of days might become very expensive).

Despite higher market penetration of EVs in the car sharing fleet than in the private fleet, we also found that EVs are utilized less compared to ICEVs. Shared EVs are not only driven fewer kilometers per trip, but they are also booked less frequently than ICEVs throughout the year. This finding implies that there is potential to increase EV usage in the car sharing fleet by financially incentivizing users or motivating them in other ways to switch from ICEVs to EVs.

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Appendix

Car segments	*Example cars*	*Hourly price 10pm-8am*	*Hourly price 8am-10pm*	*Day price Day 1*	*Day price From Day 2*	*Price per km*
Mini (without GPS)	Toyota Aygo	€1.50	€2.30	€39.00	€29.00	€0.18
Small (partly without GPS)	Citroen C-Zero, Opel Corsa, Peugeot Ion, Ford Fiesta, VW Polo, Peugeot 207, MINI-E	€1.50	€5.00	€50.00	€29.00	€0.18
Compact	VW Golf, Opel Astra, Ford Focus Turnier, Peugeot 307	€1.90	€6.00	€60.00	€39.00	€0.18
Middle	VW Passat, Ford Mondeo, MB C-Klasse, Toyota Prius Plug-In PHV, Audi A4, Opel Ampera	€1.90	€7.00	€70.00	€49.00	€0.20
Transporter (partly without GPS and with more seats)	Ford Transit, MB Sprinter, Opel Movano, VW T5	€1.90	€8.00	€80.00	€59.00	€0.20
High	Volvo XC 60	€2.50	€8.00	€90.00	€69.00	€0.22
Luxury	Volvo XC 90	€3.00	€9.50	€110.00	€89.00	€0.22

Table 5: Flinkster price list (valid between 2014 and 2020; obtained from Flinkster's website)

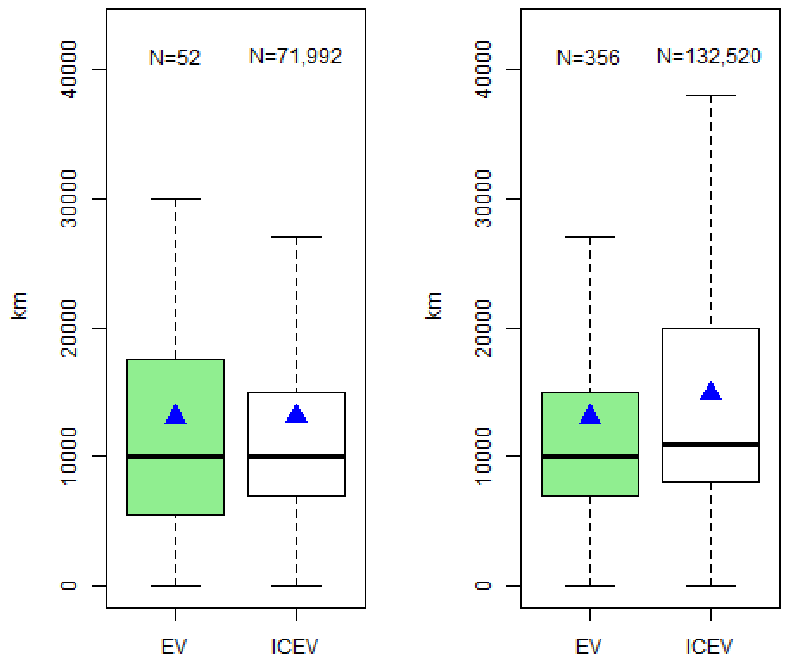

Figure 9: Boxplots for annual mileage of EVs and ICEVs by number of household cars in the private fleet, excluding outliers. Left panel cars in single-vehicle households, right panel cars in multi-vehicle households

	Mean	**Standard deviation**	**N**
EV	4,262	3,890	103
Diesel	20,308	7,759	796
Gasoline	21,142	5,527	46
ICEV aggregate	20,353	7,653	842

Table 6: Summary statistics annual mileage car sharing vehicles available throughout an entire year

	EV stations	**both**			**ICEV only**	
	EV	**EV**	**Gasoline**	**Diesel**	**Gasoline**	**Diesel**

Mean	22	20	49	57	49	58
Median	16	24	27	28	28	30
Standard deviation	20	19	66	83	59	76
N	13,247	7,907	2,034	22,867	49,949	301,759

Table 7: Summary statistics for single-day mileage with shared cars by station type

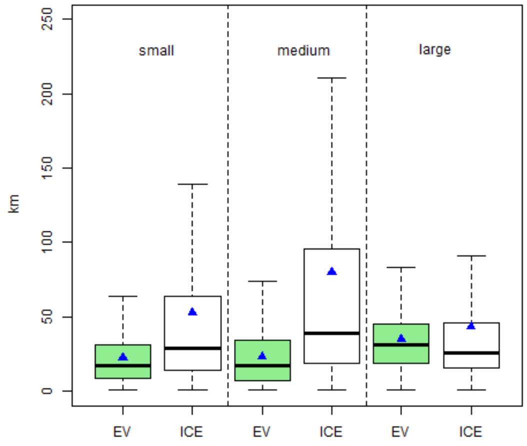

Figure 10: Boxplots for single-day mileage of EVs and ICEVs in car sharing fleet by vehicle category, excluding outliers

	(1)	(2) vehicle category	(3) station type	(4) customer type
diesel	0.79***	0.73***	0.73***	0.74***
	(0.00)	(0.00)	(0.00)	(0.00)
gasoline	0.63***	0.66***	0.66***	0.66***
	(0.00)	(0.00)	(0.00)	(0.00)
medium-sized car		0.52***	0.52***	0.51***
		(0.00)	(0.00)	(0.00)
transporter		-0.05***	-0.05***	-0.08***
		(0.00)	(0.00)	(0.00)
mixed station			0.00	-0.00
			(0.78)	(0.64)
regular customer				-0.51***
				(0.00)
_cons	2.87***	2.84***	2.84***	3.33***
	(0.00)	(0.00)	(0.00)	(0.00)
N	479572	479572	479572	479572

dependent variable: ln mileage at the booking level; p-values in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 8: Regression results

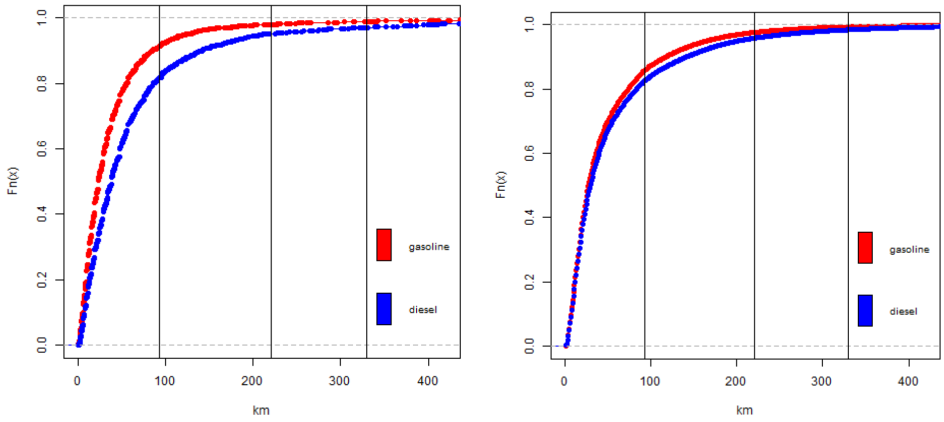

Figure 11: Cumulative distribution function single-day mileage (for diesel cars in blue and gasoline cars in red). Left panel private cars, right panel shared cars