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On the asymmetric relationship between car sharing membership and car ownership levels: Insights from the German Mobility Panel

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Abstract

Car sharing is one of the shared mobility services that can potentially cause a reduction in car ownership. The topic has been extensively addressed in the literature, yet existing evidence is mainly based on observations related only to car sharing subscribers, or cross-sectional surveys targeting a representative sample of the drivers' population at best. Since car ownership is influenced by a wide array of socio-demographic factors beyond car sharing, the association between car ownership levels and car sharing membership needs to be validated. To this effect, the present paper resorts to the 2012/2013 until 2020/2021 waves of the German Mobility Panel (MOP), an unbalanced and rotating (the same individual is interviewed in no more than three consecutive waves) annual panel survey. This study presents the results of the annual survey in which there was a steady growth in sample sizes, starting from 1173 households and 2369 individuals being interviewed in 2012/2013, up to 1963 households and 3461 individuals in 2020/2021. A treated group of car sharing subscribers is identified and related car ownership levels are compared with those of a control group that was created through propensity-score-based matching, controlling for a wide array of socio-demographic variables. Observed differences are still strong and they can therefore be safely associated with car sharing membership. Additionally, the panel nature of the data allowed for studying the patterns of car sharing subscription and unsubscription together with the changing levels of car ownership within the observation period. An asymmetry of behaviors clearly emerged, since the observed decrease in car ownership when subscribing to car sharing is much stronger than an increase when unsubscribing. By leveraging those results and projecting them to the whole universe (German car drivers), it is shown that the net balance in terms of number of cars taken out of German streets by existing car sharing systems undergoes significant changes. These changes occur according to subscription and unsubscription patterns, even when the annual growth rate of subscribers is fixed. Some additional scenarios are finally proposed assuming different annual subscriber growth rates, according to recently observed trends.

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1. Introduction

Cars are one of the most commonly used mobility types in society. Convenience and ease, travel time, flexibility, and status symbol are the main reasons people use cars (Anable, 2005), as well as two underlying influences which are undeniably important, one is habit and the second one is the availability of alternatives.

Although private cars have many benefits, drawbacks also exist. In recent years, shared mobility schemes have received significant interest from transport planners, researchers, and policymakers to seek more energy-efficient ways to meet daily transportation needs for those market segments not easily captured by public transport or active means (walk, bicycle). This interest also came from the challenges communities face from the continued growth of vehicle ownership and usage, along with the associated consequences such as increased traffic congestion, parking issues, resource usage, and air pollution (Liao et al., 2020)

Car sharing is one of the shared mobility services that can potentially cause a reduction both in private car usage and car ownership, and encourage people to use alternative modes of transport, e.g., bus, train, walking, cycling, etc. (Martin and Shaheen, 2011). Car sharing is like car rental when an individual can use a vehicle for a short distance or time. Members can pay for a shared-vehicle fleet on a per-hour and per-mile/kilometer basis. It allows users to take advantage of a private vehicle without the burden of complete ownership, such as maintenance, insurance, and repair responsibilities.

The car sharing program facilitates both an increase and decrease in vehicle use by individuals (Millard-Ball, 2005). It can increase by gaining auto access for low-income households when owning a private car is not affordable. Thus carless households also would be able to drive through car sharing in today's highly car-dependent societies (Litman, 2000). This alternative transport mode is beneficial for non-car owners. On the other hand, car sharing also facilitates a decrease in auto use by allowing households that own cars to obtain automobile access through shared vehicles alternatively. Such households can reduce their utility and shift to public transit and non-motorized modes of transportation. Therefore, due to fewer personal vehicles being needed, car sharing households often experience a reduction in travel and vehicle ownership. For many households, car sharing can either reduce or even eliminate the need for private vehicle ownership (Millard-Ball et al., 2005; Martin et al., 2010; Shaheen and Cohen, 2013).

Car sharing can come according to different operational schemes. Former services were more similar to the ones from the car rental industry, since cars had to be picked up at designated locations and dropped off at the same locations (station-based or two-way services). Especially from the latest decade, free-floating services spread over larger cities in which cars can be picked up and dropped off at any parking spot within an operational area. These two basic variants are complemented by other forms, such as a shared fleet of cars where the operator does not own the vehicles but schedules the shared use of privately owned cars (peer-to-peer services). It is important to note that such car sharing variants may have widely different impacts on the transport system of a city (Chicco et al., 2022), although in the following we will not distinguish among them.

Among the main areas of research in car sharing, the study of its impact on personal vehicle ownership is one of the significant streams. Even though the effects of car sharing have been extensively studied (see e.g. the reviews by Martin et al., 2010; Martin and Shaheen, 2011; Ferrero et al., 2018; Esfandabadi et al., 2020; Liao and Correia, 2022), there are still several challenges. Firstly, prior studies have typically relied on data from existing car sharing organizations or operators. Accordingly, all respondents were already car sharing members, and most did not own a vehicle (Martin et al., 2010). This is the situation where self-selection bias could arise, when the car sharing members who self-select themselves into the group were found to have a higher awareness of the environment and willing to commit to more sustainable behaviors (Costain et al., 2012; Ramos et al., 2020). As such, previous findings regarding the impact of car sharing on household vehicle ownership may have been overly optimistic. Secondly, the majority of prior studies were based on cross-sectional surveys.

Trying to overcome the above limitations in the study of the car sharing diffusion – car ownership nexus, this paper uses data from a well-established longitudinal survey in Germany, namely the German Mobility Panel. The respondents were a sample of the general public in Germany rather than just members of car sharing organizations.

Both car sharing membership patterns at the individual level and car ownership at the household level were observed for up to three years for each panel member. In this paper, we study the relationship between these two factors.

The paper is organized as follows. The next section introduces the experimental setting, data set description and related key descriptive statistics. Then, the analytical methodology and data preparation are discussed in section 3. Section 4 describes the results and introduces some scenarios to generalize the findings. Finally, the paper concludes with section 5 summarizing and discussing the main findings.

2. Experimental settings

2.1. Overview of car sharing in Germany

The German car sharing industry has been growing steadily in recent years, with the exception of the Corona year 2020 where market growth remained curbed due to the temporarily sharp decline in mobility demand during the two lockdowns. Looking at the most recent statistics that Bundesverband CarSharing eV (bcs) requests from all car sharing providers in Germany, as of January 01, 2021, there were 228 car sharing providers in Germany, which became 243 providers until January 01, 2022 (bcs, 2022). The number of served cities increased from 855 to 935 within the same period. There were 30,200 car sharing vehicles available to customers in 2022, therefore the German car sharing fleet grew by 15.2 percent compared to the previous year (2021). As of January 1, 2021, there were also 2,874,400 authorized drivers in Germany with German car sharing services, which increased to 3,393,000 in 2022 (+518,000 units). That is 18% more than in the previous year. However, please note that this figure is related to the number of subscriptions rather than on the number of individuals that subscribed, therefore it is affected by the fact that drivers could subscribe to more than one service. In any case, the growth shows that users trust car sharing even in times of pandemics.

Concerning different car sharing forms, station-based car sharing is the most widespread, since it is offered in all the above-mentioned 855 urban areas. This is not surprising, since it is the service configuration that does not need strong economies of scale and can work even in smaller areas. On the other hand, free-floating car sharing is offered in 15 cities, mainly the largest ones such as Berlin and Munich, and the market is dominated by four large providers. Also the number of combined systems, that offer both station-based and free-floating car sharing with a unique subscription continues to increase as well, since there are currently 20 cities in Germany with such an offer.

2.2. Overview of the German Mobility Panel (MOP)

The German Mobility Panel (MOP), or Deutsche Mobilitätspanel in German, is a longitudinal survey that has been conducted annually since 1994 on a panel of individuals that is a nationally representative sample of the German-speaking households living in the country. The study is funded by the German Federal Ministry of Transport and Digital Infrastructure (BMVI), while the Institute for Transport Studies of the Karlsruhe Institute of Technology (KIT) is in charge of its design and scientific supervision. To the best of the Authors' knowledge, it is the only example of a panel survey focused on mobility behaviours on a representative sample of the general population that is uninterruptedly being carried out for so many years and whose microdata can be accessed by researchers. For this, MOP can be considered one of the most prominent and authoritative sources to perform research implying dynamic analyses on travel behaviours.

The goal of the MOP is to gain a general overview of travel in Germany. The survey is repeated every year, so the travel behavior in Germany has been observed continuously over the last 27 years. About one-third of the panel members are rotated every year, so the same individual is interviewed in no more than three consecutive waves. The MOP contains information on the socio-demographic background of the households (including car ownership levels and car sharing membership at the individual level, which is key information in the present study), the population's everyday mobility, along with private cars' mileage and fuel consumption.

Considering that car sharing substantially spread over urban areas only in more recent years, when free-floating services started being offered, in the following we consider only the nine most recent available waves at the time of writing, namely from 2012/2013 until 2020/2021. Each wave is labelled with two consecutive years since a first survey on everyday mobility is rolled out in the autumn of a particular year, whereas an additional survey on car

mileage and fuel consumption is conducted in the following spring. Since we are only considering information collected in the autumn survey, in the following we simply reference each wave with the first of the two years. There was a steady growth in sample sizes during this period, starting from 1173 households and 2369 individuals being interviewed in 2012, up to 1963 households and 3461 individuals in 2020. Additional information on the survey can be retrieved from Ecke et al. (2021).

2.3. Key figures on car sharing membership and car ownership levels from MOP

Car sharing membership has been steadily growing in the MOP panel between 2012 and 2020, although penetration levels are still quite low in relative terms. This is fully understandable, given the fact that only a fraction of the population living in larger urban areas has access to the service. Table 1 shows the annual increase in membership both at the individual and the household (HH) level within the considered period. It should be noted that the sum of values in the second and fourth columns of the table (namely, 354 members and 296 households) is not giving the total number of car sharing members and related households in the sample, due to the fact that these data are coming from a panel with repeated observations. Thus, our overall sample across different years is constituted of 233 car sharing members after the removal of repeated observations.

Table 1. Car sharing membership in the MOP

Year	CS members in the sample	Percentage of CS members over total persons (%)	HH with at least one CS member	Percentage of HH with at least one CS member over total HH (%)
2012	12	0.63	11	0.94
2013	17	0.72	15	0.99
2014	26	0.98	24	1.41
2015	24	0.89	21	1.22
2016	29	1.01	25	1.42
2017	47	1.53	39	2.11
2018	53	1.70	42	2.28
2019	63	1.97	52	2.81
2020	83	2.40	67	3.41

The distribution of the number of cars per household where at least one car sharing member is present is shown in Figure 1, whereas the same distribution but for all households in the sample is in Figure 2. It can be noted that car ownership levels in the former case are much lower compared to those in the general population. However, it would be incorrect to conclude that the observed difference is simply due to the use of car sharing, since many other socio-demographic differences that could explain such gap are in place between households with car sharing members and households in the study area. For example, the former group tends to live more in urban areas, where alternatives to private car use, including public transport and active modes, are much more developed. It is therefore necessary to perform a comparison by matching car ownership levels of a treated group (namely, car sharing members) with those of a control group of households where nobody subscribed to car sharing, but having the same socio-demographic characteristics as the treated group. This will be achieved in the next section.

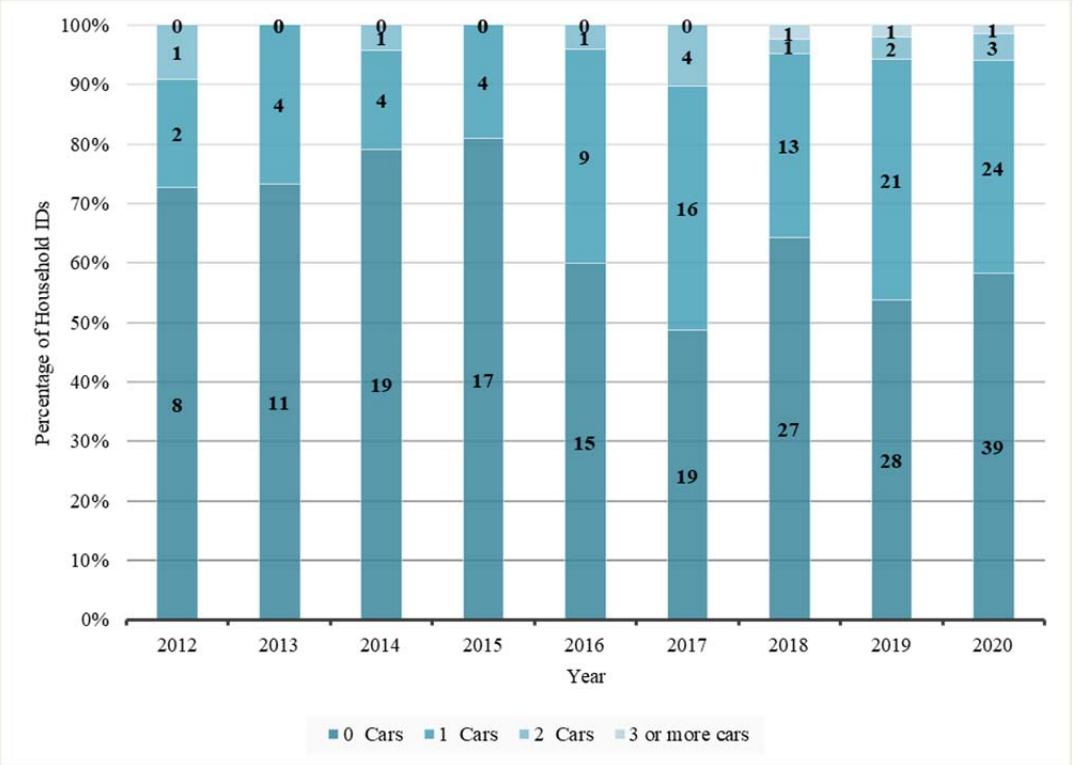

Fig. 1. Car ownership levels in households with at least one car sharing member

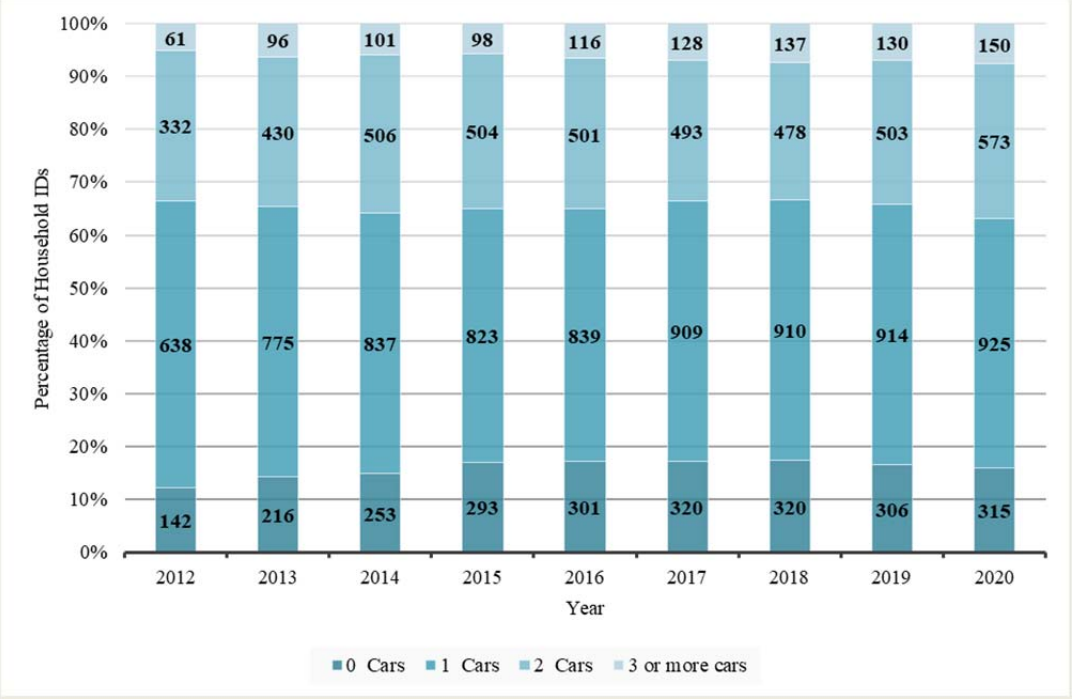

Fig. 2. Car ownership levels in households, whole MOP sample

3. Matching car sharing subscribers and non-subscribers

3.1. Method

As introduced in the previous section, it is important to control for at least the most important factors that can explain car ownership levels of a household in order to correctly capture the relationship between car ownership levels and car sharing membership. Note that this would be necessary, although not a sufficient condition to detect a causality effect between the two. At this stage, only the degree of association between these two household characteristics is being investigated.

To this effect, we identify within the MOP dataset a *treated group* that contains all interviewees who have been car sharing members for at least one year and a *control group* with individuals never car sharing members. A matching method is put in place to compare units that have the same values of the covariates, but different values of the treatment. To do so, we first identify the treated unit and then find the non-treated unit that has very similar covariates values. Thus, participants in matched samples are paired so that they share all characteristics except the one being studied. A *propensity score method* (Rosenbaum and Rubin, 1983) is used here to statistically balance a covariate of different observed socio-demographic characteristics between the treated (car sharing members) and the control group (never car sharing members). A "Nearest-neighbor" matching was then implemented using the MatchIT package of the R language (Ho et al., 2013). Details on the related computational steps can be found in Shahram (2022).

3.2. Identification of the treated group

It was mentioned in section 2.2 that 233 car sharing members have been interviewed. Yet not all of them have been retained in subsequent analyses, since observations falling into any of the following cases have been discarded:

- Car sharing members being interviewed only in one wave, since we later implement a dynamic analysis considering the joint change in car ownership levels and car sharing membership over time.
- Unclear patterns in car sharing membership, namely an individual that is switching twice between subscription and unsubscription in three consecutive years.
- Unclear patterns in car ownership levels, namely households where the number of cars first increases and then decreases (or vice-versa) in three consecutive years.
- Individual belonging to the same household as another individual that is already in the treated group, since car ownership levels are studied at the household level.

After having applied the above filters, we are left with 115 observations that constitute our treated group.

3.3. Matching of the control group

We run a parallel analysis for those MOP interviewees that never subscribed to car sharing. Therefore, 11,812 individuals fall in this group after having removed duplicated observations across years, which are reduced to 4,428 when the first, third and fourth of the filters described in the preceding subsection are applied. Covariates for the matching process were defined based on the following variables:

- *Household-related variables*: type of region where the household is located (number of inhabitants, location in core or suburban area), household size, number of children below the age of 10 and net monthly income.
- *Individual-related variables*: gender, age, educational level, employment status, driving license possession, public transport pass possession, discount railcard possession.

These are in fact those variables that are most frequently considered when specifying car ownership models. Categories related to some of the above variables have been merged, compared to the original dataset, to improve the matching between the two groups. Control groups were separately built for each of the nine years, identifying five

different never car sharing members for every car sharing member in the treated group. After having removed repeated observations as in the previous sample, the control group was made of 664 observations.

4. Results

4.1. Vehicle ownership levels of treated and control group

Car ownership levels for both the treated and the control group are shown in Figure 3. Compared with the results shown in Figures 1 and 2, it can be seen that differences between households with and without car sharing members are still substantial, although attenuated to some extent after having controlled for the socio-demographic variables listed in section 3.3. In fact, the fraction of households without cars in the control group is larger than 20%, compared to a value of about 15% in Figure 2, while households with 2 or more cars decreased from 35% to 25%. The strong association between car sharing membership and lower car ownership levels is therefore confirmed.

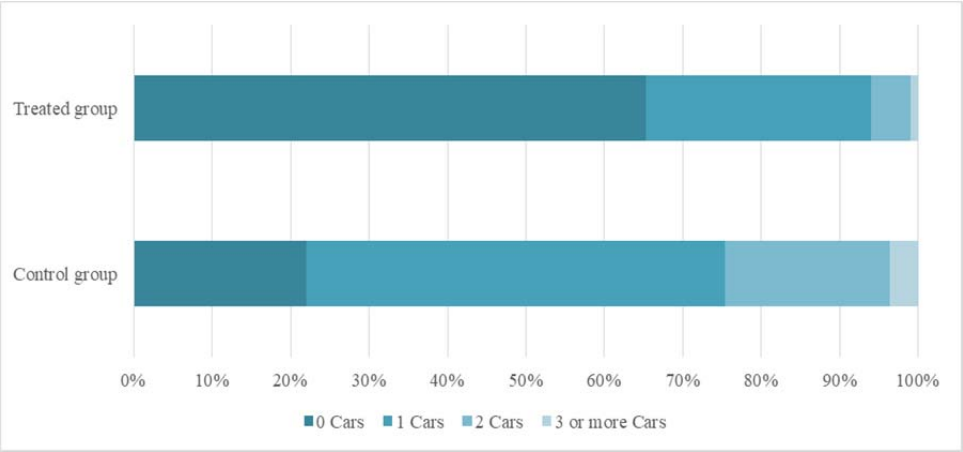

Fig. 3. Car ownership levels in households, treated and control group

However, the above analysis is not fully exploiting the real potentiality of this dataset, where repeated observations are available. Therefore, both car ownership levels and car sharing membership changes might have been detected, if answers to related questions changed from one year to another. This could help in understanding an eventual direction of causation between car sharing subscription and car ownership decrease. The following two subsections will focus the analysis on the temporal patterns of such changes and propose some scenarios based on the related findings.

4.2. Vehicle ownership temporal patterns of treated and control group

Given the opportunity to jointly consider both car sharing membership and car ownership patterns within 2-3 years period in the treated group and the corresponding car ownership patterns in the control group, we complete the analysis by checking how many individuals changed (or not) car sharing membership status and car ownership levels. Concerning the treated group, some individuals were car sharing subscribers for the whole observation period while others subscribed or unsubscribed: all these could have increased, decreased or kept constant car ownership levels. Nine different combinations are thus possible. On the other hand, the control group is made of individuals that never subscribed to car sharing members, but who could also increase, decrease or keep constant their car ownership levels (thus leading to three additional combinations). The following Table 2 reports the breakdown of both groups for these 9+3=12 different cases, furtherly differentiated on the basis of the different patterns in ownership levels (indented rows).

Table 2. Cross tabulation of vehicle ownership and car sharing membership patterns

Car ownership pattern	Always CS member	Subscribed to CS	Unsubscribed to CS	Total CS members (treated group)	Never CS member (control group)
Increasing car ownership					
From 0 to 1 vehicles	1	0	2	3	10
From 1 to 2 vehicles	0	1	1	2	15
From at least 2 vehicles to one more	0	0	0	0	12
Decreasing car ownership					
From 1 to 0 vehicles	1	3	0	4	5
From 2 to 1 vehicles	0	2	0	2	19
From at least 3 vehicles to one less	0	0	0	0	7
Constant car ownership					
0 vehicles	33	16	13	62	120
1 vehicle	10	10	14	34	335
2 vehicles	0	5	2	7	126
3 or more vehicles	0	0	1	1	15
Total	**45**	**37**	**33**	**115**	**664**

As expected, the vast majority of members of both the treated and control group did not change car ownership levels in the considered period, so the number of observations that can be found in the upper part of the table is too low to allow the setting up of a model that is trying to explain the observed choices. Nevertheless, even after having taken into consideration such limitations, some interesting patterns emerge. In particular, we see that five individuals out of 37 that subscribed to car sharing decreased car ownership in the same year, while only one of the subscribers contextually increased car ownership. On the other hand, three individuals (out of 33) increased car ownership while unsubscribing to car sharing. Despite the margins of incertitude given by such low numbers, the key result that seems to emerge is that there is a lack of symmetry in the behavioural nexus between car sharing subscription – car ownership decrease on one side, and car sharing unsubscription – car ownership increase on the other, the former effect is being stronger. By contrast, 37 individuals in the control group increased car ownership levels and 31 decreased it.

By considering the weights of each observation in the MOP, it is possible to project some of the figures in Table 2 to the universe of car sharing members in any year between 2012 and 2020 that will be used for later analyses. Focusing on subscription and unsubscription patterns, dropping the last two columns of Table 2 and compacting the third block of rows lead to results shown in Table 3.

Please note that numbers in the table are referring to data from 2012 until 2020 and only to a fraction of the sample that was selected according to the process described in Section 3, so they cannot be interpreted as counts on the number of car sharing members, subscribers or unsubscribers at any given time. In fact, it can for example be noted that the overall number of households that were observed to subscribe to car sharing (923,192) is smaller than those that unsubscribed (1,089,911), despite the steady growth over time of car sharing diffusion. These figures rather give an estimation of the proportion of households with car sharing members, subscribers or unsubscribers that changed or not changed their car ownership levels during these nine years in Germany and that will be used in subsequent analyses.

The above analysis can shed additional light on the correlation between car sharing membership and car ownership, yet it is still unclear the direction of causation between the two factors. A step towards the latter issue would be to understand, for the 9 individuals in Table 3 that changed both car sharing membership and car ownership levels, which of the two events occurred first. However, in all these nine cases, both events occurred in the same year, so that these panel data cannot help us making any progress related to the causality issue. Once more, it is quite possible that having more observations would have resulted in a different outcome. On the other hand, for example the reaction time after a car shedding that leads to a car sharing subscription, or vice versa subscribing to

car sharing and then shedding a car once one is satisfied with the service could occur in a time period of less than one year, so that the MOP structure could not be optimal to investigate such phenomenon.

Table 3. Crosstab of vehicle ownership and car sharing membership in Germany (values from part of Table 2 projected to the universe)

Car ownership pattern	Always CS member	Subscribed to CS	Unsubscribed to CS
Increasing car ownership			
From 0 to 1 vehicles	305,801	0	24,040
From 1 to 2 vehicles	0	11,115	15,799
From at least 2 vehicles to one more	0	0	0
Decreasing car ownership			
From 1 to 0 vehicles	47,640	41,531	0
From 2 to 1 vehicles	0	49,253	0
Constant car ownership	1,251,443	821,293	1,050,072
Total	**1,329,664**	**923,192**	**1,089,911**

4.3. The impact of different subscription and unsubscription patterns: German scenarios for the year 2021

Assuming that at least to some extent a causality relationship holds between car sharing and car ownership, this section highlights the importance of acknowledging the asymmetry of impacts on car ownership between car sharing subscriptions and unsubscriptions. Merely considering the final balance in terms of car sharing penetration rates could in fact lead to biased results, since the same change in the overall number of car sharing members can obviously be achieved with different combinations in terms of the algebraic sum of car sharing subscriptions and unsubscriptions. Unfortunately, only final balances are usually available in public statistics, thus leading to an additional source of uncertainty in estimating the real benefits of car sharing systems.

We showcase this issue by considering one figure that was already mentioned in section 2.1, namely the number of car sharing authorized drivers, that increased by 518,000 units in Germany during 2021. The goal is to understand how many private cars have been taken out from German streets in relation to such increase. To do so, we need first to consider that the above increase disregards multiple subscriptions, so that the same individual might be counted more than once. Then, car ownership levels are assessed at the household level in our research and as it is customarily done, therefore multiple subscriptions by different drivers within the same household need to be accounted as well.

Concerning the former issue, a survey run among a sample car sharing members in Germany in 2018 for the STARS project indicated that roughly 66.6% of the considered sample subscribed to only one kind of service (either free-floating, roundtrip or combined), whereas 27.7% to two different kinds of service and 5.7% to more than two different kinds of services (Bergstad et al., 2018, page 94 Table 30). Unluckily, this datum cannot give a clear estimate on multiple subscriptions among German car sharing members for the following two reasons: (1) roundtrip users were oversampled, and (2) multiple subscriptions for the same kind of service were not detected. Those two caveats however induce counterbalancing biases in the estimation of the real number of car sharing subscribers, since on the one hand roundtrip subscribers (who are only 23% of all car sharing subscribers according to bcs, 2022), are keener to subscribe also to free-floating services than vice-versa, thus leading to an overestimation of multiple subscriptions, whereas not detecting multiple subscriptions of the same kind of service is clearly an underestimation. All in all, we decide to use the figures from the STARS survey and therefore we estimate that the increase in the number of people having at least one car sharing subscription in German is equal to 518,600*0.666 = 345,388 individuals.

The next step is to estimate the number of households to which such individuals belong. From the MOP dataset, we recall that the overall number of surveyed car sharing members was 233 (Section 4.4.1), that belonged to 195

different households. Therefore, we have an average of 233/195 = 1.19 car sharing members in each household where at least one car sharing member is present. To sum up, the estimated increase in the number of households where at least one car sharing member is present between 2021 and 2022 is equal to 345,388/1.19 = 290,242 households.

In order to estimate the number of cars that were taken out of streets in Germany in 2021 in relation with (but not necessarily as a consequence of) this annual car sharing growth, we consider Table 3 where we can observe that 41,531 + 49,253 - 11,115 = 79,669 cars are taken out of streets when 923,192 households subscribe, whereas 24,040 + 15,799 = 39,839 cars are added in the streets when 1,089,911 households unsubscribe. Thus, we define a car sharing subscription-vehicle ownership substitution rate equal to SR = 79,669/923,192 = 0.086 fewer private vehicles for each household subscribing to car sharing, and a car sharing unsubscription-vehicle ownership complementarity rate equal to CR = 39,839/1,089,911 = 0.036 more private vehicles for each household unsubscribing to car sharing.

Given the above discussed correct way of interpreting numbers in Table 3, row and moreover column totals of that table are not representing real proportions of car sharing (un)subscribers in any given period. Therefore, we cannot consider them to infer the proportion of subscriptions and unsubscriptions that lead to the increase of households where at least one car sharing member is present that was estimated in the previous subsection (i.e., 290,242 households). Therefore, the exercise that we take here is to show through a sensitivity analysis how different proportions of subscriptions and unsubscriptions that are all leading to the same net increase (i.e., +290,242 households) could lead to different car ownership impacts related to the expansion of car sharing. For example, considering that the net increase is only due to new subscriptions and that nobody unsubscribed, we can estimate that 0.086*290,242 = 24,961 private cars have been taken out of the streets during 2021. More in general, assuming that the number of households that unsubscribed in Germany in 2021 is equal to x, the formula that is giving the number of cars taken out of streets as a function of x, considering a constant and overall increase of car sharing diffusion equal to 290,242 is the following:

$$\text{Substituted cars} = SR * (290{,}242 + x) - CR * x = 24{,}961 + 0.05 * x \quad (1)$$

Through the above equations, it is possible to run a sensitivity analysis that clarifies the impact on car ownership of different mixes of subscriptions and unsubscriptions, that are all consistent with the estimated overall net increase of households with car sharing members in Germany during 2021. It can be seen that, as both the number of subscriptions and of unsubscriptions increase by the same amount in order to keep the total increase of subscribers constant, the number of substituted cars increases as well since SR>CR. For example, assuming that nobody unsubscribed to car sharing in Germany during 2021, the number of cars taken out of streets is equal to 24,961, that would for example increase to 24,961 + 0.05 * 290,242 = 39,473 fewer cars if the assumption is made that there was one household unsubscribing for every two households that subscribed.

4.4. Generalized future car sharing scenarios for different growth rates

We can approximatively assume that, in relative terms, the observed increase of households that subscribed to car sharing is the same as the +18% increase of authorized drivers that was mentioned at the beginning of the previous section. We would therefore like to extend our results by looking at the car ownership impacts of different car sharing growing trends (ranging from -5% to +30%), for six different patterns of subscriptions and unsubscriptions. These results are presented in Table 4.

As it can be seen in such table, “Pattern 1” assumes that the growth of car sharing is only due to subscriptions (and the shrinking of car sharing to unsubscriptions), whereas both subscriptions and unsubscriptions increase by the same amount in the other five patterns to keep the same net effect. It should be noted that annual growth rates of car sharing in recent years are broadly within the ranges shown in Table 3, in Germany as in many other countries within and outside Europe. Most notably, even a slight decrease in car sharing diffusion, possibly due to major disruptions (as during the first wave of pandemics in 2020) could still be associated to fewer private vehicles on street, as apparent in the first three rows of Table 4.

Table 4. Impacts of different growth rates of car sharing on car ownership assuming different subscription unsubscription patterns

Increase		Pattern 1	Pattern 2	Pattern 3	Pattern 4	Pattern 5	Pattern 6
-5%	Subscriptions	0	15000	30000	45000	60000	75000
	Unsubscriptions	80623	95623	110623	125623	140623	155623
	Decrease of private cars	-2902*	-2152*	-1402*	-652*	98	848
0%	Subscriptions	0	60000	120000	180000	240000	300000
	Unsubscriptions	0	60000	120000	180000	240000	300000
	Decrease of private cars	0	3000	6000	9000	12000	15000
5%	Subscriptions	80623	95623	110623	125623	140623	155623
	Unsubscriptions	0	15000	30000	45000	60000	75000
	Decrease of private cars	6934	7684	8434	9184	9934	10684
10%	Subscriptions	161246	191246	221246	251246	281246	311246
	Unsubscriptions	0	30000	60000	90000	120000	150000
	Decrease of private cars	13867	15367	16867	18367	19867	21367
15%	Subscriptions	241868	286868	331868	376868	421868	466868
	Unsubscriptions	0	45000	90000	135000	180000	225000
	Decrease of private cars	20801	23051	25301	27551	29801	32051
18%	***Subscriptions***	***290242***	***350242***	***410242***	***470242***	***530242***	***590242***
(2021 increase)	***Unsubscriptions***	***0***	***60000***	***120000***	***180000***	***240000***	***300000***
	Decrease of private cars	***24961***	***27961***	***30961***	***33961***	***36961***	***39961***
20%	Subscriptions	322491	382491	442491	502491	562491	622491
	Unsubscriptions	0	60000	120000	180000	240000	300000
	Decrease of private cars	27734	30734	33734	36734	39734	42734
25%	Subscriptions	403114	478114	553114	628114	703114	778114
	Unsubscriptions	0	75000	150000	225000	300000	375000
	Decrease of private cars	34668	38418	42168	45918	49668	53418
30%	Subscriptions	483737	573737	663737	753737	843737	933737
	Unsubscriptions	0	90000	180000	270000	360000	450000
	Decrease of private cars	41601	46101	50601	55101	59601	64101

* Note: a negative sign indicates an actual increase in the number of cars

It is also possible to study a generalized version of Equation 1, not considering the net increase of car sharing observed for Germany in 2022 (i.e., 290,242 households), to calculate the net variation in the number of cars in that country (car fleet balance, where positive values indicate an increase of the number of cars), see Equation 2:

$$\text{Car fleet balance} = CR*u - SR*s \tag{2}$$

where *u* and *s* are respectively the number of household unsubscriptions and subscriptions.

The below Table 5 shows the number of substituted cars for some specific instances, based on equation (2). It is noted that values on the main diagonal (in bold) represent an unchanged number of households overall subscribing to car sharing, however, the net car fleet balance is still positive. An increase of private cars can be seen only with a sharp decrease in the number of households with at least one car sharing member (numbers in italics) in the left and lower part of the table).

Table 5. Number of substituted cars, based on Equation (2)

Unsubscribing	**Subscribing**										
	0	100000	200000	300000	400000	500000	600000	700000	800000	900000	1000000
0	**0**	-8600	-17200	-25800	-34400	-43000	-51600	-60200	-68800	-77400	-86000
100000	*3600*	**-5000**	-13600	-22200	-30800	-39400	-48000	-56600	-65200	-73800	-82400
200000	*7200*	-1400	**-10000**	-18600	-27200	-35800	-44400	-53000	-61600	-70200	-78800
300000	*10800*	*2200*	-6400	**-15000**	-23600	-32200	-40800	-49400	-58000	-66600	-75200
400000	*14400*	*5800*	-2800	-11400	**-20000**	-28600	-37200	-45800	-54400	-63000	-71600
500000	*18000*	*9400*	*800*	-7800	-16400	**-25000**	-33600	-42200	-50800	-59400	-68000
600000	*21600*	*13000*	*4400*	-4200	-12800	-21400	**-30000**	-38600	-47200	-55800	-64400
700000	*25200*	*16600*	*8000*	-600	-9200	-17800	-26400	**-35000**	-43600	-52200	-60800
800000	*28800*	*20200*	*11600*	*3000*	-5600	-14200	-22800	-31400	**-40000**	-48600	-57200
900000	*32400*	*23800*	*15200*	*6600*	-2000	-10600	-19200	-27800	-36400	**-45000**	-53600
1000000	*36000*	*27400*	*18800*	*10200*	*1600*	-7000	-15600	-24200	-32800	-41400	**-50000**

5. Conclusions

Car sharing services, in Germany and worldwide, have developed rapidly in recent years, and it is commonly believed that car sharing can generate vehicle ownership reduction benefits. Therefore, it is worthy of research to evaluate the effects. This paper has proposed an analysis of the relationship between car sharing membership and car ownership levels based on data from the German Mobility Panel, a panel survey that is annually administered to a representative sample of German drivers. As such, some of the limitations of former studies have been overcome, since previous research is mainly based on observations related only to car sharing subscribers, or use data from cross-sectional surveys targeting a representative sample of the drivers' population.

A treated group of car sharing subscribers within the survey datasets from the year 2012 until 2020 is identified and related car ownership levels are compared with those of a control group that was created through propensity-score-based matching, controlling for a wide array of socio-demographic variables. The fraction of households without cars in the control group is a little more than 20%, which becomes 65% in the treated group. The strong association between car sharing membership and lower car ownership levels is therefore confirmed, since the mediating role of other socio-demographic variables is only slightly widening such gap in car ownership levels between car sharing subscribers and non-subscribers.

Additionally, the panel nature of the data allowed studying the patterns of car sharing subscription and unsubscription together with the changing levels of car ownership within the observation period, thus moving from a static to a dynamic analysis of behaviours. An asymmetry related to mobility choices clearly emerged, since the observed decrease in car ownership when subscribing to car sharing is much stronger than an increase when unsubscribing. Leveraging those results and projecting them to the whole universe (German car drivers), it is shown how the net balance in terms of the number of cars taken out of German streets by existing car sharing systems is widely changing according to subscription and unsubscription patterns, even when the annual growth rate of subscribers is fixed. Finally, some additional scenarios were proposed assuming different annual subscriber growth rates that are in line with recently observed trends in most western countries.

This study is not exempt from limitations. The German Mobility Panel is not oversampling car sharing members, that are a tiny minority in the universe of car drivers in a given country, so the number of observations related to their behaviours is limited. In addition, the dataset is not making a distinction among different car sharing operational schemes (free-floating, round-trip, peer-to-peer, etc.), even if there is compelling evidence in the literature that different schemes have different impacts on car ownership, as discussed in the introduction. Despite

such limitations, we believe that the present study has explored a different avenue of research compared to the state of the art, focusing on the dynamics of car ownership and car sharing membership choices.

Our study primarily examines data at two levels: person and household, along with their respective socio-demographic characteristics. However, conducting further research to compare the mode of transport used, travel time and fuel usage (available in the MOP dataset) differences between the treated and control groups would be valuable to have a clearer picture on different mobility behaviours between the two groups. Additionally, considering datasets with higher sample sizes (e.g. oversampling car sharing subscribers while keeping the statistical representativeness of the sample) would allow running statistical analyses to provide additional confirmation on the causality relationship between car sharing subscriptions and private car ownership.

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