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# Mobility-on-demand pricing versus private vehicle TCO: how cost structures hinder the dethroning of the car

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## Abstract

This study uses a unique dataset on the cost of motoring in Germany to analyse cost competitiveness of emerging mobility-on-demand (MOD) services. Previous studies have focused on comparing current and projected MOD prices with the average cost of private motoring. This study quantifies which proportion of private car travel would actually turn out to be costlier than MOD given that MOD costs drop below certain levels relative to the cost of private motoring. In this context, not the average but the distribution of the costs of motoring are the key issue. These costs are strongly skewed across the cars in private households when including new and old vehicles: a large proportion of private car kilometres are driven at relatively low cost. The study uses simplified scenario settings with MOD price levels ranging from 0.1 €/km to 1.5 €/km to make predictions of hypothetical modal shifts under the assumption that car user switch to the most economic mode of travel. These modal shifts serve as an indicator of MOD cost competitiveness. The results indicate that MOD prices would have to drop to 0.5 €/km or lower to have a notable impact on use of the private car if cost was the key mode choice criterion. Only if MOD prices drop down to a level of about 0.3 €/km—quite possibly a lower boundary for automated MOD—MOD-enabled mobility packages would be the less costly alternative to the private car for a substantial proportion of mileage. However, even at that MOD price level, the private car would still be the most economic option for the majority of today's car user kilometres. Our findings illustrate that the skewed distribution of the cost of owning and running private cars—where many of those who drive much drive inexpensively—substantially dampens the disruptive potential of MOD. While we use data from Germany to illustrate this, many of our findings are more widely applicable.

**Keywords** Mobility on demand · Private car TCO · Cost distribution · Modal shift · Cost of motoring · Vehicle automation

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## Introduction

In recent years, mobility-on-demand (MOD) services have attracted much attention in both scientific and public debate. In this article, the term MOD (sometimes also referred to as Mobility-as-a-Service) denominates services which provide for access to individual mobility without ownership of necessary mobility resources such as cars (Liyanage et al. 2019). MOD encompasses a wide variety of services, ranging from station-based or free-floating car sharing to transportation network companies such as Uber or Lyft, and shared e-scooters or bicycles (Jittrapirom et al. 2017; Liyanage et al. 2019; Mulley 2017). While there are serious challenges associated with such services—for example issues with labour laws or regulations (Kari and Wong 2020)—transport policymakers, researchers and industry decision-makers generally expect them to form an essential part of the future of transport. Outside the scientific arena MOD is being promoted as a promising investment given its presumed growth perspectives; see for example (Uber Investor 2021; Lyft 2021; Green City Finance 2021; Bouton et al. 2015; Arbib and Seba 2017; Uber Technologies Inc. 2019; Alonso Raposo et al. 2019).

Moreover, MOD is regarded as a possible means of improving the sustainability of transport systems (Liyanage et al. 2019; Mulley 2017): MOD is expected to help reduce vehicle-kilometres travelled, primarily in urban transport (Kopp et al. 2015; Jang et al. 2020). This is particularly likely to be the case if users of these services forgo private car ownership, or at least give up on second or third cars (Elliot Martin 2016; Jang et al. 2020). This in turn can be expected to occur if mobility services, in combination with public transport and high-quality infrastructure for active travel, present an attractive alternative to private cars (Alonso-González et al. 2020).

Mobility services are often considered to be a key component of such alternative mobility packages because they allow for a level of flexibility which public transport and active modes are unable to offer without them (Scherf et al. 2020). The potential of these alternatives may become clear as more users join the MOD system, increasing the uptake, bringing costs down, and thus initiating a virtuous cycle towards ever-increasing usage (David Sacks 2014; Uber Technologies Inc. 2019; Bahamonde Birke et al. 2018; Gruel and Stanford 2016). This virtuous cycle is expected by some to be set in motion at the latest when vehicle automation renders the driver unnecessary and thus reduces MOD user costs substantially (Arbib and Seba 2017; Hazan et al. 2016). This has led to mobility services—particularly when operated autonomously—fuelling visions of urban transport with reduced car ownership and consequently greater use of more-sustainable modes, involving a considerable share of MOD (Xavier Mosquet 2015; Silberg et al. 2012; Burns 2013; Kornhauser 2013; Bouton et al. 2015).

While academic research has been more cautious in its conclusions (Zmud et al. 2016; Trommer et al. 2016; Bösch et al. 2018), the narrative of the inevitable success of automated MOD has been fairly persistent in the semi-scientific discourse. This is partly because convincing financial arguments are feeding the narrative: electrification of the power train and vehicle automation will reduce MOD costs, and when a sufficient number of users join in, MOD (or the combination of MOD with other non-private-car modes) has the potential to be less expensive than private car use, while at the same time offering a level of connectivity, and comfort that is comparable or even superior (Burns 2013).

Research itself has in some ways contributed to this narrative: many studies compare the projected costs of automated MOD with the costs of owning and running a private vehicle (see the review section of this article). While some studies are sceptical about

the cost competitiveness of automated vehicles (Nunes and Hernandez 2019, 2020) others arrive at the conclusion that for many parts of the world automated MOD will, on average, be less expensive than private cars when total costs are considered (Becker et al. 2020; Pavone 2015; Spieser et al. 2014). This suggests that private cars will not be cost-competitive (even if they are still attractive in other terms) once automated MOD services are sufficiently widespread. However, while comparing average costs is common in the literature, an explicit discussion of the implications of the underlying cost distributions on the adoption of MOD is lacking.

Much of the scientific debate about transport costs in the context of MOD has focused on the costs of the new services. This study looks at the flip side—that is, on the costs of the established alternatives, primarily those of private vehicles. We argue that it is harder for MOD to compete with private vehicles than the current debate suggests. The reason for this is simple but often overlooked: the costs of owning and running private vehicles vary substantially from one to another (note that throughout the article we refer to the total costs of motoring including fixed and variable costs, i.e. TCO including vehicle purchase costs); moreover, the cost distribution is also strongly skewed, with those who drive high annual mileages doing so at a low cost per kilometre.

The implications of differing cost structures between the various alternative modes can be analysed most realistically by comparing the costs of private vehicles and potential alternatives on an individual vehicle-per-vehicle basis, and taking account of individual usage patterns. Data that allows for such an analysis is very scarce. This study is based on German data from 2016 that contains both vehicle usage and vehicle cost information. With this data we run straightforward hypothetical what-if scenarios. We assume that users shift from private vehicle use to either exclusive MOD use (the ‘MOD Only’ scenarios) or combined use of MOD and public transport (the ‘Mobility Package’ scenarios) as soon as the alternative is less expensive than private car use. For these scenarios, the precise characteristics of the MOD (e.g. ticketing method, level of automation) do not really matter. However, it makes sense to imagine a service that is comparable to the private car with regard to comfort and connectivity. We imagine a motor vehicle-based service which could be an Uber-like service, or even an automated vehicle (e.g. an autonomous taxi or shared automated vehicle). In the remainder of this article we will simply refer to this unspecified service by the term ‘MOD’. Our usage of the term ‘MOD’ thus refers to car-based services, but we believe that most of our findings have relevance for other kinds of MOD services.

The modal shift scenarios in this article simply serve as a tangible representation of the cost competitiveness of MOD and mobility packages including MOD. Our study ignores many other factors which in reality also influence mode choice and concentrates on cost competitiveness. This is motivated by the fact that much of the ongoing debate about the potential of MOD evolves around cost but ignores the issue of cost distribution. Hence, we primarily address the question how the distribution of the cost of motoring influences MOD cost competitiveness.

In the next section, we first present the vehicle cost data that forms the basis for our analysis. We have placed the data presentation before the review section because being acquainted with our cost data enables a better understanding of the research gap that we go on to identify in the review. The review section focuses on the cost competitiveness of travel modes, using empirical data and previous studies. After the review section we present our data preparation and our scenarios. In the concluding sections we present our results and discuss those results and the methodology used, ending finally with a presentation of the conclusions.

## Data: travel survey data with imputed vehicle cost information

Data from the German Mobility Panel (MOP) forms the basis of our analyses. The MOP is a German national household travel survey that has been conducted every year since 1994 (Ecke et al. 2020). The survey is carried out on behalf of, and funded by, the German Federal Ministry of Transport and Digital Infrastructure. The market research firm Kantar TNS is responsible for the fieldwork (i.e. participant recruitment and data collection) and the Institute for Transport Studies of the Karlsruhe Institute of Technology is in charge of the design and scientific supervision of the survey. The MOP consists of two parts:

1. a one-week travel diary (the ‘everyday mobility survey’, abbreviated MOP-EM) conducted in *autumn* each year with an annual sample size of about 1500 households and about 3000 individuals (children under ten years of age are not covered by the survey);
2. a two-month fuel consumption and odometer reading survey (MOP-FCOR) conducted in *spring* each year, in which car-owning households of the MOP-EM participate. MOP-FCOR comprises an annual sample of about 1500 cars.

The MOP is designed as a rotating panel survey in which households report on their travel behaviour and car use in three consecutive years, starting with a one-week travel diary in autumn of year one. After three cycles, participant households are rotated out of the sample and replaced by new households. This means that a household with car ideally participates in six survey waves (MOP-EM in autumn of calendar year  $n$ , MOP-FCOR in spring of year calendar  $n + 1$ , MOP-EM in autumn of year calendar  $n + 1$  etc.). This is the reason why, later on in this study, we associate MOP-EM data from calendar year  $n$  with MOP-FCOR data from calendar year  $n + 1$ .

The MOP-FCOR questionnaire elicits vehicle details such as make, model, year of construction, engine size, propulsion technology and type of fuel. In one of our previous studies (Eisenmann and Kuhnimhof 2018), we used this information in combination with the vehicle mileage to impute vehicle costs, broken down by cost component (depreciation, tax, insurance, fuel and other). This imputation procedure was carried out for the MOP-FCOR vehicle samples from 2015 and 2016, which totalled 2977 cars. The key data source providing the cost information for each vehicle for this imputation procedure was a vehicle cost database from the German Automobile Club ADAC (ADAC Fahrzeugtechnik 2018). The procedure was validated against results from the German income and expenditure survey and found to deliver plausible results. For details see (Eisenmann and Kuhnimhof 2018).

The result of this cost imputation procedure is a dataset in which 2977 private household cars (including private cars and company cars) represent the individual observations. We re-weighted this data set to make it representative of the entirety of German private household cars (the ‘car parc’) with regard to age, engine size and propulsion technology. For each car the dataset contains technical vehicle details, average monthly mileage (for either spring 2015 or spring 2016) and monthly costs broken down by depreciation (i.e. vehicle purchase costs broken down by years of use), tax, insurance, fuel and other costs—which taken together form the total costs of ownership (TCO) or total costs of owning and running a car. Hence, we computed TCO per kilometre for each vehicle. Therefore, this data not only enables computation of *average* TCO per kilometre for the German private car fleet, but also allows for the analysis of the

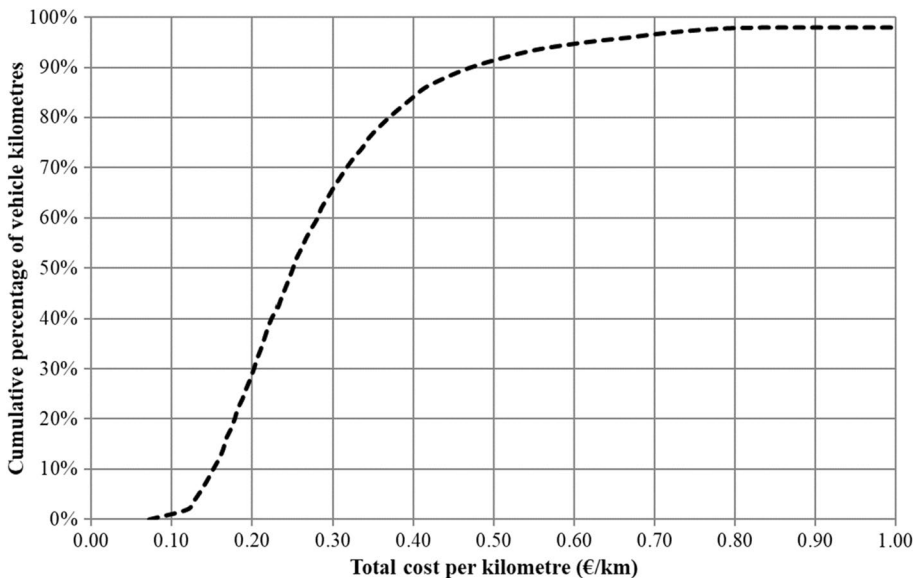
*distribution* of values of TCO per kilometre which inspired the scenarios presented in this study. Figure 1 shows, cumulatively, the cost distribution as generated with this dataset.

## Comparative review and discussion of travel mode costs

### Costs of running private cars

In recent years, an important motivation for studying vehicle TCO was assessing the cost competitiveness of new propulsion systems, chiefly electric drivetrains, from the user perspective (Bubeck et al. 2016; Letmathe and Soares 2017; Wu et al. 2015; Orsi et al. 2016; Gilmore and Lave 2013; Lin et al. 2013; Rusich and Danielis 2015; Bernd Propfe 2012). Such studies usually compare the costs of different types of vehicles for new car buyers (Letmathe and Soares 2017; Bubeck et al. 2016; Rusich and Danielis 2015); in many cases, analyses are based on selected reference vehicles (Lin et al. 2013; Bubeck et al. 2016; Letmathe and Soares 2017) and make general assumptions, grounded in real life—for example, assumptions about annual mileage or length of ownership (Letmathe and Soares 2017; Rusich and Danielis 2015). Such approaches are adequate to inform technology choices, such as those made by new car buyers, or to analyse market take-up of new technologies. They are not, however, tailored to deriving the costs of motoring for the existing car parc.

The second important motivation for studying vehicle TCO –relevant to our study– is assessing the cost competitiveness of new mobility services, ranging from car sharing (Schuster et al. 2005; Liao et al. 2018) to automated mobility services (Xavier Mosquet 2015; Becker et al. 2020; Bösch et al. 2018; Pavone 2015; Spieser et al. 2014; Burns 2013). In this case, considering the costs of motoring for new car buyers is not



**Fig. 1** Cumulative distribution of total cost of private car ownership per kilometre driven (Germany 2016)

sufficient. This is because new mobility services compete with the entire existing car parc, with a focus on the private cars.

For establishing average costs of owning and running private cars, some studies rely on average values (in particular for vehicle prices and mileages used to derive depreciation) across the vehicle parc (Spieser et al. 2014; Hazan et al. 2016). Some studies reference average vehicle costs as reported by motorists' associations such as the American Automobile Association to derive assumptions about the average costs of motoring (Stephens et al. 2016) or to validate their own results (Bösch et al. 2018)—but the motorists' associations again work with average values for reference vehicles (AAA 2017; TCS 2021). Becker et al. (Becker et al. 2020; Bösch et al. 2018) compute the production cost per passenger-kilometre for private vehicles as an intermediate step in deriving costs for automated mobility services (see below). Therefore, they use reference vehicles and corresponding assumptions about mileage, length of ownership etc.

Andor et al. (Andor et al. 2020) investigate drivers' misestimation of vehicle costs. To do this, they surveyed about 5500 households, asking for vehicle expenditure estimates, vehicle details and annual mileage. To derive the actual average TCO, the authors derived the monthly costs for depreciation, fuel, taxes and insurance, and repair, from a detailed dataset of the ADAC and other sources. This approach is similar to our approach (see the previous section). However, Andor et al. did not determine costs individually for each car in their sample. Instead, they grouped cars into six vehicle classes (e.g. compact cars, SUVs) and derived the costs for the top-selling model in each class.

Household budget surveys provide a completely different way of deriving the average costs of motoring (Destatis 2018). Such surveys (and interpolated values for years in between actual surveys) produce statistics for consumer spending per household by category. This allows for extrapolating total car-related expenditures by private households to the national level and dividing by the number of private vehicles, or by private vehicle mileage, thereby yielding the expenditure per vehicle, or per vehicle-kilometre respectively.

Table 1 lists the average costs of owning and running a private car in Germany as derived using a variety of approaches. While these different sources and approaches yield results of the same order of magnitude, there are nevertheless some noteworthy differences: as regards expenditure for fuel, (Andor et al. 2020) come up with a substantially higher value than the other sources. This may be attributed at least partly to fuel price increases between 2016 (the reference year of the other sources) and 2018 (the reference year of Andor et al.) (ADAC 2020). Andor et al. also list surprisingly high costs for insurance and tax. We believe that this is an artefact of their methodology of imputing insurance costs on the basis of the ADAC database, which fails to account for insurance discounts despite the fact that they are in actual fact very common (for a detailed discussion of this, see (Eisenmann and Kuhnimhof 2018)).

Moreover, there are differences between the listed sources regarding depreciation. We assume that the higher depreciation in Andor et al. and Becker et al. is caused mainly by their failure to account for the phenomenon of company cars adequately, which are a significant factor in countries with company car regulations which favour them, such as Germany. Here, a large proportion of expensive vehicles entering the vehicle parc spend the first stage of their life as a company car before going on to enter the private second-hand car market. Thus, a large part of the cost of depreciation of expensive vehicles is not borne by private households. We suggest that for establishing costs of private motoring, company cars should be excluded from the analysis.

To sum up the review, we discovered various approaches to establishing *average costs* of running private vehicles. Within Germany at any rate, these approaches arrive at similar

**Table 1** Average costs of owning and running a private car in Germany as derived using various approaches

| Source                            | Location, year | Approach to estimating average costs   | Harmonised costs <sup>a</sup> (€) |                      |                 |      | Costs per vehicle-kilometre |       |
|-----------------------------------|----------------|--|-----------------------------------|----------------------|-----------------|------|-----------------------------|-------|
|                                   |                |  | Costs per vehicle per month       |                      |                 |      |                             |       |
|                                   |                |  | Depre-ciation                     | Repair & maintenance | Tax & insurance | Fuel |                             | Total |
| Becker et al. (2020) <sup>b</sup> | Berlin, 2016   | Reference vehicle                      | 140                               | 56                   | 73              | 76   | 345                         | 0.34  |
| Andor et al. (2020)               | Germany, 2018  | Cost imputation for vehicle categories | 141                               | 55                   | 95              | 134  | 425                         | 0.41  |
| Eisenmann and Kuhnhof (2018)      | Germany, 2016  | Individual vehicle cost imputation     | 103                               | 67                   | 48              | 92   | 310                         | 0.30  |
| Destatis (2018)                   | Germany, 2016  | Household expenditure                  | 109                               | 48                   | 48 <sup>c</sup> | 74   | 279                         | 0.27  |

<sup>a</sup>Appendix A contains a description of the harmonisation procedure

<sup>b</sup>In the case of Becker et al. we use cost information as reported in their article for the cost components listed above. However, for reasons of comparability with the other studies cited in this table, we omit certain additional cost components which Becker et al. include. We thus arrive at a total cost per kilometre that differs from Becker et al.'s figure. For details see "Appendix A"

<sup>c</sup>Note that vehicle tax and insurance are not listed by Destatis for 2016. Therefore, we used vehicle tax and insurance expenditures as reported in Eisenmann and Kuhnhof (2018)



values: about 0.30–0.35 €/km when focusing on the same set of costs. However, in the literature we did not come across any other data that allowed for analysing the *distribution* of the cost of running private vehicles on an individual basis. Hence, there appears to be no precedent for looking at the cost distribution as presented in Fig. 1. This cost distribution analysis makes it clear that average costs tell only part of the story. For example, about two thirds of private car kilometres are actually driven at costs below average costs of about 0.3 €/km, because the costs are strongly skewed.

## Costs of emerging alternatives to private cars

We now turn to the cost of transport services competing with private vehicles. Table 2 lists average values (or ranges) of user costs per kilometre for existing and potential future transport services, including traditional public transport and various forms of MOD services. Of course, as with private vehicles, there is and will continue to be a broad variation in user costs per kilometre for transport services, depending on pricing schemes and usage characteristics. In our overview, however, we ignore this and present averages or ranges. In the scenarios presented later in this article, we will take a more detailed approach as regards the cost of public transport, for which costs per kilometre decrease as rates of use increase.

The costs for existing transport services (shown in the upper part of Table 2) focus exclusively on Germany. The costs for local public transport and rail have been sourced from business reports of the service providers (Verkehrsverbund Berlin-Brandenburg 2017; DB Fernverkehr AG 2017) and calculated on the basis of ticket revenues divided by passenger-kilometres. Hence, these costs are actually weighted by passenger mileage and truly reflect average user costs per unit distance travelled. As for the other existing services (car sharing, taxi, limousine service, e-scooter), the cost ranges presented are based on selected routes of length 5 km to 30 km within Berlin for which costs were sourced from service websites. Costs sourced using this approach cannot truly reflect average user costs per kilometre, because they are not weighted by passenger mileage. (The latter would only be possible with detailed trip data from the service providers, which was not available for this study.) For this reason, we do not present misleading averages for these transport services in Table 2, but rather ranges, in order to provide a coarse overview of the costs encountered when using these modes.

Contrasting the cost figures from Table 2 with the private vehicle cost distribution in Fig. 1 provides insight into the price competitiveness of existing MOD services. Let us suppose that current MOD prices start at approximately 0.5 €/km as a lower bound (only long car-sharing trips work out cheaper). Figure 1 shows that the TCO of 90% of private car kilometres fall below this threshold of 0.5 €/km. This is a first indication that MOD at current prices can only compete with a small part of the private vehicle transport market.

The costs for potential future transport services enabled by vehicle automation (as shown in the lower part of Table 2) give an initial glimpse into how this cost competitiveness of MOD might change with vehicle automation. The costs for potential future transport services were sourced from the literature. Approaches to establish costs for future automated MOD in previous studies fall into two broad categories:

1. *Model-based cost estimates* (Friedrich and Hartl 2016; Trommer et al. 2016; Fagnant and Kockelman 2014; Hörl et al. 2019; Nunes and Hernandez 2020): in these, comprehensive travel demand models serve to simulate the implementation of MOD in hypo-

**Table 2** Review of costs per kilometre for existing and future transport services

| Type of transport service   | Source                                      | Locale (reference year)                      | Reference basis                                  | Cost/cost range (currency unit/km) |
|---|---|--|--|------------------------------------|
| <b>Existing transport services</b>  |   |  |  |                                    |
| Local public transport  | Verkehrsverbund Berlin-Brandenburg (2017)   | Berlin, Germany (2017)                       | Average user cost per traveller-km               | 0.11 €/km                          |
| Long-distance rail (> 100 km)   | DB Fernverkehr AG (2017)                    | Germany (2017)                               | Average user cost per traveller-km               | 0.10 €/km                          |
| Free-floating car sharing (SHARE NOW)   | Authors' research                           | Berlin, Germany (2019)                       | Range of user cost per vehicle-kilometre (vkm)   | 0.40–0.75 €/km                     |
| Taxi  | Authors' research                           | Berlin, Germany (2019)                       | Range of user cost per vkm                       | 2.30–3.30 €/km                     |
| Limousine service (Uber)  | Authors' research                           | Berlin, Germany (2019)                       | Range of user cost per vkm                       | 1.80–2.30 €/km                     |
| Shared e-scooter (TIER)   | Authors' research                           | Berlin, Germany (2019)                       | Range of user cost per traveller-kilometre       | 0.80–1.90 €/km                     |
| <b>Future automated transport services</b>                                    |   |  |  |                                    |
| Individual (upper bound) and shared (lower bound) automated electric vehicle  | Becker et al. (2020)                        | Berlin, Germany (2016)                       | Range of user cost per passenger-kilometre (pkm) | 0.16–0.26 €/km                     |
| Shared autonomous electric vehicle  | Friedrich and Hartl (2016)                  | Stuttgart, Germany (2016)                    | User cost per pkm                                | 0.15 €/km                          |
| Autonomous free-floating car sharing  | Dandl and Bogenberger (2019)                | Munich, Germany (2017)                       | Range of user cost per vkm                       | 0.25–0.27 €/km                     |
| Autonomous carpooling (lower bound) and autonomous car sharing (upper bound)  | Trommer et al. (2016)                       | Germany (not specified <sup>a</sup> )        | Range of user cost per pkm                       | 0.11–0.35 €/km                     |
| Autonomous ridesharing (lower bound) and autonomous car sharing (upper bound) | Hazan et al. (2016)                         | Netherlands (not specified <sup>a</sup> )    | Range of user cost per pkm                       | 0.09–0.32 €/km                     |
| Autonomous taxi   | Bösch et al. (2018) and Hörli et al. (2019) | Switzerland (not specified <sup>a</sup> )    | Range of user cost per pkm                       | 0.32–0.43 CHF/km                   |
| Shared autonomous electric vehicle  | Chen et al. (2016)                          | Austin, USA (not specified <sup>d</sup> )    | Range of user cost per occupied km               | 0.26–0.30 US\$/km                  |
| Connected automated vehicles with and without ridesharing                     | Stephens et al. (2016)                      | USA (not specified <sup>d</sup> )            | Range of user cost per pkm                       | 0.11–0.19 US\$/km                  |
| Shared autonomous taxi  | Burns (2013)                                | Ann Arbor, USA (not specified <sup>b</sup> ) | Range of user cost per pkm                       | 0.09–0.25 US\$/km                  |

**Table 2** (continued)

| Type of transport service | Source                       | Locale (reference year)                   | Reference basis            | Cost/cost range (currency unit/km) |
|---------------------------|------------------------------|---|----------------------------|------------------------------------|
| Shared autonomous vehicle | Fagnant and Kockelman (2016) | Austin, USA (not specified <sup>a</sup> ) | Assumed user cost per pkm  | 0.62 US\$/km                       |
| Autonomous taxis          | Nunes and Hernandez (2020)   | San Francisco, USA                        | Range of user cost per pkm | 0.98–3.73 US\$/km                  |

<sup>a</sup> In many sources an explicit reference year is not specified. However, in most cases relevant cost assumptions broadly relate to the time of the publication

thetical scenarios. On the basis of assumptions about costs for providing such services and simulated usage characteristics, authors derive MOD service cost estimates.

2. *Cost-reduction-based cost estimates* (Becker et al. 2020; Hazan et al. 2016; Stephens et al. 2016): this group of approaches combines assumptions about cost reductions brought about by vehicle automation and electrification, along with costs of existing modes of travel and transport services, to arrive at costs for hypothetical services. Assumptions about cost reductions are derived from tertiary studies or—again—findings from transport models.

There are studies which relatively clearly fall into one of these two categories, while other studies combine both approaches, e.g. (Dandl and Bogenberger 2019). A more comprehensive review, together with a broad range of cost estimates for various services and different locales around the globe, can be found in Becker et al. (2020). Our overview in Table 2 concentrates on the German and European situation because this provides the most meaningful context for our scenarios. For the sake of comparison, we also include automated MOD cost estimates for the USA.

As can be seen from Table 2, lower bounds for estimates of costs per kilometre for automated MOD start at around 0.1 €/km for *pooled or shared* services. This is about the same order of magnitude of average user costs per kilometre in public transport in Germany or the marginal costs (fuel costs) of private vehicle use. Lower bounds for *individual* automated MOD services (which in terms of comfort or privacy would be much more comparable to the private car) start from about 0.25–0.30 €/km. This is in the same region as the average cost per vehicle-kilometre for private vehicles in Germany.

Comparing MOD price levels with the private vehicle cost distribution given in Fig. 1 yields first insights into MOD cost competitiveness. However, it does not give the full picture. In reality, conditions are more complex for many reasons, for example because household members use private vehicles as both drivers and passengers. Moreover, in estimating MOD-induced modal shifts away from private vehicles we should not only consider shifts towards MOD but also to other alternative modes. Our following scenarios take account of this.

It should be noted that the purpose of our study is not to investigate what constitutes realistic costs for automated or non-automated MOD. Instead, in the scenarios we present, we vary the MOD price from 0.1 €/km (our lower bound for costs of automated services) to 1.5 €/km (which reflects the price level of some of today's MOD services) and discuss potential effects on private car usage. We leave it up to the readers to choose a price level that they perceive as realistic, and provide Table 2 as an orientation to assist them.

## Data preparation for scenario analysis

Data from the German Mobility Panel MOP, specifically its springtime fuel consumption and odometer reading component (MOP-FCOR) with imputed vehicle cost information, forms the basis for our scenarios. As described above, the German Mobility Panel MOP also comprises the one-week everyday travel diary of household members (MOP-EM) conducted in autumn of the previous year. For the analysis presented in this study, we combined travel diary data from one year's MOP-EM with vehicle cost information based on next year's MOP-FCOR—that is to say, we use travel diary data from autumn 2014 (associated with spring 2015 vehicle cost data) and autumn 2015 (associated with spring 2016

vehicle cost data). The result of this data combination is a conventional trip dataset covering one week and containing detailed information on the costs of all household vehicles.

The time gap between MOP-EM (autumn) and the MOP-FCOR (next spring) may cause slight discrepancies between the imputed vehicle costs and those actually incurred by the respondents, which might arise from changes in fuel price or replacement of vehicles within households between the MOP-EM and MOP-FCOR survey period, to cite but two possibilities. Nevertheless, within our data framework this approach was the best option for combining vehicle costs with everyday travel data. Overall, we are of the opinion that this temporal offset does not greatly influence our findings.

### **Analysis subsample: households with cars and complete vehicle cost and person trip information**

At the outset, the MOP 2014 and 2015 sample included 3415 households. However, many of these were not useful for our analysis as we needed households with sufficient information to derive a full record of car usage including vehicle costs. We therefore limited the sample to households.

- that have at least one car;
- *and* in which at least one car trip has been recorded during the survey week;
- *and* in which all household members have participated in the MOP-EM;
- *and* for which cost information for all household vehicles was available.

These criteria reduced our analysis subsample to 1150 household, 2017 persons and 1453 cars. Note that the rest of the analyses in this article—including the modal share figures in “Appendix B”—refer to households to which these criteria apply, which means that households without cars (about 22% of German households (BMVI et al. 2018)), in particular, are not covered.

### **Trip level vehicle cost imputation: assigning person car trips to household vehicles**

In the MOP-EM trip diary, respondents record their mode of travel for each trip. However, for car driver and car passenger trips the questionnaire does not elicit vehicle information. Hence, for households with multiple vehicles there is an ambiguity regarding which of the household vehicles was used for a particular car driver or passenger trip. (In fact, a vehicle from outside the household could also have been used. This, however, is likely to apply to only a very small fraction of the analysed car trips and we rule out this possibility in the rest of this analysis.)

Therefore, in order to associate each car trip with concrete vehicle costs in the case of multicar households, we needed to assign specific household vehicles to the person-level car trips. For car driver trips we followed the assignment procedure as described in Eisenmann (2018). This approach essentially ranks the household cars by annual mileage and the household drivers by weekly mileage and associates the two rankings. For car passenger trips, we matched passenger and driver trip chains within the household by distance, departure and arrival times. Each passenger trip was in this way assigned a driver trip, and thus a corresponding vehicle. In cases where no match was found for passenger trips among the household driver trips, we removed these trips from the dataset (406 passenger trips, i.e. 5.6% of all passenger trips, were deleted as a result). In reality, such situations

may have been caused by either (a) situations where household members travelled as passengers in vehicles not belonging to the household or (b) imprecisions in reported data. There is no perfect solution to handling these trips, but we believe that the approach chosen does not influence the general result of our scenarios much.

## Reweighting of the resulting sample

The original MOP-EM dataset comes with weights which correct sample biases as regards age, gender, household size, car ownership and population of the municipality of residence. However, we substantially reduced the sample size (see above) and thereby also introduced new biases, which rendered the original MOP-EM weights unsuitable. We therefore generated new weights in order to ensure the socioeconomic representativeness of our analysis. The marginal distributions used in developing these weights were age, gender, household size, number of cars per household and population of the municipality of residence.

## Result of data preparation

As a result of this data preparation, we obtained a weighted trip diary dataset for 1150 households, 2017 individuals (excluding children under ten: see above) and 1453 cars. In this trip dataset, each car driver trip and car passenger trip included information about the vehicle used for the trip and the TCO per kilometre of the vehicle used. This enabled us to run the modal shift scenarios as described in the following section.

## Scenarios and methodology

### Basic scenario assumption: total costs as a key criterion for mode choice

The basic ideas behind our scenarios are straightforward: we assume that an MOD service with the following properties exists:

- it serves all of Germany irrespective of rural/suburban/urban setting for any kind of trip (e.g. with regard to trip length);
- it is comparable to the private car with regard to key parameters such as travel speed and comfort; and
- it differs from the private car only with regard to the price per kilometre.

We thus suppose, for the purpose of our analysis, that price is the only mode choice criterion for drivers. Varying the MOD price from 0.1 €/km to 1.5 €/km, we analyse the impact of the hypothetical MOD service on mode choice. In this analysis, modal shift is primarily a tangible representation of cost competitiveness. For example: let's assume that the mode shift from the car to MOD in a given scenario was 10% relative to the status quo; this illustrates that in this scenario MOD was less expensive than 10% of km travelled by car today.

Building on these basic considerations, we envision two distinct groups of scenarios:

1. ‘MOD Only’ scenarios: in these scenarios, drivers switch from private car use to MOD use if the MOD service is less costly than the private car. The use of other modes such as public transport or active modes remains unchanged and does not factor into this change in mode use.
2. ‘Mobility Package’ scenarios: In these scenarios, MOD services act like catalysts helping to replace private cars with alternative mobility packages consisting of public transport, active modes and MOD. The assumptions for these scenarios were selected with the idea that each alternative mode contributes its respective strength to the ‘Mobility Package’. Therefore, switching towards public transport is limited to commuting which today is the stronghold of public transport (Nobis and Kuhnimhof 2018). Active modes formed the alternative for short trips to provide for optimistic and multi-optional ‘Mobility Package’ Scenarios (even though the shift towards active modes influences our results only marginally, see Fig. 4 in “Appendix B”). In short, in the ‘Mobility Package’ scenarios drivers replace car use (a) on trips under 2 km by active modes (walking and cycling), (b) on commuting trips by public transport or MOD (whichever is the less expensive option), and (c) on other trips by MOD if this combination is less expensive than private car use.

Please note that we analyse potential mode shift on a per-trip basis and not on a trip chain basis. This means: If drivers abandon the car in the ‘Mobility Package’ Scenario they may turn to intermodal trip chains involving different modes, namely active modes, public transport and MOD.

### Scenario implementation

In seeking to undertake a comprehensive consideration of car passenger trips and multimodal shifting behaviour, it does not make sense to compare travel costs by mode on a per-trip basis. Instead we evaluate an entire week of car use, which may include various members of the household using the vehicle as driver or passenger. Hence, to operationalise and evaluate mode choice in the different scenarios, we carried out the following procedure for each car in our dataset:

- Firstly, in order to compute total weekly costs (TCO) per car in the dataset in the status quo, we totalled, for each car, all costs actually incurred across all driver trips during the entire MOP-EM reporting week.
- Secondly, we computed the total cost that would have resulted if the users of that particular car had instead used either MOD (the ‘MOD Only’ scenarios) or the mobility package (the ‘Mobility Package’ scenarios) as described above for the entire MOP-EM reporting week.
- Thirdly, if—taking into account all driver and passenger trips for each car over the entire MOP-EM reporting week—the alternatives to the private car in the scenarios above were found to be less costly than the car, the car was abandoned and the driver and passenger trips were reassigned to the relevant alternative mode(s).

## Travel mode costs

For each scenario, we needed cost information for the applicable modes of travel to run our analyses. For active travel modes we assumed zero cost, and for the other relevant modes, we established the costs as follows:

- *Private car costs* as explained above, no assumptions were necessary as regards the costs of private car use, since our dataset contained the imputed costs per kilometre for driver trips. Total costs for car trips of car drivers were computed by multiplying costs per kilometre by trip length. Car passenger trips were assigned a cost of zero in the status quo.
- *MOD costs* the cost per kilometre of the hypothetical MOD service is the variable in focus of our analysis, as our aim in this study is to gain an understanding of the impact of MOD costs on mode choice. For this reason, we did not make a fixed assumption for the MOD cost, but varied these costs in our scenarios from 0.1 €/km to 1.5 €/km.
- *Public transport costs* for the ‘Mobility Package’ scenario, costs for public transport use were also required, as commuting trips were to be shifted from private car to public transport. These public transport cost assumptions varied depending on trip length and trip frequency. For trips 15 km and over we assumed the average user price per kilometre of German railway (using a value of 0.129 €/km; this differs from the cost per kilometre for rail as listed in Table 2 because it covers both trips over and trips under 100 km), and computed the total cost of trips using this kilometre-price and the trip distance. For trips up to 15 km long we based public transport cost assumptions on the pricing scheme of the Berlin public transport association (Verkehrsverbund Berlin-Brandenburg, VBB). For each trip, we assumed a ticket price of €2.80 but not more than €15.20 per week in total. This is because we assumed that if single ticket costs on public transport exceed this amount, travellers would opt instead for a monthly public transport pass. €15.20 is a quarter of the monthly cost for a Berlin public transport pass, hence representing the maximum weekly public transport expenditure if commuters turn to the most economic option.

It should be noted that the cost assumptions for active modes and public transport are somewhat on the low side. The Berlin public transport pricing scheme is among the least expensive in Germany. As a consequence of these low-cost assumptions, the ‘Mobility Package’ scenarios overestimate rather than underestimate the modal shift away from the car. In other words, the scenarios tend to underestimate the cost competitiveness of the private car relative to public transport.

It should be borne in mind that all cost comparisons are based on weekly vehicle trip patterns, and that cars are the analysis units for which these weekly costs are evaluated. This considers that private cars are used by the various household members as both drivers and passengers. While car passengers do not cause additional costs in the status quo, they may give rise to costs in the alternative scenarios.

## Identifying car enthusiast kilometres

Our scenarios as described above assume that all drivers shift modes equally on the basis of very rational mode choice behaviour, with costs savings being the key factor. Logically,



under these scenario assumptions, drivers of cars with high per-kilometre costs shift first. However, there are two distinct groups of drivers with high per-kilometre costs: those who drive little, and those who drive expensive cars (Eisenmann and Kuhnimhof 2019). Among these two groups, the second group seems less likely to abandon the private car and shift modes because through their investment in cars they express an interest in private cars which goes beyond purely utilitarian motivations.

Patterns of expenditure on private cars today reveal clearly that there is a considerable group of drivers who are willing to invest substantially more in their private cars than it seems rational from a purely economic standpoint. For this group at least, cars are likely to be much more than just a utilitarian mobility tool. In the context of this paper, we dub this group ‘car enthusiasts’ and their vehicles ‘enthusiast cars’. It is logical to assume that these cars would not be readily abandoned purely for economic reasons. In other words: the mileage of these ‘enthusiast cars’ would not be part of the mobility demand that could easily be won over by MOD even if driving is costlier than alternatives.

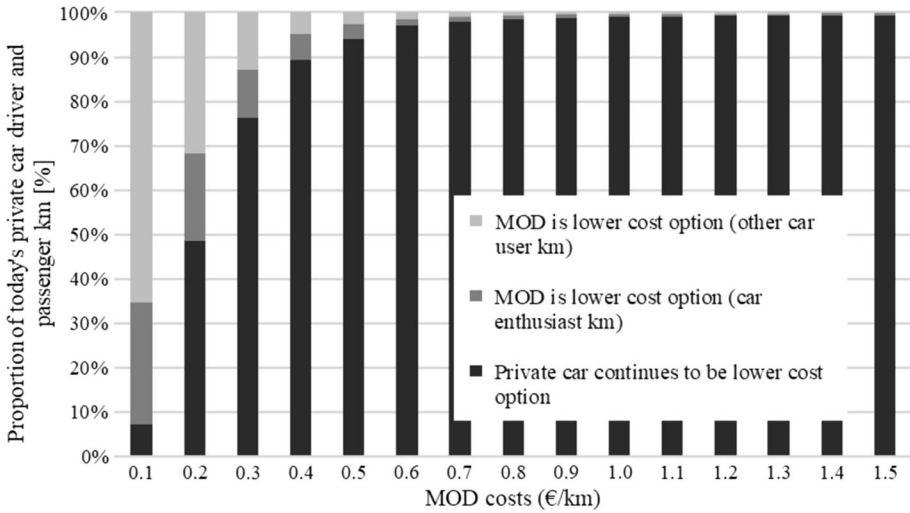
An indicator for identifying possible enthusiast cars is the monthly depreciation of the vehicle. Even today, drivers of high-depreciation vehicles could easily reduce their car-related expenditure by choosing a less expensive vehicle. By choosing not to do so, these car enthusiasts indicate that they would probably also not switch to other modes of travel simply on the basis that they are less expensive. As a threshold for monthly depreciation we chose €125; cars beyond this depreciation threshold are hence defined as ‘enthusiast cars’. This label applies to 22% of the German private car parc; mostly of high-class or new vehicles. (The €125 threshold is somewhat arbitrary. However, we did not find a reliable source which could help identify a clear limit here, and identifying about a fifth of German cars as ‘enthusiast cars’ does seem to be a realistic assumption.)

Our scenarios assume that these car enthusiasts switch to other modes in the same way as all other drivers. This very probably leads to substantially overestimating the modal shift potential induced by the hypothetical MOD service. It is for this reason that we highlight ‘car enthusiast’ kilometres in our presentation of results to indicate the proportion of driver mileage which might not be prone to shifting even though the alternatives to the private represent the lower cost option.

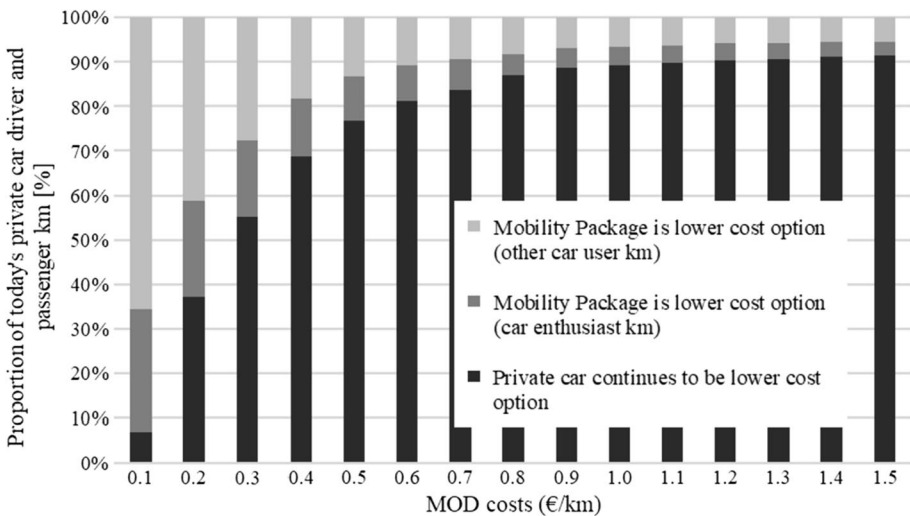
## Results and discussion

As explained above, our scenarios work with the assumption that drivers shift modes as soon as the alternatives are less costly than the private car. For the different scenarios this leads to new hypothetical mode shares which we present in “Appendix B”. These hypothetical mode shares, however, may not be very realistic because obviously drivers do not base their mode choice decisions exclusively on cost considerations. This is well illustrated by the finding that in the ‘Mobility Package’ scenarios a considerable proportion of drivers shifts towards public transport even at MOD costs of 1.5 €/km—reflecting today’s MOD prices. Hence, the scenarios give an advantage to inexpensive modes that doesn’t reflect real mode choice behaviour. Therefore, we present the scenario mode shares in the appendix as a tangible visualization of the scenario impact on mode use under the assumption that users make mode choice decisions on the basis of costs only.

In the main part of the article we focus on another indicator that provides firmer ground for interpretation: Figs. 2 and 3 show (in dark grey) the proportion of the person kilometres covered by private car today for which the car would still be the lower cost option even if



**Fig. 2** Proportion of today's car person km (driver and passenger) by cost-effectiveness of private car and MOD under 'MOD Only' scenario conditions



**Fig. 3** Proportion of today's car person km (driver and passenger) by cost-effectiveness of private car and the Mobility Package under 'Mobility Package' scenario conditions

MOD would be available ubiquitously at the respective price. The light and medium grey shades indicate the proportion of today's private car person kilometres for which shifting to either MOD (Fig. 2) or the 'Mobility Package' (Fig. 3) would be the lower cost option in the respective scenario. Among these, the medium grey shades depict the proportion of 'car enthusiast' kilometres which may not be prone to be shifted.

As can be seen in Figs. 2 and 3 and "Appendix B", only small impacts on cost competitiveness and mode use can be expected if MOD prices are above a level of 0.5 €/km

(bearing in mind that today's car users don't switch to public transport even though it is the lower cost option for about 10% of private car kilometres in the 'Mobility Package' scenario at today's price level). Hence, we concentrate in our interpretation of results on two MOD cost levels: firstly, on 0.5 €/km, the approximate price of today's free-floating car sharing in Germany; secondly, on 0.3 €/km, the approximate average price of today's private cars. 0.3 €/km is also the lower price boundary for urban automated MOD services as discussed in the literature (see Table 2). It should be borne in mind that this low a price level may not be reached for automated MOD outside urban centres, i.e. for a nationwide service as we hypothesize for our scenarios.

*At an MOD price of about 0.5 €/km* the private car continues to be the lower cost option for 94% of car user km if the alternative is 'MOD only' and for 77% if car users also consider public transport and active travel as an alternative ('Mobility Package' scenario). Assuming that car users always opt for the least expensive mode of travel, we would see a 32% combined public transport and MOD modal share in the upper-boundary 'Mobility Package' scenario (the right-hand chart in Fig. 4 in "Appendix B"). This is approximately double the public transport modal share of 15% in the status quo, and would be associated with a drop in private vehicle mileage of about a third. However, the MOD modal share would stand at only 6%. Hence, the observed modal shift (or cost advantage of the alternatives to the private car) in the 'Mobility Package' scenarios would mostly be due to an increase in public transport use—and that is very probably an overestimation looking at today's car users who do not switch to public transport simply because of the price advantage either.

*At an MOD price of about 0.3 €/km* the private car continues to be the lower cost option for 76% of car user km if the alternative is 'MOD only' and for 55% if car users also consider public transport and active travel as an alternative ('Mobility Package' scenario). However, in either scenario a considerable proportion (at least about two fifths) of private car km for which shifting to other modes would be the less expensive option are by 'car enthusiasts' and hence unlikely to be shifted. Assuming that car users always shift to the most economic option, this MOD price level would lead to a combined MOD and public transport modal share of 49% in the upper boundary 'Mobility Package' scenario (the right-hand chart in Fig. 4 in "Appendix B"). However, also in this scenario public transport (31% of the modal share) would be the dominant alternative to the private car and not MOD (19% of the modal share). At the same time, 43% of the person kilometres would still be covered by the private car (driver and passenger).

Figures 2 and 3 illustrate that MOD prices would have to drop substantially below 0.3 €/km for MOD to form a cost competitive alternative to the private car for the majority of private car user km. For urban settings, such MOD prices seem possible—from today's perspective—for (automated) ride-hailing/ride-pooling services, but not for taxi-like services even if they are automated. Ride hailing/ride pooling, however, is associated with disadvantages for travellers (e.g. detours, having to share the vehicle with unfamiliar company), which renders it an invalid comparison with private vehicles.

## Discussion of results and limitations

The key insights from these scenario results can be summarised as follows: firstly, MOD appears unlikely to have substantial impact on mode choice in Germany if it costs more than about 0.5 €/km. If prices are beyond that limit, MOD is unlikely to win over more than a small part of the private car km and the modal share even if car users always choose

the most economic option. While our scenarios specifically addressed vehicle-based MOD, we believe that this insight also to some extent applies to other types of MOD such as e-scooters or shared bicycles.

Secondly, given a price range of 0.3–0.5 €/km—which could be enabled by vehicle automation—MOD could have notable impact on mode choice if car users chose the most economic option. However, it seems likely that this would only happen if prices are at the low end of this price range. This means they would most likely have to be close to the production costs of such a service, which inhibits very profitable automated MOD business models.

Thirdly, unless prices drop below 0.3 €/km, it is rather public transport than MOD which renders the ‘Mobility Package’ a cost competitive alternative to the private car. Consequently, public transport would be the main beneficiary if car users always opted for the most economic options. Obviously, they don’t do so today, because other factors such as availability of public transport infrastructure and service as well as comfort are also relevant for mode choice decisions. Consequently, our projected increases in public transport use seem unlikely. In addition, it should be noted that under real world conditions MOD would also compete against public transport. Hence, the hypothesized increases in public transport use among car users in the ‘Mobility Package’ scenario would be at least partly counterbalanced by some of today’s public transport users switching to MOD.

Only when the MOD prices are 0.3 €/km or less, would the MOD modal share in the ‘MOD Only’ scenarios be higher than in the ‘Mobility Package’ scenarios with similar price—given that car users opt for the most economic option.

We are aware of the limitations of our analyses. We have ignored rural/suburban/urban differences, given that MOD is largely being discussed as an option for urban, and possibly suburban, areas. In any case, the effect of differences in transport supply between urban, suburban and rural areas in Germany is limited mainly to the quality of public transport (e.g. its frequency and coverage) and of the private vehicle experience (e.g. congestion, the search for somewhere to park). The cost of motoring, which is the key factor in our scenarios, is not greatly affected by whether the setting is rural or urban (except possibly when it comes to the cost of parking). Therefore, we believe our results to be meaningful when applied to all these types of areas.

It is evident that drivers do not base their decisions about mode choice on cost considerations alone. As for the modal shares presented in “Appendix B”, we believe that our simplification generally leads to an overestimation of the modal shift towards MOD and public transport in our scenarios. This is confirmed by previous research which proves benefits of car ownership beyond the mobility it enables (Moody et al. 2021) pointing to substantial additional barriers when trying to reduce private car ownership and use. Urban centres, where availability and cost of parking are a major issue, may be the exception. However, while our results regarding modal shift may be an overestimation, the findings on cost competitiveness as presented in Figs. 2 and 3 are firm ground for interpretation.

We are also aware that other authors suggest including additional cost components to account for the total costs of motoring—in particular, capital commitment costs, parking and self-service car washes (Bösch et al. 2018). If we include average costs for these cost components as estimated by (Becker et al. 2020) for Berlin to our average costs, this adds about 20% on top of our average costs, lifting the private vehicle cost per kilometre from 0.30 €/vkm to 0.36 €/vkm. As a result, the hypothesized shifts in mode use would occur at a somewhat higher price level. Nevertheless, this would not alter the overall finding of our study, which is that the skewed distribution of the cost of running private cars substantially dampens the disruptive potential of MOD. Readers should also be reminded that our study

considered TCO of private motoring in order to assume rational mode choice behaviour. Of course, in reality drivers often only consider the out-of-pocket or variable costs of driving which represents another major barrier to the adoption of alternatives to the private car that is widely acknowledged in the literature (Andor et al. 2020; Moody et al. 2021).

## Conclusions

In this study, we use a unique dataset holding individual vehicle information on the cost of owning and running private cars in Germany to analyse the market potential of emerging mobility-on-demand (MOD) services. Previous studies have focused on comparing current and projected MOD prices with the average cost of private cars. Our study aids in the understanding of what actually happens when MOD costs drop below certain levels relative to the cost of private motoring. In this context, the distribution of the costs of motoring are significant, firstly, because they vary strongly between different types of vehicle; secondly, they are also strongly skewed: a large proportion of private car kilometres are driven at relatively low cost.

We applied simplified scenario settings to analyse cost competitiveness of alternatives to the private car for different MOD price levels ranging from 0.1 €/km to 1.5 €/km. The results indicate that MOD prices would have to drop to 0.5 €/km or lower to form a cost competitive alternative for a notable proportion of private car kilometres. If MOD prices drop down to a level of about 0.3 €/km—quite possibly a lower boundary for automated MOD—substantial shifts in modal share could be expected if car users always opted for the most economic option. However, even then the private car would still be the lower cost option for the majority of today's car user kilometres. Moreover, our results indicate that MOD has stronger impact and is likely to be more successful when combined with public transport rather than competing against it.

Aside from the fact that the operation of MOD requires permission in regulated markets such as Germany's anyway, our results illustrate that a substantial impact of MOD is subject to favourable framework conditions which are also set by policymakers. This applies to issues such as parking conditions, the cost of owning and running private vehicles and the availability of high-quality public transport. As for these factors, the conditions would most likely have to toughen up for the private car in order to enable MOD to make much impact. This is because MOD prices—even under conditions of automation—may stay just above the level below which MOD could develop a disruptive potential with no external assistance. Hence, implementing an MOD service that captures a sizeable proportion of the mobility market in locales such as Germany seems possible only if the public, local authorities and policymakers support it.

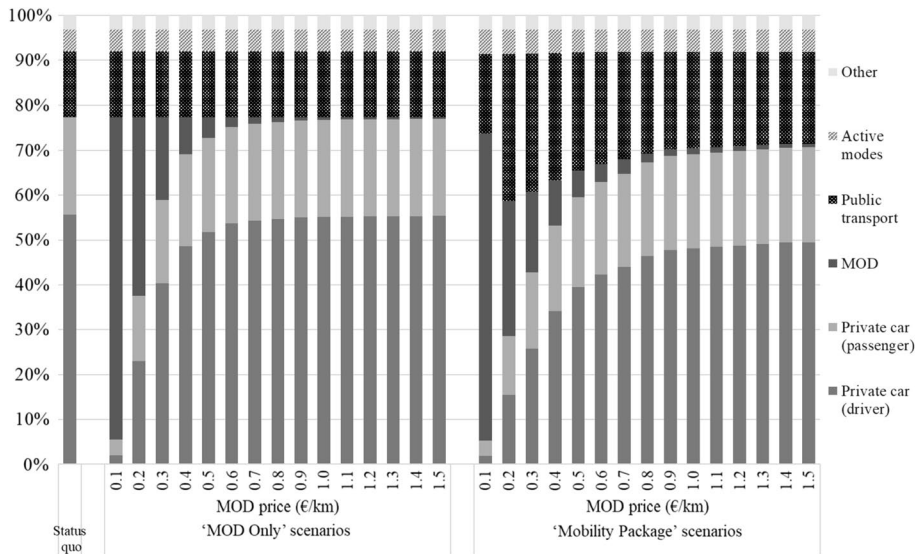
These insights are not entirely new, and they have guided the implementation of MOD in many cities in recent years. However, our analyses substantiate such insights because they illustrate how hard it is for MOD (and any other new competing mode) to compete with existing modes in terms of costs. This has much to do with the cost structure of private vehicles, which are much less expensive for many than average prices would suggest. This is mostly due to the fact that many of those who drive much drive inexpensively. While we use data from Germany to illustrate the implications of this distribution of the cost of motoring, it is evident that many of our findings are more widely applicable.

The implications of the distribution of motoring costs also point to a lever which might be crucial for the success of MOD and which we have not explored in this study: while we applied realistic cost variation across users for the private vehicle and public transport modes, we used a fixed per-kilometre price for MOD. For a fairer comparison, the impact of an MOD price that varies depending on MOD mileage should also be investigated. We propose this as an area for further investigation in ensuing studies.

## Appendix A: Harmonisation of motoring costs

This Appendix A contains a description of the calculations applied to derive harmonised figures for the costs of motoring in Germany across different studies, each of which use different indicators (Table 1).

- Becker et al. (2020) list the production cost per passenger-kilometre for conventional private vehicles as an intermediate step in deriving production costs of automated services for various cities around the world, among them Berlin in Germany. For the TCO comparison in Table 1 of this article we use cost information as listed in Table A.4 in Becker et al. (2020) and their assumptions about vehicle depreciation (linear depreciation over 15 years, i.e. 6.7% annual write-off). In a departure from their methodology we did not include costs of cleaning, parking and capital investment. The reasons for not including these costs components are: firstly, comparability (these costs are not included in the other studies cited in Table 1); secondly, in the case of parking, the costs are Berlin-specific; thirdly, when comparing the costs of motoring with those of alternative modes it is debatable as to whether capital investment should be included or not (the use of alternative modes also causes costs even if they are distributed more evenly over the study period). Moreover, in order to account for the German average, we use the average monthly mileage of private German passenger cars: 1028 km/month, as sourced from (Bäumer et al. 2017), and not the mileage assumed by (Becker et al. 2020) for Berlin (745 km/month).
- Andor et al. (2020) present the average of the imputed monthly costs for the vehicles in their household sample ( $n = 5483$ ) as €425/month broken down by depreciation (€141/month), repair and maintenance (€55/month), tax and insurance (€95/month) and fuel (€134/month). Dividing by the average monthly private car mileage (1028 km/month: (Bäumer et al. 2017)) gave us the cost per kilometre, 0.41 €/vkm.
- Destatis (2018) lists average monthly expenditures for a German household for 2016, broken down by category. Among these categories are financing of vehicles (€120/month), spare parts and repair of vehicles (€52/month) and fuel (€82/month). Note that vehicle tax and insurance are not listed for 2016. We aggregated the listed cost categories (€255/month) and then multiplied this by the number of households in Germany (37.38 million Destatis 2018) to arrive at total car-related expenditures (excluding tax and insurance) for private households in Germany (€9532 million/month). Dividing this by the number of cars with private registration in Germany in 2016 (41.183 million: (Kraftfahrt-Bundesamt 2017)) gave us the expenditure per vehicle covering these cost items (€231/month). To complete the picture, we added expenditures for vehicle tax (€12/month) and insurance (€36/month) per vehicle as measured in the 2013 German income and expenditure survey (Eisenmann and Kuhnimhof 2018). In this way we arrived at €279/month per vehicle as our average.



**Fig. 4** Kilometre-based modal share in the scenarios

## Appendix B: Scenario mode shares

Figure 4 shows the mode use of today's car users under the described scenario conditions, i.e. the hypothetical kilometre-based modal share if car users always opted for the most economic option in the 'MOD Only' and 'Mobility Package' scenarios.

**Authors' contributions** The authors confirm contribution to the paper as follows: study conception and design: CE, TK; scenario analysis: CE; interpretation of results: CE, TK; draft manuscript preparation: TK. All authors reviewed the results and approved the final version of the manuscript.

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**Availability of data and material** See data description in paper.

**Code availability** R-Code can be made available by the authors upon request.

## Declarations

**Conflict of interest** The authors declare that they have no conflict of interests.

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