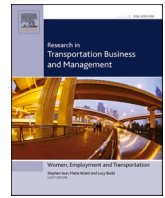


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Cost and viability estimation of shared mobility services

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ABSTRACT

The regulation of novel shared mobility services including their meaningful integration into existing transport systems is widely discussed. While knowledge about the demand side is growing steadily, there is a gap in knowledge regarding the services' supply side, such as their true cost and revenue structures. Therefore, our work presents an extensive cost analysis that captures five different shared mobility operating types: free-floating and station-based car sharing, on-demand ride-pooling, hybrid bike sharing, and shared e-scooters. We aim to provide insights into the services' cost components their magnitudes and resulting viability. To achieve this, we first collect cost information based on an extensive literature review and guideline-based expert interviews. Second, cost components and their cost-generating activities are extracted for subsequent cost modelling. Finally, by adding empirical cost, revenue, and utilisation data, we model operating type-specific costs and viability. Our results indicate that the total costs per passenger kilometre are heavily dependent on the exact operating type. However, in relative terms operations-related costs and vehicle leasing account for more than 50 % of the total costs per passenger kilometre in all services. When comparing the relative shares of the operations-related costs, three different cost structures stand out. First, in both car sharing models, more than half of the operations-related costs originate from cleaning and parking activities. Second, in shared e-scooters and bike sharing, the expenses for field agents and mechanics dominate the operations-related costs. Third, in ride pooling, the operations-related costs are dominated by driver salaries. When estimating the viability almost all services indicate questionable profitability. Since we find a low share of variable costs to be present in all services, we conclude increased vehicle utilisation to be crucial for shared mobility's path to profitability.

1. Introduction

Shared Mobility Services (SMS) allow users short-term access to transportation according to their needs and without ownership (Shaheen, Cohen, Chan, & Bansal, 2020). In recent years, the variety of services has continuously increased (e.g. Arias-Molinares & García-Palomares, 2020) and existing concepts in car- and bike sharing have evolved or been complemented by new services such as ride pooling or shared e-scooters (Krauss et al., 2020b). Due to the novelty of SMS and the fact that operators are mostly private companies (e.g. TNMT, 2019), their impact and interaction with existing transport systems are widely discussed. Questions concerning the services' benefits and limitations, towards meaningful integration, and a proper regulatory framework arise (e.g. Cohen & Shaheen, 2018; Feigon & Murphy, 2016; Machado, de Salles Hue, Berssaneti, & Quintanilha, 2018; Oeschger, Carroll, & Caulfield, 2020).

To answer these questions, profound knowledge about the supply

and demand side of SMS is required. The demand side has already been in the focus of diverse research (e.g. Dia & Javanshour, 2017; Kostorz, Fraedrich, & Kagerbauer, 2021; Krauss, 2020; Krauss et al., 2020a; Schuster, Byrne, Corbett, & Schreuder, 2005). However, knowledge about the supply side, such as the services' costs, is sparse (Vosooghi, Puchinger, Jankovic, & Sirin, 2017). The reasons for this could partly be attributed to both the novelty and the continuous development of SMS (e.g. Button, Frye, & Reaves, 2020; Kagerbauer et al., 2020). Additionally, a competitive market environment leads to difficulties in information collection for two reasons: first, operators treat information about their business models as confidential (Bösch, Becker, Becker, & Axhausen, 2018) and second, inferring costs from the services' pricing yields inaccuracies since profitability is often sacrificed for growing market shares (Weinberg, 2020).

Increasing knowledge about the costs of SMS is crucial for both research and practice. The costs of a service determine its acceptance on the market (Bösch et al., 2018). They are the basis for economically

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viable pricing (Bösch et al., 2018) which itself is a key determinant for the level of demand (Wadud & Mattioli, 2021). Thus, examining cost structures and economic viability of SMS is of utmost importance for transport researchers, planners, and policymakers to assess competitiveness, predict usage, and to derive recommendations for successful integration and regulation of SMS.

To address this knowledge gap, we provide an examination of the costs and viability of multiple SMS. Since operational details of SMS fundamentally influence economic calculations (e.g. Jia, Ma, Xue, & Kong, 2020), we cover a range of five different services: for sequential vehicle sharing we analyse station-based car sharing (SBCS), free-floating car sharing (FFCS), hybrid bike sharing (HBS), and shared electric scooters (SES). For simultaneous vehicle sharing we cover on-demand ride pooling (ODRP). The construction of cost models based on empirical data for these five services allows us to shed light on the general economics of novel shared mobility services and how they perform cost-wise as well as profit-wise.

The structure of our work is as follows. In Section 2 we provide an overview of previous research on the costs and viability of SMS. Subsequently, Section 3 illustrates our methodological approach and cost modelling, including input data and assumptions. Section 4 presents the results, i.e. the calculated cost and viability estimates. In Section 5, we discuss our findings. Section 6 concludes the article and provides an outlook.

2. Background on shared mobility and cost estimation

Our literature review first contains research with a main focus on economic details of SMS. Since we find this kind of literature to be particularly sparse, we then extend our scope to literature that contains economic details of SMS while mainly focusing on other transport-related objectives.

2.1. Previous work with a main focus on SMS economics

For car sharing, Jia et al. (2020) economically analyse two Chinese providers and determine the break-even utilisations for each company's primary vehicle model. Within their use cases with a utilisation of 100 to 400 min per day, the accumulated total costs range from €25,500 to €29,000 per vehicle over three years. The suggested break-even utilisation is between 180 and 325 min per day. When assessing sensitivities, they find the manufacturer's retail price to be among the most influential variables on economic viability, followed by the rental price. The work is specifically adapted to electric car sharing, Chinese market conditions, and based on static costs (e.g. no cost changes for changing fleet sizes). Consequently, possibilities for transferring these results to dynamic developments and real world operating costs in (European) markets are limited.

The work of Stolle, Steinmann, Rodewyk, Gil, and Peine (2019) includes a cost and revenue examination for car sharing for some German cities. By taking into account operating costs, acquisition, fuel and maintenance data, average costs are indicated with €8 to €11 per car and day. Quoted daily revenues range from €3 to €16 per car, depending on the operating model and city. Stolle et al. (2019) indicate a strong case sensitivity and a strong correlation of profitability with exogenous factors like population density. However, the analysis is limited in traceability due to uncertainty about underlying input data and assumptions.

A techno-economical assessment of hub-centric bike sharing and SES is provided by Demeyere (2020). The work contains a dynamic cost model with different scenarios to derive viability conditions. In the base scenario, the costs for an SES operator of 300 scooters are calculated with €6.23 per ride and with €12.54 per ride for a bike sharing operator of 350 bikes. For bike sharing major costs are identified to be operating expenditures and originate from vehicle rebalancing and wage for maintenance workers. For SES systems, charging costs are found to be the dominant cost driver. Results concerning viability suggest that

positive scale effects could lead to profitability for bike sharing systems, if demand was high enough. SES are found to have a high potential for becoming viable based on an identified sensitivity to improvements in battery swapping and vehicle durability. However, the modelled fleet sizes between 300 and 1500 vehicles for both services seem to be comparatively low, given the fact that major German SES and bike sharing providers operate fleets of 12,000 vehicles and larger (Ermisch, 2020; Statista, 2020a; Tack, Klein, & Bock, 2019).

SES have also gained much attention in several kinds of grey literature reports (e.g. Burnins, 2020; Dickey, 2019; Heineke, Kloss, Scurtu, & Weig, 2019; Kamps, 2018; Krummel, Gernant, Stolt, Stolze, & Moschner, 2019; Rose, Schellong, Schaetzberger, & Hill, 2020). These contain conclusions about vital parts of SES' cost and revenue structures with total costs between €2.16 and €2.46 per ride (Burnins, 2020; Dickey, 2019). Profits are calculated to range from €0.57 to €1.22 per ride (Burnins, 2020; Heineke et al., 2019). However, the reports share the common limitation of lacking transparency concerning input data and assumptions. Additionally, many of the calculations were conducted at a time of the business start of SES. The vast development of services since that time, their massive scaling (Bellan, 2021, e.g.), and the focus on the special time of founding a business indicate the necessity for a repeated analysis with comprehensible data and assumptions.

In Bösch et al. (2018) the cost analysis of shared vans, largely corresponds to the definition of ODRP in our work. The analysis is based on consumer retail data that is adjusted to commercial scenarios. The authors identify a multitude of fixed and variable cost components based on which they calculate the operating costs and required minimum charges for economic viability. For shared vans in urban environments they calculate a minimum price of €1.55 per passenger-kilometre (pkm).

2.2. Previous work containing economic details of SMS

When economic aspects are not the primary research focus (e.g. optimising vehicle rebalancing: Clemente, Fanti, Mangini, & Ukovich, 2013), previous research has often drawn on simplified business cases to include economic data of SMS (e.g. Jorge, Molnar, & de Almeida Correia, 2015; Schuster et al., 2005; Yoon, Cherry, Ryerson, & Bell, 2019).

While researching market entry determinants of FFCS, Rühl (2019) includes a calculation on economic viability. It is based on a contribution margin analysis considering usage-dependent variable costs and vehicle-related fixed costs. Results indicate costs of €0.28 per kilometre. Due to the analysis' focus on economic sensitivity of FFCS to policy measures, the modelling scenario is simplified and only includes a uniform fleet of small cars. Additionally, business-related fixed costs such as management are neglected.

The work of Fazel (2014) assesses factors influencing the acceptance of electric mobility, also including an economic analysis of purely electric FFCS. The research approach is based on a net present value (NPV) method accentuating a financial investment perspective. The results suggest total costs of €0.75 and profits of roughly €0.01 per kilometre, indicating potentially viable operations. However, the analysis remains highly case-specific due to factors such as a single-model vehicle fleet, a purely electrical fleet or the full cost assignment of charging pile installation in the free floating zone to the operator.

Wortmann, Syré, Grahle, and Göhlich (2021) simulate e-moped fleet sizes in Berlin. Their goal is to examine the substitution potential to car trips including possible economical and environmental effects. Their results indicate costs between €0.11 and €0.13 per kilometre. However, the simulation applies relatively high utilisation rates (up to 20 rides per vehicle and day) in comparison to other empirical shared mobility studies that indicate four to seven trips per vehicle and day (Giordano, Vassio, & Cagliero, 2021; Habibi et al., 2017; Tack et al., 2019).

Valuable insights about the economic viability of shared mobility business cases are also contained in pitch decks of operators, i.e. presentations aiming at attracting venture capital (see Bird Rides, 2021; Palella, Profumo, & Hannestad, 2019). For example, Palella et al. (2019)

provide qualitative and quantitative data of cost components assuming different fleet sizes for SES. SES costs are assumed to be US\$ 2.44 per trip with a fleet of 250 scooters and US\$ 1.84 with a fleet of 750 scooters. Again, limited insights into underlying input data restricts the reproducibility of these results.

2.3. Research gap and contribution

To conclude, previous work on costs and viability estimations of shared mobility is noticeably heterogeneous in its findings. A summary about the estimated cost ranges per service in literature can be drawn from Table 1. Common limitations of previous work are a neglect of the real-world diversity of cost components and fully traceable, empirical input data. Further limitations include simplified cost modelling or a research focus on simplified operations of one single SMS. These limitations underline the need for our research on costs and viability of SMS building on a diverse and traceable set of real world data and assumptions. By using a highly detailed approach drawing on dynamic costs and applying this to five services, we aim to build a basis for real world cost and viability modelling of SMS. This way, we aim to answer three research questions: Which cost components are inherent to business models of SMS (RQ I)? What are the estimated magnitudes of these cost components when offering SBCS, FFCS, HBS, SES or ODRP in Germany (RQ II)? And, how viable are current German B2C business models of the five selected SMS based on our cost modelling (RQ III)?

To answer these questions, we first derive general cost-related information on shared mobility from literature and industry. From this, we infer cost components and arrange them into key cost areas in the second step. Third, we break down the inferred cost components into their underlying cost generating activities to yield a systematic cost estimation framework. Fourth, quantitative estimates and economic viability for each of the five SMS are modelled by adding their individual empirical cost, utilisation, and revenue data. Following this approach, we are able to provide an empirically-based cost-model for five SMS that allows insights into cost magnitudes and viability.

3. Material and methods

To yield as accurate costs and viability results as possible, we synthesise a four-step procedure, as illustrated in Fig. 1.

First, since a firm's costs stem from its performed activities (Porter, 1996), we qualitatively identify cost-related details based the SMS value chain. This is done based on a systematic literature review and guideline-based expert interviews. We draw and adapt the

Table 1
Overview of cost ranges, sources, and limitations for various service types.

Cost Ranges of SMS in literature				
Service Type	Cost Range	Source	Limitations	
FFCS	0.25–0.78	€/km	Rühl (2019), Fazel (2014)	Simplified modelling
	8–11	€/car & day	Stolle et al. (2019)	Limited insights into input data/assumptions
SBCS	0.03	€/km	Jia et al. (2020)	Chinese market, Simplified modelling
SBBS	12.54	€/ride	Demeyere (2020)	Limited insights into input data/assumptions, comparably small fleet
SES	2.14–6.23	€/ride	Demeyere (2020)	Limited insights into input data/assumptions, comparably small fleet
ODRP	1.55	€/Pkm	Bösch et al. (2018)	Focus on cost reduction effects by automation
E-moped Sharing	0.11–0.13	€/km	Wortmann et al. (2021)	Special service type, comparably high utilisation

methodological approach for the systematic literature review (SLR) from Brocke et al. (2009) and Webster and Watson (2002) (for search strategy see Appendix A). As we find primary data in literature to be scarce, we extend the knowledge by conducting 37 guideline-based expert interviews based on the method of Meuser and Nagel (2002) and Valenzuela and Shrivastava (2002) (for questionnaire see Appendix B).

Second, we categorise the gained qualitative knowledge on cost-related details of SMS into four key areas of vehicle-related, operations-related customer-related and overhead-related cost components. In order for the reader to better follow our line of argumentation throughout this section, we provide the final categorisation of 22 cost components at this stage although it represents a first result of our work. We identify the following four key cost areas of SMS: 'Vehicle-related costs' feature cost components that are already entailed in private vehicle ownership. 'Operations-related costs' are incurred by an operator's daily activities for providing and maintaining sharing-ready vehicles. 'Customer-related costs' are associated with all activities that are required for selling and distributing the mobility service to customers. 'Administration and overhead' costs arise to enable general business activities irrespective of the actual business case or industry. Table 2 shows these four identified key cost areas of SMS and the cost components that we systematically assign as described in Section 3.

In the third step of our methodology, each cost component is decomposed into its underlying cost-generating activities. This is since the cost components are composed of multiple integral parts (called activities) that react to different cost drivers. Therefore, these activities need to be modelled separately. An illustrative example are the costs of vehicle acquisition and leasing which react to vehicle-holding time (time-based depreciation) and utilisation (usage-based depreciation). Following this logic, all cost components from Table 2 are broken down into their underlying cost-generating activities. Based on an activity's primary cost driver, the activities are then systematically assigned to a five-level hierarchy of activity-based costing (ABC), adapted from Wouters, Hilton, Selto, and Maher (2012). All activities with immediate utilisation-dependent cost magnitudes are assigned to the 'unit-level'. Their primary cost driver is the services' utilisation expressed by the quantity of trips, the distance of an average trip, and the number of vehicles (which is why we will also need to collect empirical usage data for each service later on). The 'batch-level' contains all operations-related activities that are carried out on a per-vehicle basis and that are required to keep the vehicles in a sharing-ready state (Demeyere, 2020). The number of vehicles (fleet size) represents the cost driver on this level. 'Product-level' activities are required for the distribution and sales of the SMS. They occur irrespective of vehicle utilisation or fleet size. Finally, the 'company-level' contains activities that are necessary to assure general business capability, such as general management and administration. The final activity assignment then represents our general cost estimation framework and can be drawn from the left of Table 4.¹

Fourth, by adding individual utilisation, revenue and cost data, the general cost estimation framework is adapted for each of the five examined SMS. This generates five operating type-specific cost models that allow to dynamically model cost and revenue estimates of our five selected services. The details of this fourth step are provided in the following section.

Before developing the type-specific cost models, we describe our overall modelling assumptions: First, we limit our research to a general estimation of industry-representative cost and revenue structures of country-wide operating businesses in general German market conditions. Our research focus is on direct monetary costs and revenue

¹ Since we assume operators with a general market of uniform customers, activities for individual clients do not occur and we exclude the 'customer-level' in our modified ABC.

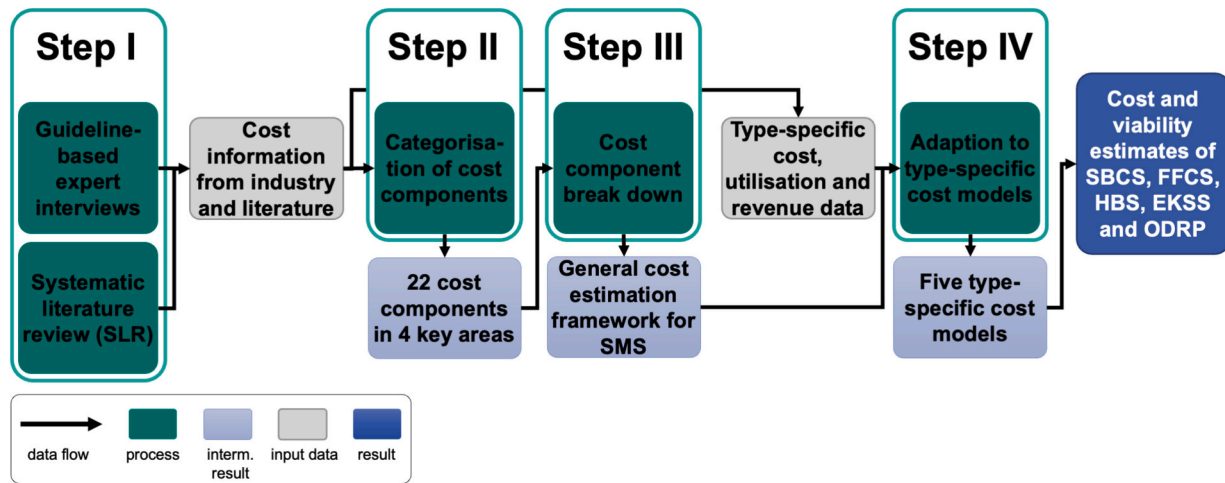


Fig. 1. Four step sequential research approach to assess the cost and revenue structures of SMS (own visualization).

Table 2

22 identified cost components of SMS value chains and their assignment to four key areas.

1. Vehicle-related cost components	
Acquisition/Leasing	Expenses for acquiring/ leasing vehicles for sharing operation.
Fuel/ Energy	Expenses for fuel/ energy and refuelling/ charging processes.
Insurance (&MVT)	Premiums of motor vehicle insurance and motor vehicle tax.
Maintenance	Expenses for vehicle maintenance and repair parts.
Cleaning	Expenses for vehicle cleaning.
Parking	Rent of parking spaces/ Expenses for municipal parking permits.
2. Operations-related cost components	
Driver salaries	Wages of driving personal.
IoT & Fleet software	Expenses for hard- and software that enables digital fleet and sharing management.
Rebalancing	Expenses for relocating sharing vehicles in the operating area to increase system capacity and user satisfaction.
Infrastructure	Expenses for charging infrastructure/ physical hardware installations within the area of operation/ the central depot.
Vandalism/ Theft	Expenses that are caused by deliberate damage/ theft of vehicles.
3. Customer-related cost components (Sales/ Distribution)	
Mobile app	Expenses for development/ operation of customer mobile app.
Website	Expenses for development/ operation of customer website.
Customer support	Expenses for service-centre agents (e.g. customer hotline/ chat/ mail).
Marketing	Expenses for marketing activities (e.g. ads, vouchers).
Payment provider	Fees/ commission of digital payment services (e.g. PayPal/ credit card).
Billing/ Invoicing	Expenses for invoicing services (creation, transmission and archiving).
4. Cost components of administration and overhead	
Management salaries	Wages and expenses for management and admin personal.
Office & Utilities	Office rent and expenses for utilities such as IT etc.
Capital costs/ Interest	Expenses for access to borrowed capital or resources.
R&D	Expenses for product/ service development/ refinement.
Permit fees	Region- / city-specific charges service deployment.

streams of representative profit-oriented shared mobility providers with a business to consumer focus in Germany. In order to draw conclusions about the independent economic viability of SMS business models, we consider local case-specific modelling parameters as exogenous and only include endogenous variables like technical and organisational system design. While exogenous factors such as climate, local demographics,

population density, local regulations, governmental subsidies, technological advancements or pandemic-related effects are of utmost importance for a provider’s viability (e.g. Becker et al., 2020; Stolle et al., 2019), they are highly context-specific, beyond the provider’s direct control, and may distort an assessment of general business viability of SMS. Hence, these factors are excluded from modelling^{2,3}. Second, a further key assumption is SMS businesses’ relation to assets. As SMS are primarily from the start-up-sector (Ackermann, 2021), flexibility and scaling (growing market shares) are among their primary goals (Shulman, 2019). We hence assume a tendency towards avoiding capital tie-up for SMS in order to achieve a higher degree of flexibility (Kachaner & Whybrew, 2014), scale more rapidly and inexpensively (Libert, Beck, & Wind, 2016), and have benefits at attracting investors (Libert et al., 2016). Thus, a central modelling assumption of this work is that SMS tend towards outsourcing business activities as much as possible (e.g. Surve Mobility, 2021). When asset acquisition (e.g. vehicle acquisition or mobile mobile application (app) development) can not be avoided, we assume assets to either be leased or acquired with borrowed capital, yielding interest payments. For cost modelling, the calculation of loan repayments and lease payments is based on the assumption of linear depreciation over the respective economic planning period as per Wortmann et al. (2021) and Bösch et al. (2018). Third, all considered wages are converted into employer burdens as described by Brändle (2013) also including additional such as a lump sum for office rent, information technology (IT), utilities and training for management and admin personal. The full details concerning further assumptions can be drawn from Appendix E.

3.1. Constructing operating type-specific cost models

To adapt the general cost estimation framework to operating type-specific models, two steps are required for each examined service: first, a synthesis of operating type-specific input data reflecting real-world scenarios is necessary, i.e. utilisation, revenue, and cost data. Second, building on this data, operating type-specific cost formulas for each of the cost-generating activities must be formulated. The aggregate of these cost formulas per operating type then forms the final operating type-specific cost model.

² Remainders of exogeneous influences may only indirectly be reflected by our averaged empirical demand data.

³ The exclusion of 14.5 % accounts for non-availability in the fleet (e.g. maintenance).

3.1.1. Deriving data input

Utilisation data is required to model costs that are driven by the services' usage (e.g. costs of energy or fuel).

Data of SES utilisation is shown in Table 3. For readability we only provide SES utilisation at this place. The derivation of utilisation data on HBS, ODRP, SBCS, FFCS can be found in Appendix C.

Together with fleet size, we can calculate the total demand for each operating type as utilisation (U) (see Appendix C). The fleet sizes are derived using data from previous work of (Krauss, Reck, & Axhausen, 2023) that is based on multiple sources (e.g. project insights, reports, newspapers or provider data) for the 14 largest German cities as per German federal bureau of statistics (2020). Due to isolated missing data points, we average the available data for each examined service, and then multiply it by 14 to simulate operators that are active in all 14 largest German cities at once. This is to assume the same market conditions among our examined services and to not introduce a bias due to different economies of scale.

Since some costs are revenue-based commissions (e.g. payment provider fees), revenue estimates are required. Furthermore, revenue estimates are crucial for later viability estimation of our selected services (RQ III). We derive revenues by combining our calculated utilisation with publicly available pricing information. For the assumed pricing we average German pay-per-use fees of major providers and exclude dynamic pricing (e.g. ShareNow, 2021a), reduced tariffs during interim parking and subscription-based pricing (e.g. Cambio, 2021, see Appendix D).

For the derivation of cost data, a multitude of assumptions and interim calculations are necessary. Table 4 summarises our synthesised data input for all examined SMS. For consistency, common data inputs are used for cost modelling on the product- and company-level. This assures that a later comparison of results between different operating types refers to true operational differences (further details on this data are in Appendix E). In contrast to this, the input data on the unit- and batch-level are highly operating type-specific and must be derived separately for each examined service.

Again, for readability, we only illustrate the derivation of unit- and batch-level data for SES and refer to Appendix F for the other four examined services.

Given the lack of data for usage dependent e-scooter depreciation, we assume the full depreciation of SES to be time dependent. In case of SES depreciation costs are hence exceptionally assigned to the batch-level only. The associated costs are approximated by average e-scooter acquisition costs and average e-scooter lifetime. Acquisition prices vary considerably between sources (e.g. Demeyere, 2020; Joyride, 2021a). We assume the Okai ES 400 B model currently used by major German

SES-providers (e.g. Floemer, 2020). As stated by experts during the interview process, e-scooters are usually imported from China. Based on the pricing scheme of Joyride (2021a) and adding German turnover tax, customs and shipment insurance, total costs per e-scooter of €736.81 are approximated.⁴ Interpolating between Schellong et al. (2019) and Bird Rides (2021), an e-scooter lifetime of one year is assumed as depreciation period with a residual value of zero.⁵ Following Wortmann et al. (2021), we assume that 50 % additional e-scooter batteries are necessary to enable swapping empty e-scooter batteries in the field. Due to the limited availability of SES-specific battery price data, we use pedelec battery price data for SES approximation. According to Hommen (2021) and assuming a price decrease of 35 % since 2018 (Statista, 2020b), we calculate pedelec batteries with €325.50. By linearly scaling this price using the nominal battery capacities of e-scooters and pedelecs (0.69 kWh for e-scooters (Okai, 2021) and 0.40 kWh for pedelecs as average of Röttig (2020) and Wertgarantie (2021)), e-scooter battery price is estimated as €561.49. Battery depreciation is assumed identical to e-scooter depreciation. Finally, the sharing-vehicle costs can be calculated as sum of the vehicle and battery depreciation costs, as shown in Table 4. The costs are translated into a lease rate including interest since acquisition is assumed to be based on borrowed capital.

Electricity costs for e-scooters are usage dependent and hence assigned to the unit-level. To calculate the associated charging costs including losses, several interim calculations are necessary. First, the nominal e-scooter battery capacity of 0.69 kWh is translated into an effectively usable capacity of 0.45 kWh.⁶ Charging consumption is assumed to be subject to a surcharge factor of 1.11 to include charging inefficiencies ($\eta = 90\%$). This way an energy consumption of 0.50 kWh per battery charge is calculated. Electricity price is set to €0.36/kWh or all services, as per ADAC (2021). Using the charging consumption and electricity price, this translates into costs of €0.18 per battery charge. To transfer these costs into variable costs per usage within the cost model, the e-scooter range per charge needs to be known. Manufacturer data for our model indicates a 55 km range (Okai, 2021), based on the battery's nominal capacity and thus translates into 36 km for our calculated usable battery capacity. However, this value is still high and might not adequately reflect e-scooter usage patterns within sharing scenarios (e.g. more but shorter rides with higher amount of accelerations and brake applications). Combining range information of major providers and the interviews, e-scooter range within the cost model is hence set to 22 km.

The expenses for maintenance parts per e-scooter and month are assumed to be usage dependent (unit-level) and adopted from Palella et al. (2019).

Based on expert interviews with a German insurance start-up, the costs for liability insurance are determined as €25 per e-scooter and year and assigned to the batch-level.

The costs for service vehicles are based on averaged cost data of eight typical service vehicle models (such as Nissan E-NV200, Mercedes Vito/Sprinter and more) that were mentioned in the interviews. Daily mileage is assumed to be 120 km. The average service vehicle holding period is assumed as four years. Based on the cost data of ADAC (2021), lease payments are derived as follows: first, a residual value of the average vehicle is determined using the holding period and value loss of ADAC (2021). Second, purchasing prices are assumed to be subject to a discount rate of 30 % following Bösch et al. (2018) due to the large volume of acquired cars. To account for optional equipment and technical

Table 3
Assumed utilisation data of SES.

SES utilisation data			
Name	Value	Unit	References/ Notes
Avg. trip duration	14.80	min	Calculated using avg. trip distance and speed of McKenzie (2020), Button et al. (2020) and Almannaa et al. (2020). ^a
Avg. trip distance	1.86	km	Based on German cities of Tack et al. (2019).
Avg. trips/veh.	3.70	trips/day	Based on German cities of Tack et al. (2019).
Avg. mileage/veh.	2505.18	km/year	Calculated using avg. trip distance and avg. trips/veh.
Avg. veh. Depreciation period	1.00	years	Based on medium range of 3 months in Schellong, Sadek, Schaetzberger, and Barrack (2019) and 24 months in Bird Rides (2021).

All values rounded to two decimal places.

^a Due to higher maximum speeds of scooters in US, these values are scaled by ratio of German to US maximum speeds.

⁴ Assuming shipment insurance of 10\$, 6,5 % customs duty and 19 % turnover tax.

⁵ The expert interviews conducted underlined working with the assumption of 0 as final costs for the vehicles in the SES business.

⁶ Adjustment is based on an assumed 90 % average capacity due to ageing (LG Chem, 2014), preventive capacity capping of 15 %, temperature induced capacity drop of 10 % (see E-Scooter Blog, 2020; Statista, 2020d; Ma et al., 2018), and expected self discharge of 1 % per day.

Table 4
Synthesised input data for all operating type-specific cost models, rounded to full Euros.

Activity	FFCS	SBCS	ODRP	HBS	SES	Unit	Period
Unit-level							
Vehicle depreciation (usage-based share)	20	43	32	n/a	n/a	€/veh.	/month
Fueling/Charging	–	–	–	–	–	–	–
Energy/Fuel	83	122	305	0	2	€/veh.	/month
User incentives for refuelling, /–charging	5	n/a	n/a	n/a	n/a	€/refuel	
Maintenance parts	49	58	246	7	25	€/veh.	/month
Payment provider (incl. Billing & invoicing)			2			% of rev.	/trip
Batch-level							
Vehicle depreciation (time-based share)	244	208	194	28	86	€/pers.	/month
Insurance & motor vehicle tax		124	160		2	€/pers.	/month
Operations	–	–	–	–	–	–	–
Depot/Warehouse & Garage			5			€/m ²	/month
Field agents & mechanics			34,467			€/pers.	/year
Service vehicles	n/a	n/a	n/a	1082 ¹	994 ¹	€/veh.	/month
Customer-support			2460			€/agent	/month
Drivers	n/a	n/a	34,467	n/a	n/a	€/pers.	/year
Variable rebalancing	14	n/a	n/a	n/a	n/a	€/reloc.	
Cleaning		116	232	n/a	n/a	€/veh.	/month
Vehicle parking	105	100	n/a	n/a	n/a	€/veh.	/month
IoT & Fleet software	–	–	–	–	–	–	–
Vehicle telematics		7			5	€/veh.	/month
Fleet management software		7			5	€/veh.	/month
Sharing operations software			5			€/veh.	/month
Vandalism/Theft	n/a	n/a	n/a	38	89	€/veh.	/year
Infrastructure depreciation	–	–	–	–	–	–	–
Station infrastructure depreciation	n/a	n/a	n/a	2743	n/a	€/station	/year
Charging infrastructure depreciation	n/a	171	398	n/a	n/a	€/BEV	/year
Product-level							
Customer facing mobile app			219,145			€	/year
Customer facing website			14,690			€	/year
Marketing activities			9.10			% of rev.	/year
Company-level							
Overhead/Management (incl. Office etc.)			63,389			€/pers.	/year

n/a = not applicable. Calculated figures are gross prices and include assumptions as outlined in Table E.5.

1 = figures represent gross prices that are not directly convertible into net prices since they contain an amount of insurance costs which are not subject to VAT.

modifications of new vehicles that enter the service vehicle fleet such as retrofitting to fit e-scooters and batteries in the loading areas, or telematic devices (e.g. Initiative [Leverkusen, 2020](#); [Intellicar, 2020](#)), an increase of 25 % of the original list price is assumed. Third, with the adjusted purchasing price and the previously calculated residual value, a linear depreciation rate is derived. Fourth, based on this depreciation rate and an assumed interest rate of 3 % (see Table E.5), value loss can be converted into a leasing rate plus interest as described in [Maple Tech \(2021\)](#). This finally yields expenses of €993.70 per service vehicle and month as the sum of calculated lease payments and fuel, insurance, motor vehicle tax (MVT), and maintenance costs of [Maple Tech \(2021\)](#). The associated costs are assigned to the batch-level since the number of required service vehicles of an operator is assumed to vary with fleet size, following ([Palella et al., 2019](#)).

Since today's providers rely on advanced IoT and fleet software to digitally manage and operate sharing-ready vehicles, the cost model needs to address this. First, telematic devices are required to connect vehicles to the internet, enabling digital access for users and operators (e.g., locking/ unlocking). Second, two software layers enable the digital operations of the fleet: fleet operations software for real-time vehicle monitoring and sharing operations software to manage customer interactions with the fleet, operating areas, and pricing. Finally, a mobile application is required as a customer access point to the ser. For internet of things (IoT) and fleet software costs, the data of two providers of telematics and fleet software are obtained during the research period. We interpolate this data with [Joyride \(2021b\)](#) and [Fleetio \(2021\)](#) to obtain the displayed costs in Table 4.

According to [Potor \(2019\)](#), a share of 1.00 % of the sharing vehicle price is assumed for vandalism and theft per e-scooter and month. The corresponding expenses are assigned to the batch-level.

3.1.2. Operating type-specific cost models

Using the synthesised input data from above, we formulate operating type-specific cost models. For each of the cost-generating activities within the general cost estimation framework, a cost formula is developed, which dynamically models the associated costs.

Again, for the product- and company-level, common cost modelling for all five services is applied. The cost calculation of mobile app, website and marketing costs is covered by an overall cost function addressing all marketing- and distribution-related costs.

$$C_{mktg}[\text{€/day}] = \left[\text{share}_{mktg} \cdot (\text{fleet} \cdot \text{trips}_{veh} \cdot \text{rev}_{trip} / 1.19) + c_{app} + c_{web} \right] / 365 \cdot \frac{1}{1.19} \quad (1)$$

share_{mktg} is the annual share of revenue spent for marketing (see Table 4), fleet is the operator's fleet size, trips_{veh} marks the average trips per vehicle, rev_{trip} the average revenue per average trip, and c_{app} as well as c_{web} mark the annual costs for the mobile app and the website as stated in Table 4.

Since it is indicated that the operational system-designs and the utilisation of the operating types considerably differ (see e.g. Tables C.2 and 3 in the Appendix), the calculation of management costs needs to allow operating type-specific labour intensities in terms of Full Time Equivalents (FTEs) per vehicle. At the same time distortions to the scaling behaviour of management costs between the five examined

operating types need to be avoided, to allow unbiased comparison of the results. To meet both of these requirements, we use a common cost formula and adjust it to the five examined operating types via a scaling factor f that is derived from real-world data (see Appendix E).

$$C_{mgmt}[\text{€}/\text{day}] = [f \cdot \sqrt{\text{fleet}}] \cdot c_{mgmt-wage} / 365 \quad (2)$$

with f as the operating type-specific adjustment factor, fleet as the operator fleet size, and $c_{mgmt-wage}$ as the costs per management employee of Table 4.

The unit- and batch-level cost formulas are modelled individually for each operating type. Again, we use SES as an example and refer to Appendix F for the other services. All cost calculations of this section consider input tax deduction to transform the gross prices of Table 4 into net prices.⁷

The total energy costs for SES are calculated by

$$C_{fuel}[\text{€}/\text{day}] = \text{fleet} \cdot c_{fuel} \cdot \frac{12}{365} \cdot \frac{1}{1.19} \cdot d \quad (3)$$

with fleet as the assumed fleet size and c_{fuel} as the costs for energy per vehicle and month (Table 4). d is a scaling factor to allow changing the utilisation data within the cost model. It linearly scales any utilisation input in relation to the assumed base case from Appendix C.

With $c_{maint-parts}$ as the cost for maintenance parts per vehicle and month (Table 4), the maintenance parts costs are calculated using

$$C_{maint-parts}[\text{€}/\text{day}] = \text{fleet} \cdot c_{maint-parts} \cdot \frac{12}{365} \cdot \frac{1}{1.19} \cdot d \quad (4)$$

Payment provider costs are calculated by

$$C_{paym}[\text{€}/\text{day}] = p_{paym} \cdot \text{fleet} \cdot \text{trips}_{veh} \cdot \text{rev}_{trip} \cdot \frac{1}{1.19} \quad (5)$$

with p_{paym} as the commission of the payment provider in percent of the total revenue, trips_{veh} as the average number of trips and rev_{trip} as the average revenue per trip.

The time-dependent vehicle-leasing costs are

$$C_{Veh_{time}}[\text{€}/\text{day}] = \text{fleet} \cdot c_{depr_{time}} \cdot \frac{12}{365} \cdot \frac{1}{1.19} \quad (6)$$

with $c_{depr_{time}}$ as the time dependent loan repayments per vehicle based on depreciation and interest (see Table 4).

The insurance and MVT costs are

$$C_{ins}[\text{€}/\text{day}] = \text{fleet} \cdot c_{ins} \cdot \frac{12}{365} \quad (7)$$

with c_{ins} as the cost for insurance and MVT per vehicle and month of Table 4.⁸

Based on the interviews, an SES depot including warehouse and garage is assumed to have a size of approximately 400 m² on average with a rate of approximately 0.5 m² of necessary space per e-scooter. This is also in line with Demeyere (2020).⁹ Hence, the costs for depot, warehouse and garage are assumed as

$$C_{whs}[\text{€}/\text{day}] = \left| \frac{\text{fleet}}{800} \right| \cdot 400 \text{m}^2 \cdot \text{rent} \cdot \frac{12}{365} \quad (8)$$

with rent in €/m² (see Table 4).

Following Palella et al. (2019), we use a rate of one service vehicle per 188 e-scooters. Thus, the total costs for the operation of service

vehicles in SES are calculated as

$$C_{s-veh}^*[\text{€}/\text{day}] = \left| \frac{\text{fleet}}{188} \right| \cdot c_{s-veh} \cdot \frac{12}{365} \cdot \frac{1}{1.19} \quad (9)$$

with c_{s-veh} as the monthly full costs for service-vehicles from Table 4.¹⁰

To derive a cost function for the field agents and mechanics in SES, their dependencies on the fleet size have to be known. For the mechanics, based on Palella et al. (2019), an average rate of one mechanic per 375 e-scooters is assumed. The number of field agents is assumed to be linked to the required amount of service vehicles: as a baseline we assume one field agent for each service vehicle and 0.4 additional agents per service vehicle (Palella et al., 2019) per increase in average number of daily trips. Hence, the cost calculation for field agents and mechanics in SES is

$$C_{agent_{field}}[\text{€}/\text{day}] = \left(\left| \frac{\text{fleet}}{375} \right| + \left| \frac{\text{fleet}}{188} + \frac{\text{fleet}}{188} (\text{trips}_{veh} - 1) \cdot 0.4 \right| \right) \cdot \text{wage}_{field} / 365 \quad (10)$$

with $\text{fleet}/188$ as the number of required service vehicles and wage_{field} as the field agent and mechanic annual wage expressed as employer full costs (Table 4).

For the customer support agents per sharing vehicle, we assume outsourced customer support agents and slightly increase the base value of moped sharing in (Wortmann et al., 2021). This is based on the assumption of higher utilisation of SES than mopeds. Therefore, the costs for customer support agents are

$$C_{agent_{cs}}[\text{€}/\text{day}] = \left| \frac{\text{fleet}}{1000} \right| \cdot c_{agent_{cs}} \cdot \frac{12}{365} \cdot \frac{1}{1.19} \quad (11)$$

with $c_{agent_{cs}}$ as the monthly costs per agent (Table 4) and fleet as fleet size (Appendix C).

The total costs for vehicle telematics, fleet operations software and sharing operations software are

$$C_{IoT}[\text{€}/\text{day}] = \text{fleet} \cdot \left(c_{tel} + c_{fleet_{ops}} + c_{share_{ops}} \right) \cdot \frac{12}{365} \cdot \frac{1}{1.19} \quad (12)$$

The costs for vandalism and theft are calculated using

$$C_{vand}^*[\text{€}/\text{day}] = \text{fleet} \cdot c_{vand} / 365 \quad (13)$$

with c_{vand} as the annual costs of vandalism and theft per e-scooter (Table 4).

All individual cost functions for single activities return the activity's respective costs in Euro per day. Hence the total costs per pkm (or pkmb),¹¹ C_{pkm} , can be derived by summing up the results of all individual cost functions and dividing this sum of costs by the daily utilisation of an operator's whole fleet.

Revenue estimates are derived based on the utilisation and revenue data from above, Appendix C and D. The total revenue of each operating type is calculated as

$$\text{Rev}[\text{€}/\text{day}] = \text{fleet} \cdot \text{trips}_{veh} \cdot \text{rev}_{trip} / 1.19 \quad (14)$$

Following Fazel (2014), the profit calculation uses a corporation tax rate of 15 % and the assumption of simplified trade tax rate of 15 %. Hence, a total tax rate of 30 % on all profits (except for an allowance deduction of €24,500 as in, Gründerplattform, 2020) is assumed, leading to the profit and loss calculations (PnL) as

⁷ Assuming German value added tax (VAT) of 19 %

⁸ Since insurance premiums are not eligible for input tax deduction, the German VAT is not considered in this equation (Prosaldo, 2018).

⁹ Since rent prices usually do not contain VAT (Brennecke, 2007), VAT is not considered.

¹⁰ The formula is simplified for consistency. The shown c_{s-veh} in Table 4 cannot directly be converted into net prices by division by VAT since they include a sum of insurance and MVT costs of €204.25 which is not subject to VAT.

¹¹ For ODRP the total passenger-kilometres booked (pkmb) are used since this is the most suitable unit of reference for the achieved revenue. Further explanations on pkmb can be found in Appendix C

$$PnL[\text{€}/\text{day}] = \begin{cases} (Rev - C_{pkm} \cdot U) \cdot 0.7 & \text{for } Rev - C_{pkm} \cdot U \geq 0 \\ Rev - C_{pkm} \cdot U & \text{else} \end{cases} \quad (15)$$

with *Rev* as the total sales revenue of Eq. 14, *C_{pkm}* as the total costs per pkm and day and *U* as an operator fleet’s accumulated utilisation per day.

4. Results

The results of our work are divided into three sections. We first provide findings about SMS’ cost structures. Second, we find it important to validate our calculations in relation to other existing cost analyses. Third, after validation the viability estimates are provided.

4.1. SMS cost structures

Our cost models yield the total costs per pkm for all five examined shared mobility operating types. To obtain aggregate cost results in respect to our identified cost components mentioned in Table 2 we now recompose the cost-generating activities again that were decomposed to different cost functions for separate cost modelling in Section 3 (e.g. time-based and usage-based vehicle depreciation together build the total vehicle leasing costs). The resulting cost estimates and their respective shares are visualised in Fig. 2 including the assumed total utilisation and fleet size. The total estimates of FFCS, SBSCS, HBS, and SES are provided in Euro per pkm. For ODRP, the costs are provided per customer-paid transport kilometre, respectively pkmB. It is again important to note that the costs are calculated using the characteristic empirical utilisation and fleet sizes for each examined service (see Section 3), since we focus on reflecting their real-world sharing scenarios as close as possible.

The total costs for all services range from €0.66 per pkm in case of SBSCS to €1.76 per pkmB in case of ODRP. Whereas the costs of most cost components noticeably differ between the operating types, the sum of business-related fixed costs for management/ administration and marketing/ distribution is almost constant and lies between €0.14 and €0.18 per pkm for all services. For FFCS, SBSCS and ODRP, the costs of energy/ fuel are in an identical absolute range and amount to €0.07 or €0.08 per pkm (or pkmB). With a share of at least 30 % of the total costs per pkm, the operations-related costs represent the major cost category for all operating types. In case of ODRP, it even accounts for more than 80 % of the total costs per pkmB. After the operations-related costs, the vehicle leasing costs represent the second largest cost component for all operating types, except for ODRP. The associated shares are in the range of 21 % in SBSCS to 35 % in SES. Consequently, the share of operations-related costs and vehicle leasing costs together account for more than 50 % of the transport costs per pkm for all operating types.

Since the operations-related costs represent the major cost component for all examined services, we present a more detailed analysis of their integral parts in Fig. 3. The total sum of operations-related costs ranges from €0.20 per pkm in case of SBSCS to €1.43 per pkmB for ODRP. Hence, with a difference of €1.20, the overall sum of operations-related costs per pkm differs even more than the total costs per pkm between the operating types. Focusing on the relative shares of operations-related costs, we find that the five operating types can be clustered into three different patterns: First, in FFCS and SBSCS the operations-related costs are mostly dominated by the costs of cleaning and parking. Together they account for over 50 % of the operations-related costs. Furthermore, within this pattern, the sum of maintenance parts and field agents & mechanics represents a major share accounting for 30 % of operations-related costs. Second, in HBS and SES the share of costs for field agents & mechanics is much more pronounced than in the first pattern and accounts for 50 % of operations-related costs. At the same time, the costs of IoT & fleet software and maintenance parts account for 40 % within this pattern. Third, ODRP is dominated by the costs of drivers, accounting for 83 % of the operations-related costs. Accordingly, in ODRP other operations-related cost components account for less than 5 % each.

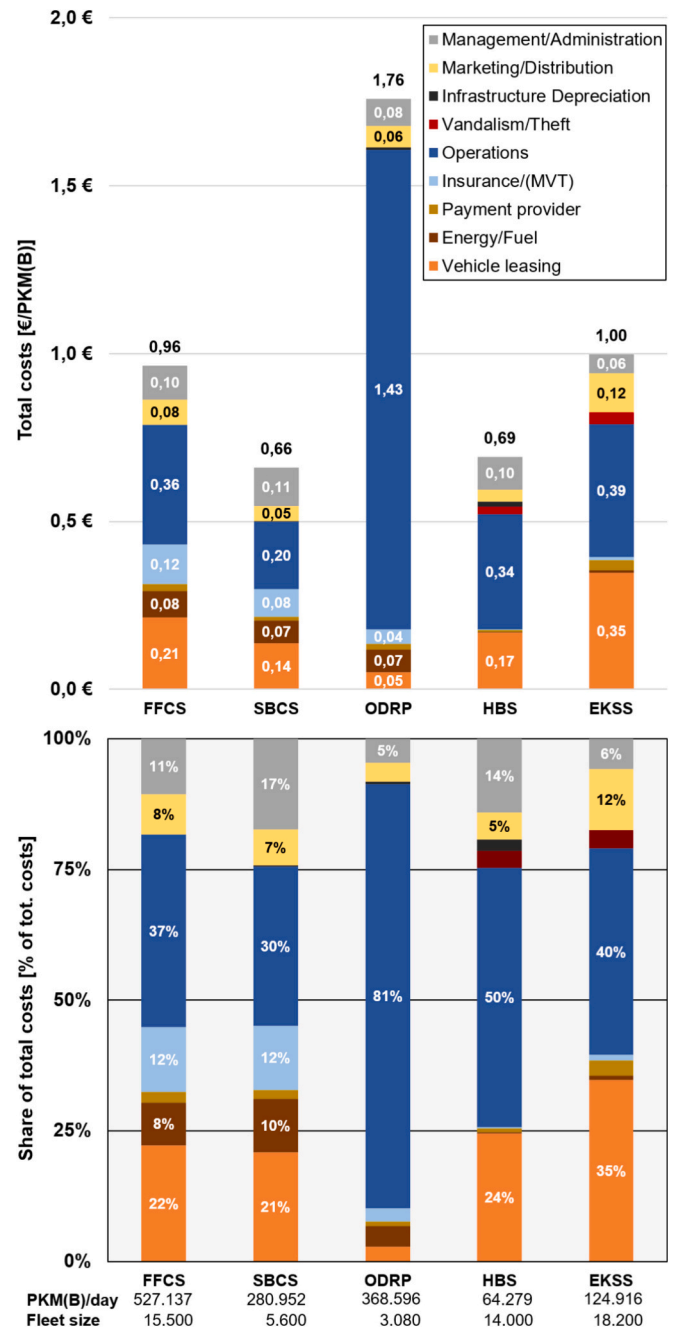


Fig. 2. Illustration of total costs per pkm/ pkmB and respective shares. For clarity, numbers lower than €0.05 or 5 % are excluded.

The cost components can also be regrouped into variable costs, vehicle-related fixed costs and business-related fixed costs. For this purpose, we consider the costs of all unit-level activities as variable costs. All costs of the batch-level activities are assigned to the vehicle-related fixed costs and all costs of the product- and company-level are regarded as business-related fixed costs (see Fig. 4).

It is discernible that for all examined operating types, the vehicle-related fixed costs represent the by far largest cost group, accounting for 60 % to 87 % of the total transport costs per pkm. Business-related fixed costs account for a small to moderate share of 8 % to 24 % of the total costs per pkm. Instead, the share of variable costs per pkm is rather small. However, with a range of 1 % in case of HBS to 16 % in case of SBSCS, a large difference between the individual shares of variable costs is noticeable.

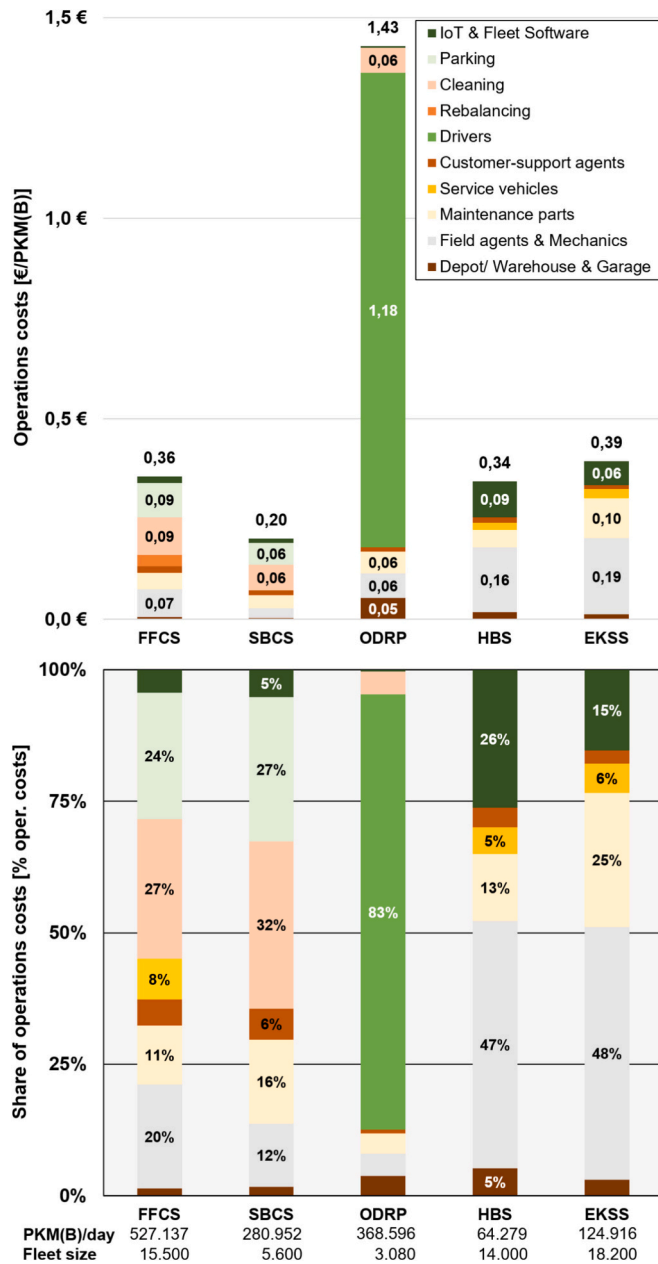


Fig. 3. Illustration of operations-related costs per pkm/ pkmB and respective shares. For clarity, numbers lower than €0.05 or 5 % are excluded.

4.2. Validation of the results

To assess the validity of our results, we validate the cost models with available data where possible. For FFCS, we use publicly available data of *ShareNow*. According to [Bundesanzeiger \(2021\)](#), the cumulative leasing payments of *ShareNow* amounted to €25.3 million in 2019. Using *ShareNow*'s fleet size of 7400 vehicles ([Statista, 2020a](#)), this can be transformed into an average monthly leasing rate of €285 per vehicle. When adjusting the fleet size of our FFCS model to *ShareNow*'s fleet size, results indicate leasing payment rates in a very similar range of €264 per vehicle.

Due to the fact that operational characteristics of SBSCS are more similar to private car operation than FFCS, we use cost data of private car ownership for validation. According to [Bösch et al. \(2018\)](#), the full costs for private car operation amount to €0.65 per driven kilometre. Our SBSCS cost model yields €0.66 per pkm. Additionally, [Abrahamczyk \(2020\)](#) state that the full costs of private car operation per pkm vary

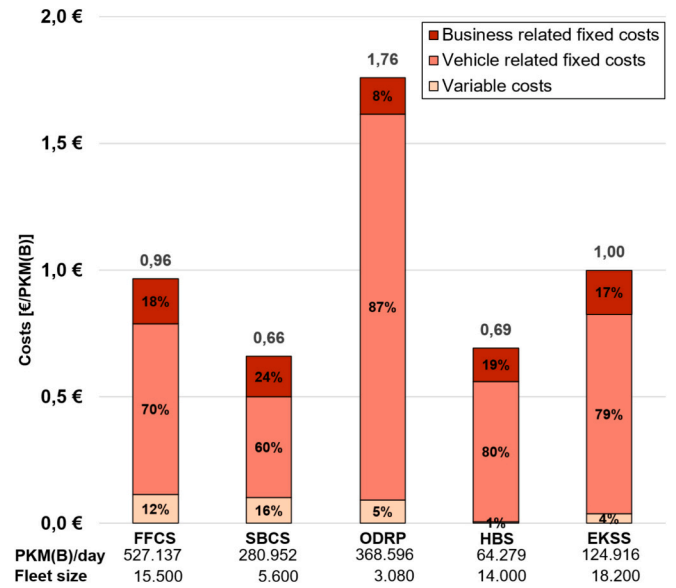


Fig. 4. Illustration of variable, vehicle-related fixed and business-related fixed costs and their relative shares per pkm.

between €0.28 for very small cars up to €1.20 for upper class cars. Since our assumed fleet mix (see Appendix, F) mostly consists of small to medium sized cars, our SBSCS costs of €0.66 per pkm appear to be plausible within that provided range.

Regarding ODRP, we use [Bösch et al. \(2018\)](#) for comparison. They estimate €1.55 per pkm for non-autonomous, pooled urban on-demand transport services. Our modelled costs of ODRP yield approximately €1.60 per pkm.¹² Given the fact that [Bösch et al. \(2018\)](#) do not consider costs such as payment provider fees, IoT and fleet software and depot and warehouse rent, slightly increased costs of our ODRP model seem plausible.

When adapting the main parameters of [Demeyere \(2020\)](#) in our SES cost model (utilisation of 3 trips per vehicle and day with a length of 1.5 km each, fleet size of 500 vehicles and 60 days e-scooter lifetime), the costs of €3.2 per pkm are comparable to the results of €3.4 per pkm of [Demeyere \(2020\)](#). Additionally, [Dickey \(2019\)](#) indicates a contribution margin of €1.04 per ride. When using the similar e-scooter lifetime of 170 days, a contribution margin of €1.04 can also be derived with our cost model. When again using our derived lifetime data of 365 days, the cost model yields a margin of €1.20 per ride. As e-scooter durability is described to have increased since 2019 (e.g. [Rose et al., 2020](#)), this slightly increased contribution margin of our SES cost model appears reasonable.

[Büttner and Petersen \(2011\)](#) state the running costs per bike and year in a station-based bike sharing system to range from €1500 to €2500. This translates into a cost range of €1200 to €2000 per bike and year when neglecting the stated station-related costs. Our modelled HBS running costs amount to approximately €1157.33 per year and bike, and can thus be considered to be on the lower end of these costs but still in a plausible range.

4.3. SMS viability

After validating our cost estimates we derive the potential viability of

¹² Whereas the stated cost estimates of the ODRP model are stated in relation to pkmB earlier, they are transferred to pkm for this validation. This is done by a division by the average detour factor of 1.1 from Table C.2. Hence, the costs of €1.76 per pkmB (requested transport distance) are equal to the costs of €1.60 per pkm (actual transport distance including pooling-related detours).

the examined services. For this the revenues per pkm (or pkmB in case of ODRP) are calculated as described in Section 3.1.2. Fig. 5 summarises the viability results in terms of profits and losses for all operating types.

The revenue estimates are in the range of €0.30 per pkm for HBS to €1.47 per pkm for SES. Taking into account the total costs per pkm and a taxation on profits of 30 % (see Section 3), this yields profits or losses in the range of €0.33 per pkm for SES to €- 0.94 per pkmB for ODRP. It is striking that with profits of €0.33 per pkm only SES seems to yield a viable business model, whereas all other modelled operating types are either in a neutral profit and loss situation or indicate high losses per pkm. In FFCS, the costs and revenues seem to be of equal magnitude leading to a situation where neither strong profits nor losses are indicated by our cost model. SBSCS cost modelling indicates a loss of €0.09 per pkm. The losses per pkm are even higher in HBS and culminate in a loss of €0.94 per pkmB in case of ODRP. Further discussion of these results is contained in the next section.

5. Discussion

Looking at the costs per pkm, the results vary noticeably with the considered operating type. The total costs per pkm differs by up to €1.10. When considering the magnitudes of the underlying cost components, this difference is mainly caused by differences in operational details of the services. Costs, such as driver salaries in ODRP or parking and cleaning costs in FFCS and SBSCS, play a major role for the costs of these services. However, they do not apply to the other services, which yields a difference for the total costs per pkm between the examined operating types. It can thus be followed that the cost structures of SMS are highly dependant on the exact operating type and its underlying cost-generating activities. This result supports Jia et al. (2020) or Wortmann et al. (2021), who state that economical calculations of SMS are highly case-specific.

Looking at the relative shares of cost components, the operations-related cost components turn out to be the dominating type of costs in all services. When breaking down these operations-related costs, three different patterns of cost structures reveal. Service types with similar utilisation patterns and vehicle characteristics such as FFCS and SBSCS or

HBS and SES seem to be subject to similar cost structures and operations-related cost shares (see Appendix C).

When comparing the results of this work to other scientific examinations (e.g. Bösch et al., 2018; Fazel, 2014; Wortmann et al., 2021), the cost estimates of this work seem to be slightly higher. This may be a consequence of the level of detail we apply, yielding additional cost components within our models. For example, when adding our estimates for IoT, depot rent, and payment provider fees to the total costs of €1.55 per pkm of ODRP in Bösch et al. (2018), the result almost matches the calculated total costs of €1.60 per pkmB in our model.

Comparing our cost estimates of SMS to other forms of transportation, like public transport, it shows that SMS cannot operate at the same level of cost efficiency. In relation to the total costs of €0.30 per pkm in public transport (Regling, Stein, Werner, & Karl, 2020), even our lowest calculated costs across all services of €0.66 per pkm in SBSCS are much higher. Even in comparison to the costs of private car ownership of approximately €0.65 per pkm, as stated by (Bösch et al., 2018), FFCS, ODRP and SES, yield at least €0.30 additional costs per pkm. However, when comparing SMS to operations-related costs of over €2.2 in individual transport options like taxis (Ennen & Heilker, 2020), even ODRP as the most service in our calculations is nearly 20 % more cost efficient.

Looking at the viability, our results indicate that in all examined services, except for SES, a profitable operation must be questioned. Especially, the losses of €0.4 and €0.9 per pkm and pkmB of HBS and ODRP indicate that these services currently operate in deficit covering less than half of their costs. This deficit may still be underestimated in our results due to the exclusion of exogenous factors and one-time upfront costs which must be expected to additionally drive costs. At the same time, the modelled revenue streams of the operating types only consider average pay-per-use tariff structures. The true revenues must be expected to be lower due to subscription-based offers for heavy users (e.g. Voi, 2021). Hence, it might be necessary to consider our viability estimates as an upper boundary of true SMS viability. This may be the reason why challenging profitability conditions for SMS are also stated by multiple other sources. A striking example are local station-based bike sharing implementations in City of Davis (2014), City of Baton Rouge (2016) or City of Redmond Washington (2016). All of these

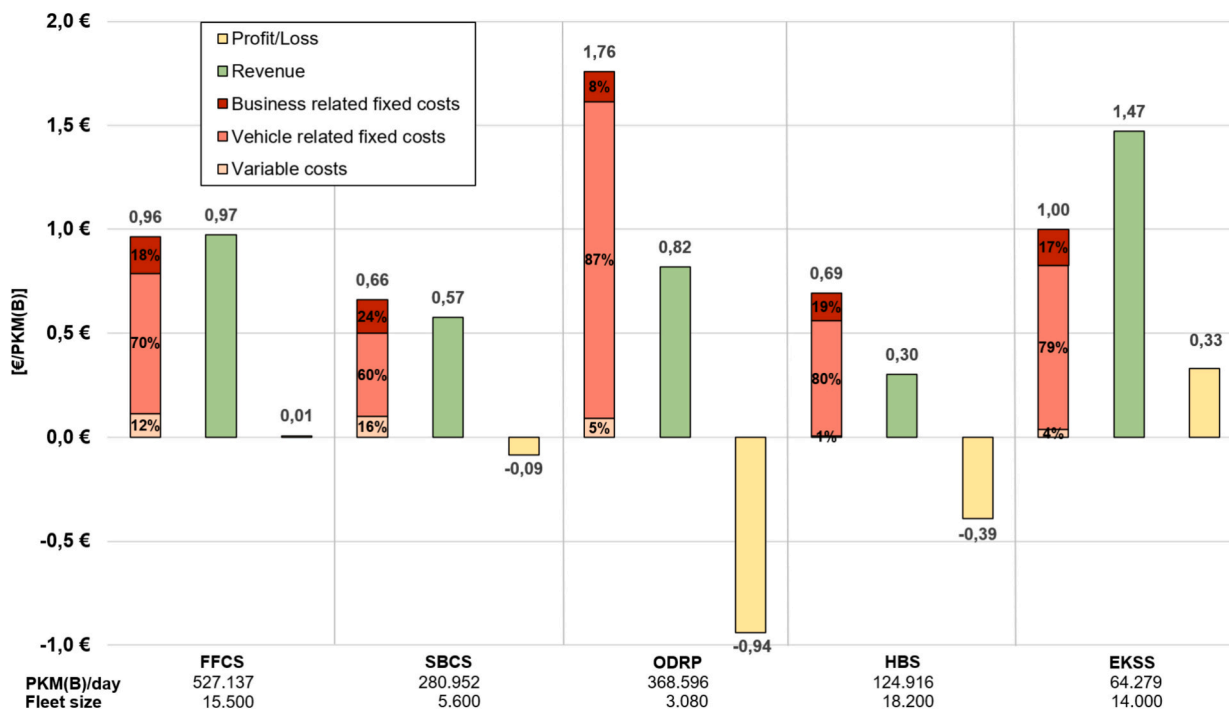


Fig. 5. Illustration of the viability estimates. All profits are subject to an assumed taxation of 30 % to account for a simplified German corporate and trade tax (see Section 3).

services are predicted to require a considerable amount of subsidisation by local government or other sponsors since they are found to only cover 50% of their true costs.

It must however be kept in mind that our viability results of SMS may partially reflect a common strategy of rising businesses. Although businesses need a positive cash flow at some point, start-up ventures regularly sacrifice profitability by heavily reinvesting into their growth (Coleman, 2018; Shulman, 2019). Doing so enables higher service levels and thus higher market shares (e.g. Jorge et al., 2015). Depending on how much operators value their service quality, large effects on viability arise (Wortmann et al., 2021). The financial assessment of young ventures can thus be challenging and misleading when only comparing their economic viability and it must be kept in mind that low profitability may also be a sign of an active decision to strive for market share (Schroeder, 2021).

Given today's difficult viability of SMS, the question about long-term strategies towards profitability arises. Our results indicate that the total costs per pkm of all operating types are dominated by vehicle-related fixed costs. Variable costs only account for 16 % of the total costs at maximum. Hence, an increase in vehicle utilisation must be expected to increase profits by directly increasing the revenues and only marginally increasing the total costs per pkm.

Our work does not come without limitations. One limitation arises from the quantity and quality of input data. Due to the sparse availability of empirical or scientifically proven cost and revenue data, it was inevitable to use a broad variety of non unified input sources as the basis for modelling. As a counter measure we apply such a high level of detail and validate our results against other work. Further, it needs to be kept in mind that our costs are assumed to be driven by the explanatory variables of average vehicle utilisation, fleet size and number of employees. Whereas the modelling with a subset of explanatory variables often represents a valid simplification (e.g. Giordano et al., 2021) and we explicitly decouple our research from exogenous influences (see Section 1), it should be noted that real world SMS cost dependencies are subject to further influencing factors such as size of the service area, population density or employment rates (see e.g. Stolle et al., 2019).

6. Conclusion and outlook

Addressing the question of costs and viability of SMS, we present a comprehensive cost and viability estimation for free-floating car sharing (FFCS), station-based car sharing (SBCS), on-demand ride pooling (ODRP), hybrid bike sharing (HBS) and shared electric scooters (SES).

Applying a four step procedure, we first gather details about general cost components of SMS. We find that SMS' cost structures can be explained by 22 distinct cost components and cost-generating activities in the four key cost areas vehicle-, operations-, customer- and administration-related costs.

Second, we estimate the magnitudes of these cost components for all services in today's German market. With a range of total costs per pkm or pkmB ranging from €0.66 of SBCS to €1.76 of ODRP, the absolute cost magnitudes of shared mobility operating types are shown to be highly service-specific. Nevertheless, with an accumulation of more than 50 % of the total costs per pkm or pkmB, the main cost drivers of all examined SMS appear to be the operations and vehicle leasing costs. A detailed examination of the operations-related costs shows that the five operating types can be clustered into three different cost patterns, according to their dominating operations-related cost components. For FFCS and SBCS, more than half of the operations-related costs originate from

cleaning and parking expenses. In SES and HBS, the labour costs for field agents and mechanics dominate the operations-related costs. In case of ODRP, more than 80 % of the operations-related costs are caused by driver salaries.

Third, we assess the viability of the five operating types by comparing their cost and revenue magnitudes. Our results indicate that the viability of almost all examined services must be questioned. FFCS and SBCS show either neutral profits or slight losses. With losses of €0.40 per pkm in HBS and €0.90 in ODRP, these two services currently indicate unviable operation. Since all operating types show a low share of variable costs, strategies for future profitability could focus on increasing vehicle utilisation. Additionally, secondary revenue streams (e.g. Gschwendtner & Krauss, 2022) could yield viability improvements.

To the best of knowledge, this work is the first that captures cost and viability estimates for five different shared mobility operating types at once and from an empirical view with accountable data sources and assumptions. We extend existing scientific knowledge by providing a highly detailed SMS costing approach including a set of 22 integral cost components, a general SMS cost model, and elaborated cost models for five specific SMS. The application of our four-step methodology and data is new to transportation literature and yields detailed insights into SMS' cost structures and viability.

Since true costs of a service are the basis for its economically viable pricing (Bösch et al., 2018) and prices are among the most important criteria for mode choice (Wadud & Mattioli, 2021), this implies that based on our cost estimations further conclusions about the level of usage and competitiveness of the examined mobility service are possible. Additionally, future work could try to include case specific variables such as demographics, employment rates, tourism or climate into our approach since these factors have a high impact on the case-specific cost and viability (e.g. Büttner & Petersen, 2011; City of Baton Rouge, 2016; Stolle et al., 2019). Further, integrating externalities to the cost analysis of SMS, such as environmental burden or social costs, and comparing their magnitudes to other forms of transport could be a promising way forward to help transport researchers, planners, and policymakers clarify the social, environmental or macro economic impact of SMS.

CRedit authorship contribution statement

Raphael Abt: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Konstantin Krauss:** Writing – review & editing, Visualization, Validation, Resources, Funding acquisition, Conceptualization.

Declaration of competing interest

None.

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Appendix A. Systematic literature review

The SLR is conducted using *Scopus*, *Web of Science* and *Google Scholar* with the following search string:

Table A.1: Search string combinations of the SLR.

Cost accounting terms	Shared mobility terms
Cost drivers/ structure/ estimation	car sharing/ bike sharing/ (electric) scooter sharing
Economic viability	ride pooling
Unit economics	shared mobility
Kostenstruktur/ Kostentreiber	car sharing/ bike sharing/ (electric) scooter sharing
Kostenabschätzung	ride pooling

Slashes and brackets mark search string variations.

Appendix B. Guideline-based expert interviews

Of the 33 experts, 25 are representatives of shared mobility operators and their supplying industry, 5 have expertise in the start-up financing ecosystem, 1 expert has expertise in venture capital and 5 experts are from the field of cost-accounting.

1. In advance to the interview process, interviewees are given a description of the research and its objectives including a description of the research problem as laid out in Chapter 1.
2. Cost components identification

Q: What are inherent cost categories/ components of shared mobility?

Q: How would you rank the importance of the mentioned cost components? (e.g. by a qualitative ranking from highest to lowest relative share of total costs)

3. Cost components magnitudes

Q: What are underlying values/ data/ magnitudes of the stated cost components?

Q: What is the scaling behaviour of the mentioned cost components?

4. Method

Q: Do you know methodological approaches of cost estimation that you consider suitable for the context of shared mobility cost estimation?

5. Method discussion

Q: Having heard the explanation of the ABC or NPV methods, what advantages and disadvantages do you foresee in estimating cost components of shared mobility with these methods?

6. Start-ups

Q: What is the general economic goal of start-ups?

Q: Can this goal be expected to change over time (e.g. with the maturity of the business)?

7. Economic viability

Q: Do you consider start-ups in the field of shared mobility economically viable?

Q: What is your personal opinion on current and future strategic goals of shared mobility start-ups?

8. Investing in start-ups

Q: What are decisive factors for start-up investors to invest in shared mobility start-ups?

Q: What goals do investors pursue when investing in shared mobility start-ups?

9. Literature

Q: Do you know of scientific or grey literature that contains cost estimations, cost components or other valuable information for cost estimation processes in shared mobility?

10. Further contacts

Q: Can you refer to any colleagues or contacts who can help with providing further information on the research context described?

Appendix C. Utilisation data

For ODRP, Pkm are the cumulative kilometres of all passengers that travel with a vehicle per day. Vehicle revenue kilometres (VRkm) are the cumulative kilometres that the vehicle is occupied by at least one passenger and thereby generates revenue (Federal Transit Administration, 2019). Total vehicle kilometres (TVkm) mark the total sum of kilometres a vehicle travels per day (including VRkm, detours and empty rides). The booked

kilometres (Bkm) are the sum of service kilometres booked and indicate the cumulative mileage of all bookings, irrespective of the number and mileage of pooled rides. The overall requested transport capacity is pkmB. Since, ODRP pools bookings with slightly differing origins and destinations, this introduces a detour factor indicating the difference between a passenger's booked mileage and the actually driven mileage. The share of bookings that are pooled are indicated by the pooling-index (Knie, Ruhrort, Gödde, & Pfaff, 2020; Liebchen, Lehnert, Mehlert, & Schiefelbusch, 2021).

Since, to the best of our knowledge, no empirical data of German ODRP services is available, the derivation of empirical ODRP utilisation data for this examination has to rely on alternative sources. We hence base our derivation of ODRP utilisation data on the US database of Federal Transit Administration (2019). As we focus on profit oriented shared mobility providers, operators with less than a total revenue of \$ 100 per day are excluded from the examination, since these are expected to be non-profit operators. The remaining data is filtered for active and fully reporting ODRP operators of demand responsive transport services in urban settings. This yields 124 operators whose data is used to derive passenger-kilometres travelled (PKMT) VRkm, average vehicle occupancy, amount of passenger trips per day and vehicle, as well as average passenger trip length. Since these figures must be expected to reflect US travel behaviour including exogenous factors, it is scaled to German mobility behaviour with the help of the average empirical German and American trip lengths as in Bureau of Transportation Statistics (2018) and Nobis and Kuhnimhof (2018). To mitigate the influences of differing German and US mode choice preferences, the US occupancy data feature is replaced by data of Doll et al. (2019), Bösch et al. (2018) and Werwitzke (2018). After conversion with data from Knie et al. (2020), Ke, Yang, Li, Wang, and Ye (2020) and Bösch et al. (2018), utilisation data for German ODRP can be constructed as depicted in Table C.2.

Table C.2: Assumed utilisation data of HBS, FFCS, SBSC and ODRP.

Name	Value	Unit	References/ Notes
HBS utilisation data			
Avg. trip duration	17.70	min	Based on avg. trip distance and avg. speed of Fishman, Washington, and Haworth (2014).
Avg. trip distance	3.54	km	Avg. of Fishman et al. (2014) and Ljubenkov, Kon, and Ratti (2020).
Avg. trips/veh.	1.30	trips/day	Avg. of Fishman et al. (2014), Fishman, Washington, and Haworth (2013), Fishman (2016), Bonilla-Alicea, Watson, Shen, Tamayo, and Telenko (2020), Sophrin, Kacanda, and Kurth (2016), City of Davis (2014), and City of Redmond Washington (2016)
Avg. mileage/veh.	1675.85	km/year	Based on avg. trip distance and avg. trips/veh.
Avg. veh. Depreciation period	4.00	years	Based on Yanocha et al. (2018).
FFCS utilisation data			
Avg. trip duration	30.27	min	Avg. of 5 German cities in Sprei (2018) and 7 German cities in Habibi et al. (2017).
Avg. trip distance	8.12	km	Calculated using avg. trip duration, and calculated mean velocities of Bundesverband CarSharing (2016).
Avg. trips/veh.	4.19	trips/day	Average of 5 German cities in Sprei (2018) and 7 German cities in Habibi et al. (2017).
Avg. mileage/veh.	12,413.22	km/year	Based on avg. trip distance and avg. trips/veh.
Avg. veh. Holding period	1.00	years	Based on Statista (2011) and rounded to full years for compatibility with input limitations of later used car cost calculator of ADAC (2021). Value confirmed in expert interviews.
SBSC utilisation data			
Avg. trip duration	454.89	min	Avg. of Bundesverband CarSharing (2016) and Knie et al. (2016).
Avg. trip distance	66.06	km	Avg. of Bundesverband CarSharing (2016) and Knie et al. (2016).
Avg. trips/veh.	0.76	trips/day	Calculated using values of Knie et al. (2016).
Avg. mileage/veh.	18,312.04	km/year	Based on avg. trip distance and avg. trips/veh.
Avg. veh. Holding period	2.00	years	Derived in the same manner as FFCS veh. Holding period.
ODRP utilisation data			
Pkm/veh.	135.79	km/day	Based on US data of Federal Transit Administration (2019) and adjustment to German mobility behaviour as described in text.
Avg. occupancy/pkm	1.72	passengers	Avg. of Werwitzke (2018), Bösch et al. (2018), Doll et al. (2019).
VRkm/veh.	78.78	km/day	Based on pkm/veh. and avg. occupancy/pkm.
Share of empty TVkm	34.17	%	Share of TVkm in which vehicle is empty due to e.g. access, drop off or maintenance trips. Calculation based on Knie et al. (2016) and Bösch et al. (2018).
TVkm/veh.	119.67	km/day	Based on VRkm/veh. and share of empty TVkm.
Avg. detour factor	1.10		Derived from Ke et al. (2020).
pkmB/veh.	123.15	km/day	Based on pkm/veh. and avg. detour factor.
Passengers/booking	1.17		Based on formula of Liebchen et al. (2021).
Bkm/veh.	105.38	km/day	Based on pkmB/veh. and passengers/booking.
Avg. bookings/veh.	11.87	trips/day	Based on US data of Federal Transit Administration (2019).
Avg. trip length	8.88	km/booking	Based on Bkm/veh. and avg. bookings/veh.
Avg. mileage/veh.	43,681.01	km/year	Calculated using avg. trip distance and avg. trips/veh.
Avg. veh. Holding period	4.00	years	Limited by maximum mileage input of 200 thousand km by cost calculator of ADAC (2021).

All values rounded to two decimal places.

Following the provided utilisation data and combining it with our fleet size estimation, we obtain the total utilisation and utilisation for each SMS as presented in Table C.3.

Table C.3: Assumed fleet sizes and average utilisation per operating type.

	FFCS	SBCS	ODRP	HBS	SES
U /veh. [pkm/day]	34.01	50.17	119.67	4.59	6.86
Entire fleet size [#veh.]	15,500	5600	3080	14,000	18,200
U [pkm/day]	527,136.92	280,951.91	368,595.89	64,279.32	124,915.70

Appendix D. Revenue data

For our calculation, we assume that customer vehicle choice is equally distributed across available vehicles. Thus, average revenue for FFCS, SBCS and HBS can be derived in two steps. First, based on average utilisation, revenue per trip is calculated individually for each implemented vehicle category. Then, by considering relative shares of the vehicle size categories in the fleet (e.g. Table F.8), a weighted average can be derived. This weighted average corresponds to the average revenue. Results are provided in Table D.4.

Table D.4: Assumed average revenue per trip.

Operating type	Revenue [€]	References/ Notes
FFCS	9.61	Assuming avg. pricing of ShareNow (2021a) , Miles Mobility (2021) , WeShare (2021) being the three largest German FFCS providers (Statista, 2020a).
SBCS	46.20	Assuming avg. pricing of DB Flinkster (2021) , Stadtmobil (2021) , Cambio (2021) , being the three largest German SBCS providers (Statista, 2020a).
ODRP	10.12	Assuming 45 % discount of taxi ride pricing as per Ennen and Heilker (2020) .
HBS	1.27	Assuming avg. pricing of KVB-Rad (2021) , KVV.nextbike (2019) , Berlin.de (2019) , DB Call a Bike (2021) and MVG (2020) .
SES	3.25	Assuming avg. German pricing of €1 unlock fee and €0.15 per minute of usage as per Schwär (2020) .

The assumed underlying utilisation is mentioned in Tables C.2 and 3. All values rounded to two decimal places.

Appendix E. Common modelling assumptions and cost data

For the operator-type-specific cost function adjustment, it is assumed that for a fleet size of zero, no management would be required in any case. Hence, the operating type-specific adjustment of the assumed square root function can only be realised by a factor influencing the slope of the root function.¹³ Following, based on real-world data of representative operators, the slope of the root function is modulated to fit an average of real-world data points. To not introduce distortions between FFCS and SBCS, the data for both operating types are averaged resulting in the same adjustment factor. Results are displayed in Table E.7.

Table E.5: Common modelling assumptions for all five examined operating types.

Common assumptions concerning vehicle-related cost components		
Acquisition/ Leasing		- no common assumptions possible -
Fuel/ Energy	Fuel and electricity prices assumed according to ADAC (2021)	
Insurance (&MVT)		- no common assumptions possible -
Maintenance	Costs are assumed to be caused by maintenance parts, mechanics salaries and warehouse/ garage rent. Expenses for maintenance parts are calculated individually. Warehouse/ garage rent is assumed as mean of storage/logistic space rent in eight major German cities as per BNP Paribas (2020) . Gross wage of mechanics is assumed as per Fazel (2014) and transferred into full employer burden of €27.5 thousand (excl. utilities) per mechanic and year using Brändle (2013) .	
Cleaning		- no common assumptions possible -
Parking		- no common assumptions possible -
Common assumptions concerning operations-related cost components		
Driver salaries		- no common assumptions possible -
IoT & Fleet software	Basic pricing indication is taken from Joyride (2021b) and Fleetio (2021) and adapted to each operating type using interview insights and obtained supplier pricing data.	
Rebalancing	Employer burden for field agents is assumed to be identical to employer burden for mechanics.	
Infrastructural	Charging infrastructure depreciation period is assumed as eight years with a residual value of 5 % as per Jia et al. (2020) . Commercial charging pile prices are based on obtained industry data of Alwin Otten GmbH (2021) and complemented with Nelder and Rogers (2019) .	
Vandalism/ Theft		- no common assumptions possible -
Common assumptions concerning customer-related cost components		
Mobile app	Development costs based on ADC Calculator (2021) and converted into three-year depreciation period. Additionally 35 % of development costs assumed as annual running costs.	
Website	Development and running costs based on WebFX (2021) . Depreciation assumed to be identical to mobile app.	
Customer support	Agents assumed to be based on service contracts with pricing as per Kompareit (2021) .	
Marketing	Cost assumed as share of total revenue using mean of tech and transport industry according to Leone (2020) .	
Payment provider fees	Based on interviews variable fee of Stripe (2021) is adjusted and fixed costs are neglected. Adjusted variable fee for payment also includes costs of billing and invoice.	
Billing/ Invoicing		
Common assumptions concerning administration and overhead-related cost components		

(continued on next page)

¹³ Since all other adjustments would lead to a parallel shift of the root function, causing the function to miss the coordinate origin.

(continued)

Management salaries	Based on Fazel (2014) avg. gross salary of €42 thousand is assumed and converted into full employer burden (incl. Office rent, IT, utilities etc.) using Brändle (2013) .
Office & Utilities	
Capital costs/ Interest	Based on Barkow Consulting (2021) , above average nominal interest of 3,00 % p.a. for corporate credits is assumed for all loan repayments. This reflects above average creditor risk in start-ups (see Hayes, 2021). Processing fees for the borrower are ignored. For lease payment calculations, the nominal interest is converted into a money factor as per (Maple Tech, 2021).
R&D	Omitted, as assumed to negligible or highly case specific.
Permit fees	
Additional	
\$ to € exchange rate	Exchange rate of \$ 1 = €0.82 (18. May 2021) is used for currency conversions.

Table E.6: Common data for all five examined operating types.

Activity-name	Value	Unit	Period
Unit-level			
Sharing-vehicle (usage dependent)*			
<i>Fueling/ Charging</i>			
Electricity	0.36	€/kWh	
User incentive*			
Maintenance parts			
Payment provider (incl. Billing & invoicing)	2.00	% of revenue	/transaction
Batch-level			
Sharing-vehicle (time dependent)			
Insurance (&MVT)			
<i>Operations</i>			
Depot/ Warehouse & Garage	5.00	€/sqm	
Field agent & Mechanic salary burden	34,466.72	€	/year
Service vehicle*			
Customer-support agent	2460.00	€/agent	/month
Driver* salary burden			
Rebalancing* (variable)			
Cleaning*			
Parking*			
<i>IoT & Fleet software</i>			
Vehicle telematics			
Fleet operations software			
Sharing operations software	5.00	€/vehicle	/month
Vandalism/ Theft*			
Station infrastructure depreciation*			
Charging infrastructure depreciation*			
Product-level			
Mobile app (depreciation & running costs)	219,145.09	€	/year
Website (depreciation & running costs)	14,689.72	€	/year
Marketing	9.10	% of revenue	/year
Company-level			
Management salary burden (incl. Office rent, IT,utilities)	63,389.10	€	/year

* Activities marked with an asterisk are only relevant for a subset of the examined operating types.

Table E.7: Derived adjustment factors for adjusting the general management cost function to operating type-specific data.

Operating type	adjustment factor f
FFCS	2.47
SBCS	2.47
ODRP	3.15
HBS	0.3
SES	0.3

For FFCS and SBCS, the figures of fleet size and FTEs result in a combined averaged fleet of 5227 vehicles and 179 FTEs, based on ([Statista, 2020a](#); [Bundesanzeiger, 2021](#); [Statista, 2021a, 2021b](#)). This data point is then approximated by the mentioned square root in Eq. 2 to yield the factor of $f = 2.47$. For SES and HBS, the factor of $f = 0.3$ is derived by 15 FTEs for the first 2500 vehicles as stated in [Wortmann et al. \(2021\)](#). The factor of $f = 3.15$ in ODRP is derived based on [Moia \(2021a\)](#) and [Moia \(2020\)](#); Hamburger [Morgenpost \(2020\)](#).

Appendix F. Cost models of FFCS, SBCS, ODRP and HBS

F.1. Assumed FFCS and SBCS fleet mix

Since vehicle depreciation varies by vehicle model (Wadud & Mattioli, 2021), we derive average vehicle depreciation for our input data of FFCS and SBCS cost estimation based on a representative fleet of German carsharing providers. The vehicle fleet of the three largest German SBCS and three largest FFCS providers, as per (Statista, 2020a), are analysed and the respective cost values for all entailed vehicles are derived using ADAC (2021) based on the utilisation of Table C.2. For the vehicle acquisition costs, the list prices of the cheapest available vehicle models within ADAC (2021) are considered. The analysis is performed for both, internal combustion engine vehicles (ICEVs) and battery electric vehicles (BEVs), since German carsharing providers are assumed to have a share of 18.5 % BEVs in their fleet (Bundesverband CarSharing, 2021).

The vehicle of all providers are then grouped into five different categories of different vehicle sizes, ranging from “XS” to “Van/Transport” as shown in Table F.9. Derived cost data of ADAC (2021) is averaged for each of these vehicle categories to obtain representative cost values per size category. The share of 18.5 % BEVs is assumed (Bundesverband CarSharing, 2021). Due to the different utilisation of FFCS and SBCS (see Table C.2), the calculation of cost averages per size category is done separately for both FFCS and SBCS, resulting in different vehicle cost input values for FFCS and SBCS.

Table F.8: Assumed share of size categories in the carsharing fleet mix.

Vehicle size category	Share in fleet in %
XS	40
S	30
M	20
L	5
Van/Transport	5
Share of BEVs in each category	18.5

Table F.9: Assumed fleet for ADAC (2021)-based cost derivation of average vehicle-costs in carsharing models.

Vehicle size category (& assumed tank volume)	ICEVs	BEV equivalents
XS (42 L)	Toyota Aygo 1.0	Fiat 500e Action
	VW up! 1.0	smart fortwo coupe EQ
S (45 L)	Audi A1 Sportback	MINI Cooper SE
	Ford Fiesta 1.1	Opel Corsa-e
	Hyundai i20	Renault Zoe R110
	MINI One	smart forfour EQ
	Opel Corsa 1.2	
	Toyota Yaris 1.0	
	VW Polo 1.0	
M (53 L)	Audi A3 Sportback	BMW i3
	Audi A3 Limousine	Nissan Leaf
	BMW 116i	VW ID.3
	BMW 216i	
	Ford Focus 1.0	
	Mercedes A 160	
	Mercedes B 160	
	Opel Astra 1.2	
	VW Golf 1.0	
	Audi A4 Avant 3	Hyundai Kona E
	BMW 318i	Mercedes EQA 250
L (55 L)	BMW X1	VW ID.4
	BMW X2	
	Citroen Berlingo Kombi	
	Ford Focus Turnier	
	Ford Mondeo Turnier	
	Opel Astra Sports Tourer	
	Opel Combo Life 1.2	
	Renault Megane TCe	
	VW Golf Variant 1.0	
	VW Passat Variant 1.5	
	VW T-Roc 1.0	
	VW Caddy Kombi	
	Ford Tourneo Custom 320	Mercedes EQV 300
	Ford Tourneo Custom 320	Mercedes eSprinter Kastenwagen
	Ford Transit Kombi 310	Nissan e-NV200 Evalia
	Mercedes Sprinter Kastenwagen	Nissan e-NV200 Kastenwagen
	Mercedes Vito Kastenwagen	VW e-Crafter Kastenwagen
Opel Vivaro Kombi S		
Opel Vivaro Cargo S		
VW Caddy Cargo 1.5		
VW Crafter 30 Kastenwagen		

F.2. FFCS

In FFCS field agents do not need additional service vehicles since they move through the field by using sharing vehicles (Haschek, 2013).

$$C_{Veh_{use}} [\text{€}/\text{day}] = \text{fleet} \cdot c_{lease_{use}} \cdot \frac{12}{365} \cdot \frac{1}{1.19} \cdot d \quad . \quad (\text{F.1})$$

$$C_{fuel} [\text{€}/\text{day}] = \text{fleet} \cdot c_{fuel} \cdot \frac{12}{365} \cdot \frac{1}{1.19} \cdot d + \text{incent} \cdot (\text{ref} + \text{rech}) \cdot \frac{1}{1.19} \quad . \quad (\text{F.2})$$

incent marks the user incentive for refuelling and *refuel* (and *recharge*) the number of cars that need refuelling (or recharging).

For the calculation of *refuel* and *recharge* some explanations are necessary. First, based on the assumed tank capacities of the vehicle size categories and the assumed FFCS fleet mix, an average tank capacity of the fleet mix is calculated (47,4 Litres). Since a refuelling incentive in FFCS is often paid starting from a threshold of 25 % remaining fuel (see ShareNow, 2021b), it is assumed that the tank has a remaining fuel level of 20 % when the vehicle is refuelled. This reduces the amount of consumable fuel between refuelling to 37.92 Litres. Second, the FFCS average fuel efficiency of the fleet is derived. The average FFCS fuel consumption is assumed to be higher than the German overall average due primarily urban use of FFCS. Thus, based on Statista (2020c) we assume 8 l per 100 km. This results in an average range until refuelling for the FFCS fleet $((37.92/8) \cdot 100 = 474 \text{ kilometres})$. Together with utilisation (data see Table C.3), the total number of refuelling operations per time can now be calculated as $\text{refuel} = ((527 \cdot 136.92 \cdot 0.815)/474) = 907$ refuelling processes per day.

A similar approach is chosen for *recharge* processes of BEVs. The range of all BEV models is derived with the help of EFahrer.com (2021) and based on the assumed fleet mix a weighted average is calculated. Similar to the battery capacity calculations of SES scooter-range the range is then adjusted to 68.40 % of the original average range resulting in an adjusted range of 161.23 km. Applying the share of BEVs in the fleet (18,5 %) and the fleet utilisation, *recharge* is calculated with.

$((527 \cdot 136.92 \cdot 0.185)/161.23) = 605$ recharging processes of FFCS per day.

Both *refuel* and *recharge* are scaled dynamically based on the entered utilisation in the cost model.

$$C_{maint_{parts}} [\text{€}/\text{day}] = \text{fleet} \cdot c_{maint_{parts}} \cdot \frac{12}{365} \cdot \frac{1}{1.19} \cdot d \quad . \quad (\text{F.3})$$

$$C_{paym} [\text{€}/\text{day}] = p_{paym} \cdot \text{fleet} \cdot \text{trips}_{veh} \cdot \text{rev}_{trip} \cdot \frac{1}{1.19} \quad . \quad (\text{F.4})$$

$$C_{Veh_{time}} [\text{€}/\text{day}] = \text{fleet} \cdot c_{lease_{time}} \cdot \frac{12}{365} \cdot \frac{1}{1.19} \quad . \quad (\text{F.5})$$

$$C_{ins} [\text{€}/\text{day}] = \text{fleet} \cdot c_{ins} \cdot \frac{12}{365} \quad . \quad (\text{F.6})$$

Based on the interviews, a depot including warehouse and garage is assumed with approximately 400 m^2 on average. A new depot is assumed every 400 vehicles since a rate of approximately one m^2 of necessary depot space per vehicle is stated in the interviews. VAT is neglected (Brennecke, 2007).

$$C_{whs} [\text{€}/\text{day}] = \left\lfloor \frac{\text{fleet}}{400} \right\rfloor \cdot 400 m^2 \cdot \text{rent} \cdot \frac{12}{365} \quad . \quad (\text{F.7})$$

Based on Fazel (2014), it is assumed that 10 field agents and mechanics are sufficient for the first 250 vehicles and linear scaling is assumed until that point. Thereafter, linear growth is reduced to one field per 40 additional vehicles adopting the data of Haschek (2013).

$$C_{agent_{field}} [\text{€}/\text{day}] = \begin{cases} \left(10 + \left\lfloor \frac{\text{fleet} - 250}{40} \right\rfloor \right) \cdot \text{wage}_{field} / 365 & \text{for } \text{fleet} \geq 250 \\ \left\lfloor 10 \cdot \frac{\text{fleet}}{250} \right\rfloor \cdot \text{wage}_{field} / 365 & \text{else} \end{cases} \quad (\text{F.8})$$

The rate of customer support agents per sharing vehicle is adopted from Haschek (2013).

$$C_{agent_{cs}} [\text{€}/\text{day}] = \left\lfloor \text{fleet} \cdot \frac{35}{4000} \right\rfloor \cdot c_{agent_{cs}} \cdot \frac{12}{365} \cdot \frac{1}{1.19} \quad . \quad (\text{F.9})$$

The number of necessary vehicle rebalancing processes is averaged between Götz (2021) and Fazel (2014) and expressed as a percentage of the overall fleet size.

$$C_{reb_{var}} [\text{€}/\text{day}] = \left\lfloor \text{fleet} \cdot 0.08 \right\rfloor \cdot c_{reb_{var}} \cdot \frac{1}{1.19} \quad . \quad (\text{F.10})$$

$$C_{clean} [\text{€}/\text{day}] = \text{fleet} \cdot c_{clean} \cdot \frac{12}{365} \cdot \frac{1}{1.19} \quad . \quad (\text{F.11})$$

$$C_{park} [\text{€}/\text{day}] = \text{fleet} \cdot c_{park} \cdot \frac{12}{365} \cdot \frac{1}{1.19} \quad . \quad (\text{F.12})$$

$$C_{IoT} [\text{€}/\text{day}] = \text{fleet} \cdot \left(c_{tel} + c_{fleet_{ops}} + c_{share_{ops}} \right) \cdot \frac{12}{365} \cdot \frac{1}{1.19} \quad , \quad (\text{F.13})$$

F.3. SBCS

For the SBCS cost model, the cost functions C_{s-veh}^* , C_{driv}^* , $C_{reb,var}^*$ and C_{vand}^* are not applicable. The calculations of $C_{Veh,use}$, $C_{maint,parts}$, C_{paym} , $C_{Veh,time}$, C_{ins} , C_{whs} , $C_{agent,cs}$, C_{clean} , C_{park} and C_{IoT} are similar to the FFCS model. The remaining formulas are provided below.

For SBCS the user incentive in case of refuelling is omitted (see [Stadtmobil CarSharing, 2021](#)).

$$C_{fuel} [\text{€}/\text{day}] = fleet \cdot c_{fuel} \cdot \frac{12}{365} \cdot \frac{1}{1.19} \cdot d \quad . \quad (\text{F.14})$$

Due to the fixed stations of the vehicles, efficiency gains of 50 % are assumed for SBCS compared to FFCS. This is because it is assumed that less field agents are required due to the absence of rebalancing tasks.

$$C_{agent,field} [\text{€}/\text{day}] = \begin{cases} 0.5 \cdot \left(10 + [fleet - 250] \cdot \frac{1}{40} \right) \cdot \frac{wage_{field}}{365} & \text{for } fleet \geq 250 \\ [0.5 \cdot 10 \cdot \frac{fleet}{250}] \cdot wage / 365 & \text{else} \end{cases} \quad (\text{F.15})$$

$$C_{infra}^* [\text{€}/\text{day}] = share_{bev} \cdot fleet \cdot C_{charg-infra} \cdot \frac{12}{365} \cdot \frac{1}{1.19} \quad . \quad (\text{F.16})$$

F.4. ODRP

First we have to derive a representative ODRP fleet. Among the current German services, the business model of *Moia* is the most similar to our assumed ODRP business model. Since *Moia*'s fleet only consists of BEVs ([Ecomento, 2020](#)), the base case of our cost estimation adopts the average of BEV costs of Table F.10 based on within [ADAC \(2021\)](#).

Table F.10: Assumed fleet for [ADAC \(2021\)](#)-based cost derivation of average vehicle-costs in ODRP.

ICEVs	BEV
Mercedes Vito Tourer lang	Mercedes eVito Tourer lang
Mercedes V 220 d lang	Nissan e-NV200 Kombi
Nissan NV300 Kombi	VW e-Crafter mittellang
VW T6.1 Kombi lang	

In ODRP model, C_{s-veh}^* , $C_{reb,var}^*$, C_{park}^* and C_{vand}^* can be omitted. The calculations of $C_{Veh,use}$, $C_{maint,parts}$, C_{paym} , $C_{Veh,time}$, C_{ins} , C_{clean} , C_{IoT} are similar to the FFCS model. The calculations of C_{fuel} and C_{infra}^* are similar to the SBCS model. The remaining formulas are provided below.

Since the vehicles are assumed to be located at the central depot when inactive and overnight, the overall depot sizes must be assumed to fit the entire fleet. Additionally, the garage and warehouse need to be included. The calculations for the space required are conducted in a similar approach to SBCS. The space per vehicle is approximated by 40 square metres in total (which is approximately twice the space of regular cars as derived by [Koeln \(2009\)](#)). This additional space is assumed to be required for the larger vehicles, more manoeuvring area as well as more warehouse and garage space.

$$C_{whs} [\text{€}/\text{day}] = fleet \cdot 40m^2 \cdot rent \cdot \frac{12}{365} \quad . \quad (\text{F.17})$$

To keep the naming consistent, the name of the cost function maintains field agents and mechanics, although field agents are assumed to not be required in ODRP. Based on the interviews, it is assumed that the rate of field agents and mechanics in FFCS (see Eq. [F.8](#)) needs to be increased by a factor of three to adequately reflect the required mechanics for ODRP due to the intense use.

$$C_{agent,field} [\text{€}/\text{day}] = \begin{cases} \left(3 \cdot 10 + [fleet - 250] \cdot \frac{3}{40} \right) \cdot \frac{wage_{field}}{365} & \text{for } fleet \geq 250 \\ [3 \cdot 10 \cdot \frac{fleet}{250}] \cdot wage / 365 & \text{else} \end{cases} \quad (\text{F.18})$$

The rate of customer support agents per sharing vehicle is adopted from [Haschek \(2013\)](#). Due to more intense daily usage (see Table C.2), the amount of agents per vehicle in ODRP is assumed to be twice as high as compared to FFCS.

$$C_{agent,cs} [\text{€}/\text{day}] = 2 \cdot [fleet \cdot \frac{35}{4000}] \cdot c_{agent,cs} \cdot \frac{12}{365} \cdot \frac{1}{1.19} \quad . \quad (\text{F.19})$$

We assume 16 operational service hours per vehicle and day (approximated by averaging [Moia, 2021b](#); [ViaVan, 2021](#); [CleverShuttle, 2017](#); [KvgOF, 2021](#)). This yields accumulated annual operating hours per vehicle of $52 \frac{\text{weeks}}{\text{year}} \cdot 7 \frac{\text{days}}{\text{week}} \cdot 16 \frac{\text{hours}}{\text{day}} = 5824$. Dividing this result by an employee's average available working hours per year (mentioned in the tool of [Brändle, 2013](#)), the theoretical amount of FTEs per vehicle (when the full fleet is in service for 16 h) can be derived as $5824 \text{ hours} / 1584 \frac{\text{hours}}{\text{FTE}} = 3,68$ FTEs. However, since the service utilisation can not be assumed to be at peak continuously, a reduction is necessary. This reduction is derived for three temporal cases (following the partition of [Bösch et al., 2018](#)). For the first case, it is assumed that at peak demand hours (7 am until 8 am and 5 pm until 6 pm) 85.5 % of the fleet is operative (value adopted from [Wortmann et al., 2021](#)). For the second and third case, the assumed ratios of peak, to off-peak and night hour demand are estimated. This is done by scaling the peak demand to diurnal mobility behaviour (such as depicted in [Balzer, 2012](#)) with 50 % of peak-behaviour from 8 am until 5 pm and 25 % from 6 pm until 9 pm and 5 am until

7 am. Following these three temporal cases and their shares of the peak demand, the correcting factor for required FTEs can be derived by $85.5\% \cdot ((2 \text{ hours} \cdot 100\%(\text{peak demand}) + 9 \text{ hours} \cdot 50\% + 5 \text{ hours} \cdot 25\%) / 16 \text{ hours}) = 41.41\%$. To additionally account for standby personal this values is rounded to 42%. Hence, the final required number of FTEs per vehicle are calculated as $0.42 \cdot 3.68 \text{ FTE} = 1.55 \frac{\text{FTE}}{\text{vehicle}}$. Finally, the total costs for driver can be calculated.

$$C_{\text{driv}}^* [\text{€}/\text{day}] = \lceil 1.55 \cdot \text{fleet} \rceil \cdot \text{wage}_{\text{drive}} / 365 \quad . \quad (\text{F.20})$$

F.5. HBS

The cost functions C_{vehuse}^* , C_{driv}^* , C_{rebuar}^* , C_{clean}^* and C_{park}^* are not applicable. $C_{\text{maintparts}}$, C_{paym} , C_{ins} , C_{IoT} are similar to FFCS. The remaining cost functions are explained below.

$$C_{\text{fuel}} [\text{€}/\text{day}] = \text{fleet} \cdot \text{share}_{\text{ped}} \cdot 0.25 \text{€} \cdot \frac{12}{365} \cdot \frac{1}{1.19} \cdot d \quad , \quad (\text{F.21})$$

with $\text{share}_{\text{ped}}$ as the share of pedelecs in the fleet mix (5 %). The costs of €0.25 are the costs for the average energy consumption per pedelec and month.

$$C_{\text{vehtime}} [\text{€}/\text{day}] = \text{fleet} \cdot c_{\text{deptime}} \cdot \frac{12}{365} \cdot \frac{1}{1.19} \quad . \quad (\text{F.22})$$

Based on the interviews a new depot is assumed to be required every 800 vehicles.

$$C_{\text{whs}} [\text{€}/\text{day}] = \lceil \frac{\text{fleet}}{800} \rceil \cdot 400 \text{m}^2 \cdot \text{rent} \cdot \frac{12}{365} \quad . \quad (\text{F.23})$$

Based on Kugoth (2017) and Oesterreich (2020), an average rate of approximately 131.35 bikes per field agent is derived. For consistency with the SES model, a ratio of 375 bikes per mechanic is assumed which is roughly in line with Kugoth (2017).

$$C_{\text{agentfield}} [\text{€}/\text{day}] = \left(\lceil \frac{\text{fleet}}{195.35} \rceil + \lceil \frac{\text{fleet}}{375} \rceil \right) \cdot \text{wage}_{\text{field}} / 365 \quad (\text{F.24})$$

For the required service vehicles, it is assumed that the field agents work in two shifts as per Kugoth (2017). Thus, the required number of service vehicles is based on half the number of required field agents for HBS.

$$C_{\text{s-veh}}^* [\text{€}/\text{day}] = \lceil \frac{1}{2} \cdot \frac{\text{fleet}}{195.35} \rceil \cdot c_{\text{s-veh}} \cdot \frac{12}{365} \cdot \frac{1}{1.19} \quad (\text{F.25})$$

The rate of customer support agents is adopted from Wortmann et al. (2021).

$$C_{\text{agentcs}} [\text{€}/\text{day}] = \lceil \frac{\text{fleet}}{1250} \rceil \cdot c_{\text{agentcs}} \cdot \frac{12}{365} \cdot \frac{1}{1.19} \quad . \quad (\text{F.26})$$

$$C_{\text{vand}}^* [\text{€}/\text{day}] = \text{fleet} \cdot c_{\text{vand}} / 365 \quad , \quad (\text{F.27})$$

It is assumed that only 1 % of the stations that would normally be needed in a station-based bike sharing are physically installed for the HBS system. Following the average number of 10 bikes per station for station-based bike sharing-systems is derived as an estimate from City of Baton Rouge (2016), Yanocha et al. (2018), City of Davis (2014) and City of Redmond Washington (2016), the costs of the station infrastructure are then derived by

$$C_{\text{infra}}^* [\text{€}/\text{day}] = \lceil \frac{\text{fleet}}{10} \cdot 0.01 \rceil \cdot c_{\text{stat-infra}} / 365 \cdot \frac{1}{1.19} \quad . \quad (\text{F.28})$$

Appendix G. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.rtbm.2025.101436>.

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