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Free-floating car-sharing electrification and mode displacement: Travel time and usage patterns from 12 cities in Europe and the United States

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ABSTRACT

Free-floating car-sharing (FFCS) allows users to book a vehicle through their phone, use it and return it anywhere within a designated area in the city. FFCS has the potential to contribute to a transition to low-carbon mobility if the vehicles are electric, and if the usage does not displace active travel or public transport use. The aim of this paper is to study what travel time and usage patterns of the vehicles among the early adopters of the service reveal about these two issues.

We base our analysis on a dataset containing rentals from 2014 to 2017, for 12 cities in Europe and the United States. For seven of these cities, we have collected travel times for equivalent trips with walking, biking, public transport and private car.

FFCS services are mainly used for shorter trips with a median rental time of 27 min and actual driving time closer to 15 min. When comparing FFCS with other transport modes, we find that rental times are generally shorter than the equivalent walking time but longer than cycling. For public transport, the picture is mixed: for some trips there is no major time gain from taking FFCS, for others it could be up to 30 min.

For electric FFCS vehicles rental time is shorter and the number of rentals per car and day are slightly fewer compared to conventional vehicles. Still, evidence from cities with an only electric fleet show that these services can be electrified and reach high levels of utilization.

1. Introduction

The transportation system of today is faced with challenges such as emissions of greenhouse gases, urban air quality and congestion. At the same time, there are major trends that may have a disruptive effect on the system (Sprei, 2017). Shared mobility is one of them and there is a need to better understand how shared services are used and how they relate to electrification, another major trend.

Shared mobility includes different sharing options from services in which the vehicle itself is shared as in various forms of car-sharing, to where the ride is shared as in ride-hailing or carpooling (for definitions and examples of shared mobility see (Cohen and Shaheen, 2018; Shaheen et al., 2016). In this paper, we focus on a specific form of shared mobility, i.e., free-floating car-sharing

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(FFCS). Free-floating car-sharing allows users to book a vehicle through their phone, use it and then return it anywhere within a designated area of a city. It is a relatively new form of car-sharing service which provides users with greater flexibility compared to station-based car-sharing. Vehicles in station-based car-sharing have to be returned to the place where they were picked-up. Normally FFCS fees are based per minute while for station-based car-sharing the fee is per hour and distance traveled.

Free-floating car-sharing started as pilot tests in the early 2000s. The first pilot program that led to continuous services took place in Ulm Germany in 2008 (Kortum et al., 2016; Shaheen et al., 2015). Since then the service has rapidly developed and is present in over 40 cities. In Europe and North America, it is mainly dominated by two operators: Car2go and DriveNow. There are other smaller actors that operate in just a few cities or within a country. While Car2go and DriveNow are both FFCS they offer slightly different services to the users given the vehicles that they provide. Car2go offers only a smaller two-seater, while DriveNow has a larger variety of models in their fleet.[1] FFCS has not been as extensively studied as traditional car-sharing. Most studies are based on user surveys from one or a few cities and some on vehicle movements. Here we focus on the literature explicitly related to FFCS since this is our focus area. For a broader overview of car-sharing in general, please see Shaheen and Cohen (2016) and Shaheen et al. (2016).

Firnkorn and Müller surveyed the first users of the services in Ulm, Germany (Firnkorn and Müller, 2011, 2012). They focused on the potential to reduce carbon emissions and reduce vehicle ownership by asking stated preference questions based on future scenarios for the FFCS service.

Studies such as Namazu and Dowlatabadi (2018), Le Vine and Polak (2017), Becker et al. (2017b, 2018) study the effect of FFCS on vehicle ownership. They try to answer the question if becoming a member of a FFCS service has resulted in the shedding of a vehicle or facilitated a postponement of vehicle purchase. They find that vehicle ownership is reduced but not as much as for station-based car-sharing. Firnkorn and Müller (2015) incorporate different electrification scenarios into an online survey of Car2go-users. The results indicate that having driven an electric Car2go increased the respondent's willingness to decline a private car purchase.

Frequency and purpose of trips are other themes of survey-based studies. Stated purposes for using FFCS are: to visit family and friends (Becker et al., 2017b; Louvet, 2014), to connect to public transport (Le Vine and Polak, 2017), and shopping (Becker et al., 2017b; Le Vine and Polak, 2017). Becker et al. (2017b) find that compared to station-based users, commuting and airport transfers are more common purposes even if these are still only around 10% of the trips.

Relationship with other modes of transport is another subject of FFCS studies. Louvet (2014) find that the users of Autolib, which was a one-way car-sharing in Paris, have a negative perception of public transport and prefer Autolib to using it. It should be pointed out that Autolib had designated parking in Paris, a city with large parking problems. Martin and Shaheen (2016) find that for the users of Car2go in five cities in North America, FFCS both substitutes and complements public transport, with the majority of users having no change in public transport use. However, they find that more members reduce public transport use than increase it. In four out of five cities walking is increased, probably to reach the vehicles. Similarly to Louvet (2014), they find that the services compete with taxis. Ciari et al. (2014), based on simulations, find that the demand for FFCS is drawn from car travel (30%) followed by bike, public transport, and walking. Overall, car travel increases with FFSC compared to the station-based car-sharing scenario.

There are also studies in which FFCS are compared to station-based car-sharing services (see e.g., Ciari et al. (2014) and Kopp et al. (2015)). They show that FFCS does not reduce the attractiveness of the station-based car-sharing and is complementary to it. Based on surveys to FFCS users and station-based car-sharing user in Switzerland, Becker et al. (2017a) conclude that FFCS are used complementary to public transport as opposed to station-based car-sharing which is dependent on high-quality public transport.

Another approach to study FFCS is to follow the movements of the vehicles. Kopp et al. (2015) not only follow the vehicles but the users as well to understand their overall mobility patterns and compare this with a control group. They find that DriveNow users are more multi-modal and tend to choose their transport mode based on the purpose of the trip and therefore have more flexible mobility patterns compared to non-FFCS users.

Kortum et al. (2016) use vehicle movement from 33 different cities from 2011 to 2015. They look at the growth and find that the usage has been increasing over time. The city factors that affect growth rate are household size and residential density. Schmöller et al. (2015) look at similar data but only for Berlin and Munich. They look at the driving patterns and try to identify hot spots where the vehicles are used the most. They find hot spots in areas with high population density and a high density of shopping possibilities and working places. Another study that relies on vehicle movement data is Wang et al. (2017). In their study, they compare travel time between FFCS and public transport in Seattle and find that public transport has longer waiting time and in-vehicle time. However, they find that Car2go is more costly and is not used disproportionally more for trips that offer larger time savings compared to public transport. Another study that compares travel times is Schwieterman and Michel (2016), however, they compare another type of mobility service, i.e., UberPool (a pooled ride sharing service) and public transport in Chicago. They find that the difference in time gain depends on the time of day and district, with UberPool performing worse during rush hour and to and from the central business districts.

By being an alternative to the privately owned car FFCS has the potential to contribute to a transition to low-carbon mobility (Becker et al., 2018; Shaheen and Cohen, 2013). However, two preconditions have to be fulfilled: first, the vehicles in the fleet should be electric and second, they should not compete with more sustainable modes such as biking, walking and public transport but rather complement these. The aim of this paper is to study what the usage pattern of the vehicles reveals about these two issues.

For the electrification of the vehicles, our research question is: are electric vehicles (EV) in the fleet used differently, e.g., for shorter trips, compared to the internal combustion engine (ICE) vehicles? This can give an indication if users choose EVs for different types of trips compared to ICE.

[1] The models range from smaller vehicles such as MINIs, to sedans and station-wagons. No SUVs or larger vehicles are included in the fleet.

For the competition with other modes, we focus on travel time. While mode choice is complex and influenced by many factors (Van Acker et al., 2010), travel time is one contributing factor in the decision (Schneider, 2013). The research question addressed is: how does travel time by FFCS compare with travel time for walking, biking and public transport? Better knowledge of the differences in travel time for trips taken with FFCS will give a suggestion on how FFCS compares to other modes. Do users choose FFCS because there is a major time gain compared to other modes? While our analysis cannot fully answer the question, it can give a first indication.

We base our analysis on a dataset of sampled rentals for 12 cities in Europe and the United States collected between 2014 and 2017. There are similarities between our data and that collected by Kortum et al. (2016), however, our analysis focuses more on the usage pattern of the vehicles rather than comparing and explaining growth rates. Similarly to Wang et al. (2017), we compare travel times with public transport. However, in our study, we have also collected alternative trip travel times for walking and biking.

To our knowledge, this is the first study that analyses different aspects of the usage of FFCS in various cities, both looking at the use of EVs and comparing with other modes of transport. Our study does not provide the same detailed analysis as Wang et al. (2017) and Schmöller et al. (2015). However, these studies focus on one and two cities respectively and Wang et al. (2017) only compare with public transport. Our study loses in depth but allows us to compare more modes and cities and thus gives a broader picture of how these services are used.

Our analytical approach is based on driving patterns with a special focus on travel time. Since our data is based on the vehicles, we don't have information about users and thus don't know how travel time is perceived and how it interacts with other factors that affect vehicle choice or mode choice. While data sets that follow the users such as in Kopp et al. (2015) give more detailed information, these are more cumbersome to collect making it hard to get a large sample and to compare between cities. Even if FFCS membership is growing, especially in Europe, it is still covers a small share of the population and thus the users are early adopters of the innovation. Usage patterns and choice might thus differ when (and if) a larger share of the urban population starts using FFCS.

The strength of our approach is that it allows us to have a more accurate account of how the vehicles are actually used, not colored by users' subjectivity or recollection. Travel time by other modes, as well as by car, is something that local policymakers can affect through regulations, infrastructure development and urban planning. There is thus an interest to better understand how travel time differs between the modes for actual trips taken. The results of our study can be useful for future simulation studies, input for user surveys, policymakers, as well as a better understanding of the generalizability of the results from individual cities.

The paper is structured as follows. At first, we present the data collected and the methods used. Thereafter, we present as background information general usage patterns, such as time of day and weekday variations for the studied cities. The next section compares the usage of EVs and fossil fueled vehicles in FFCS fleets. In Section 6 we compare travel times between different modes of transport and FFCS and we end the paper with discussions and conclusions.

2. Description of data used

There are two data sources that we use for this study: FFCS booking data and data on alternative transport modes.

FFCS operators provide users with information about the positions of parked vehicles, vehicle type and fuel level through webpages and/or smart phone applications to enable users to find and book available vehicles. FFCS booking data is sampled from FFCS rentals through logged data of vehicle movements. The sampling rate is one minute. We expect that any lag from when the vehicles are booked/returned to when they appear on the web-page is negligible.[2]

The dataset on FFCS consists of vehicle availability data sampled between 2014 and 2017 from two different operators in 12 different cities located in Europe and the US. Sampling restrictions on travel time with alternative modes limited the number of cities that we were able to sample. In total we collected data on alternative modes for seven cities, four in Europe, namely Amsterdam, Berlin, Madrid and Stockholm and three in the US: Denver, Seattle and San Diego. Two of the cities, Amsterdam and Madrid were selected since they had a battery electric vehicle (BEV) only fleet. Berlin and Madrid are cities with a high demand for these services and Seattle has the highest demand of the US cities. This allowed us to compare the usage in cities from different geographical areas, with and without BEV in the FFCS fleet, while capturing the cities where the service is used the most. To these cities, five cities with BEV in their fleet were added with only sampling of the FFCS vehicles.

An overview of the cities sampled can be found in Table 1 showing the number of vehicles in each city, the share of BEVs, if data has been collected on alternatives modes and the number of days sampled.

Start location for each movement corresponds to the last sample before the vehicle is no longer indicated as available to the user, and end location to the first sample where it once again can be booked. The data contains the following variables for each rental during the data collection period: vehicle ID, starting and ending time of the rental, vehicle make and model, the position of vehicles at the start and end time. The data lacks information on the users; thus we do not know the purpose of the trip or how frequently different users use the vehicles. Moreover, the data lacks actual distance traveled during the trip, instead we use the geo (straight line) distance between origin and destination of each trip.

The second data base is data on alternative transport modes for the selected cities. For each sampled FFCS trip, a query has been sent to Google Maps with the same start to end locations as the equivalent FFCS trip to obtain travel time if the trip was made by

[2] Technically there should be no reason for a lag since this can be done in less than 500 ms (far smaller than the sampling rate of once per minute). For the operators perspective there is an interest to reduce this time to avoid customer annoyance. To ensure that this was not an issue the authors contacted the operators who confirmed this.

Table 1
Total number of FFCS vehicles in the studied cities, share of BEV (%), if there is data on travel time for alternative modes (green: yes; red: no) and the number of days sampled.

City	FFCS vehicles	% BEV	Data on alternative mode	Number of days sampled
Amsterdam	340	100 %		735
Berlin	2064	5%		736
Cologne	483	5%		79
Denver	334	0%		451
Düsseldorf	399	5%		79
Hamburg	1334	3%		79
Madrid	463	100%		443
Munich	1040	6%		79
San Diego	388	0%		686
Seattle	725	0%		769
Stockholm	462	6%		78
Vienna	425	4%		79

public transport, cycling, walking and by car. Since a query can only be put to Google Maps in advance, the query has been set for a trip starting exactly one week after the actual FFCS trip occurred so that congestion and other conditions are about the same. There is a limited number of queries that can be sent to Google Maps for free, limiting the number of alternative trips to fewer than collected FFCS trips. This implies that we only collect data for seven cities (see Table 1). For each of these seven city, we randomly select FFCS trips for which alternative trips are collected.

2.1. Data cleaning

To prepare the data for calculations, we first remove the outliers. To do so, we remove the following trips: 5% of the longest rentals in time and distance, the start and end locations with the longitude and latitude outside 99th percentile, trips with speeds higher than 130 km/h. All these trips either have very long rental times or very short geo distance. By removing trips with a very long duration, it is likely that the maintenance trips and cancelled trips are also removed. In Madrid where the FFCS fleet is entirely electric, we can identify the trips in which the operators take the vehicles to charge at their fast charging stations. Recharging trips are trips in which the state of charge of the battery is higher at the end of the trip than the beginning of the trip.

3. Methods

3.1. General usage patterns

In this section, we calculate the basic statistics for usage patterns for all the 12 cities observed in this study. For geo-distance, rentals per car and day and utilization rate averages and standard deviations are calculated. The utilization rate is defined as the total time (minutes) all cars are used each day divided by how many minutes they can be potentially driven per day. The distribution of rental times is not Gaussian and symmetrical, but rather right-skewed and thus median and 1st and 3rd quartiles are presented instead.

Histograms are calculated on an hourly basis for workdays and weekends in the cities. We also look into whether the number of trips per day during weekends is significantly different from the workdays, this is done by a simple *t*-test at the 95% level of significance.

3.2. BEVs usage pattern

To compare usage patterns between BEVs and fossil vehicles in the fleet, we plot averages and standard deviation for the number of trips per day and geo-distance per trip for seven cities where both types of vehicles are present. For rental duration, given the right-skewed distribution, we instead plot median and quartiles. T-test with 95% significance level is also performed.

3.3. Trip types

In the description of the general usage pattern, we categorize FFCS trips into three different trip types: short, round and one-way trips. Short trips are trips with a rental time below 15 min. We single out trips with shorter rental time since one could presume that they could more easily be replaced by walking and cycling. Round trips are those trips where the cars are returned to the vicinity of the start point of the trip. They are identified as trips in which the geo distance between origin and destination is less than 0.65 km. This distance is twice as the access/regress walk to/from FFCS cars reported in the literature (see e.g., Becker et al. (2017a),

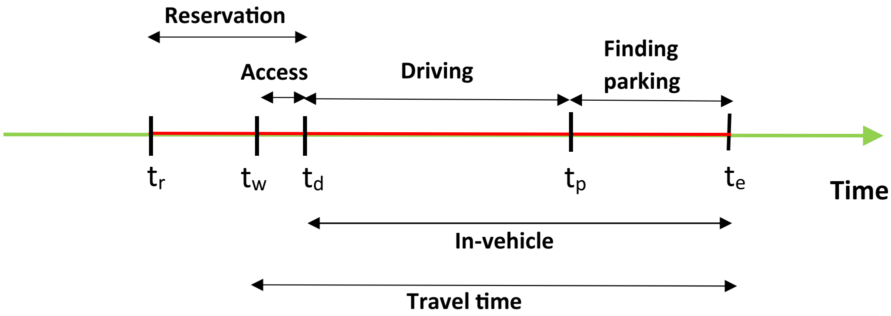

Fig. 1. Different time components of the FFCS rental time.

Schmöller et al. (2015); (Wang et al., 2017)) . Also, in these trips, the rental time should be over 15 min to ensure that cancelled booking are not counted as round trips. Customers have up to 15–30 min between booking and starting a trip in different cities. One-way trips are the remaining trips, i.e., those that are neither short nor round.

3.4. Comparison with alternative trips

We have gathered data for alternative trips in seven different cities. For these cities, we compare the travel time of the FFCS trips with travel time with alternative modes. The observed rental duration in our data represents the time the vehicle is not available for a new booking and thus contains the reservation time as well. Fig. 1 shows the different time components of a trip with FFCS. The green part, before time t_r and after time t_e, indicates when a specific car is available for booking. $(t_d - t_r)$, represents the reservation time, i.e., the time the vehicle is reserved prior to usage. This time also includes the access time, $(t_d - t_w)$, i.e., the time to walk to the vehicle. This period is free of charge and the maximum allowed duration differs between operators and cities. The range is between 15 and 30 min. When the car is reached and unlocked, then the in-vehicle time starts, $(t_e - t_d)$. This includes both driving time and parking time. The total rental time in FFCS is thus the sum of the access time, driving time and parking time. It should be noted that we cannot identify different time components in our data. However, through Google Maps we can identify the driving time and thus we can get an indication how the travel time by other modes compares both to rental time and driving time, giving an indication of the time difference when traveling by another mode.

For this part of the study, we exclude round trips since it is not possible to have Google Maps data for them as the path taken is not observed. Regarding chaining trips (i.e., trips with intermediate stops) Wang et al. (2017) exclude these based on the assumption that these are trips where rental time minus driving time from Google Maps exceeds 50 min. We have instead chosen to study the travel time in three different time slots: short (< 15 min), medium (15–30 min) and long (> 30 min) since the longer the rental time, the larger the discrepancy with driving time (in absolute terms), as can be seen in the results section. This allows us to discern possible trips where the reservation time might be longer and where there might be a larger share of chaining trips, allowing a more transparent presentation of the time differences between modes and rental time. Studies based on user surveys do not report results regarding trip chaining; thus this could be included in future user studies to better understand the prevalence of and preference for these type of trips.

Table 2
Usage patterns for 12 cities. For rental duration median, 1st and 3rd quartile are presented, for geo distance, rentals per car and day and utilization rate means and standard deviation, in parenthesis, are presented.

City	Rental duration (min)			Geo distance (km)	Rentals/car/day	Utilization rate (%)
	1st quart	Median	3rd quart	Mean (SD)	Mean (SD)	Mean (SD)
Amsterdam	17	26	39	3.0 (1.9)	4.6 (3.2)	9 (5)
Berlin	19	27	39	3.7 (2.4)	5.3 (3.0)	10 (3)
Cologne	19	26	38	3.6 (2.5)	4.4 (2.6)	7 (2)
Denver	13	20	31	2.5 (1.5)	3.2 (1.9)	4 (1)
Dusseldorf	19	27	42	3.0 (1.9)	3.6 (2.1)	5 (2)
Hamburg	18	27	38	3.4 (2.2)	4.6 (2.6)	9 (3)
Madrid	19	26	34	2.7 (1.4)	9.5 (4.1)	17 (6)
Munich	20	28	42	4.7 (–)*	2.8 (1.7)	5 (2)
San Diego	13	21	33	3.2 (2.5)	3.2 (2.0)	5 (2)
Seattle	17	26	37	3.6 (2.5)	4.8 (2.8)	8 (2)
Stockholm	17	27	42	2.9 (–)*	1.2 (0.5)	1 (0)
Vienna	19	27	38	3.2 (2.2)	4.4 (2.4)	9 (2)

* For Munich and Stockholm median is presented instead.

4. Background: General usage patterns parameters

In this section, as background information we present some parameters regarding overall usage patterns of the FFCS in the cities. For a more detailed overview of these, see Habibi et al. (2017). We present in Table 2 rental duration, geo-distance, rentals/car/day and the utilization rate. The first two are parameters related to the type of trips while the other two give an indication of how much FFCS is used.

The distribution of the rental duration in the cities follows a right-skewed distribution implying that there is a difference between the mean and the median and that standard deviations are not a proper measure for spread. We therefore present the median and the first and third quartile to give a sense of the distribution. The median rental duration is roughly around 26–28 min expect in Denver and Sand Diego that have a median rental duration around 20 min instead.

For the majority of the cities, the distribution of the geo-distance is normal like and thus mean and standard deviation are presented. The exceptions are Munich and Stockholm that have a more right-skewed distribution (the reason for not presenting standard deviation for these cities). Both these cities have the airport as a location for pick-up and drop-off increasing longer distance trips.[3] The average geo-distance is around 3.0 km with the exception of Munich having a median of 4.7 km.

The rental duration and geo-distance illustrate that these services are geographically bound and used within a city compared to station-based car-sharing. The pricing scheme per minute also discourages longer rentals. User surveys show that these services are used for different types of trips with a prevalence of leisure trips but also a fair share of commuting (Becker et al., 2017b; Louvet, 2014; Martin and Shaheen, 2016).

To give a picture of how often the vehicles are used the average number of rentals per car and day are presented as well as the utilization rate. The utilization rate is defined as the total time (minutes) cars are used each day divided by the time (minutes) they are potentially available to be booked per day. For the 12 cities analyzed in this paper, the cars are rented 3–5 times per day. However, there are large variations. Madrid stands out for having the highest number of rentals per car and day, over 9, while the cars in Stockholm only are rented around once per day.

These numbers are also reflected in the utilization rate where Madrid has the highest mean utilization rate of 17% while Stockholm only has 1%. For the rest of the 12 cities, we find two main groups: Amsterdam, Berlin, Hamburg, Seattle and Vienna have a utilization rate between 8 and 10%, while Denver, Dusseldorf, Munich and San Diego have an average utilization rate closer to 5%. Habibi et al. (2017) find an average utilization rate of 6% among 35 cities with FFCS.

Generally, we find that the usage of FFCS follows a similar daily pattern as other modes of traffic during the workday. There is a morning peak and a longer afternoon/evening peak. To exemplify, histograms over the distribution of trips over the day for Amsterdam and Seattle are presented in Fig. 2. For these cities, the morning peak is shorter in time and the afternoon peak is higher and longer. This pattern is observed in the majority of the other cities. However, the shape, i.e., height and duration, and the length of the peak varies between the cities. In the case of San Diego there is no pronounced morning peak at all. During the weekend there is no morning peak which is not surprising and the afternoon peak is longer and spreading from noon to late evening in several cities (see Fig. 2 for Amsterdam and Seattle). Especially after midnight, we find that there are more trips made on weekends compared to workdays.

In most European cities observed, there is no significant difference (see Table 3) between the average number of trips per day on workdays and weekends. On the other hand, in US cities plus Amsterdam and Madrid, there are more trips on workdays compared to weekends. Louvet (2014) on the other hand finds that the one-way service in Paris is more frequently used on weekends.

Fig. 2 also shows the distinction between short, one-way and round trips. As can be seen in the figures the majority of trips are one-way trips, followed by short trips and last round trips. For all the cities we find that on average 70% of the trips are one-way, 20% are short trips and the remaining 10% are round trips. There is no major difference in distribution of the three trip types between workdays and weekends. Even during weekends the one-way trips dominate.

5. Usage patterns of battery electric vehicles in FFCS fleets

Battery electric vehicles (BEVs) in the FFCS fleet can be found in nine cities during the observation period. Two of these cities, Amsterdam and Madrid, have only BEVs while the remaining seven, Berlin, Cologne, Düsseldorf, Hamburg, Munich, Vienna, and Stockholm have both BEVs and internal combustion engine vehicles (ICEs) in their fleet. In both Amsterdam and Madrid the BEVs have a range of approximately 100 km and in the other cities there are also BEVs with a range up to 160 km. In all cities with a mixed fleet, the number of BEVs are only about 5% of the vehicles (see Table 1). This will affect the spread of the parameters and should be taken into consideration in evaluating the comparison of usage patterns.

We look at the average and standard deviation of distance per trip, and the average number of trips per car and day for the cities with both BEVs and ICEs. For rental duration, we look at mean and 1st and 3rd quartiles. The results can be seen in Fig. 3.

The average distance per trip differs between fossil and BEV vehicles according to the *t*-test and is larger for the fossil vehicles. The largest difference can be found in Munich. This may be explained by trips to the airport where the vehicles can be dropped-off and picked-up. The airport is 35 km away from the city and for these trips, fossil fueled vehicles are more frequently used.

For all cities the average number of trips per vehicle and day is slightly higher for fossil vehicles, indicating that they might be used more frequently. T-tests also show that there is statistical significant difference, with the exception of Dusseldorf. In Berlin and Munich, the difference between the averages is the largest. Still, we find a spread in the number of trips per day for both ICE and BEV

[3] The distance from city center to Munich airport is roughly 35 km and between Stockholm and Arlanda airport it is roughly 40 km

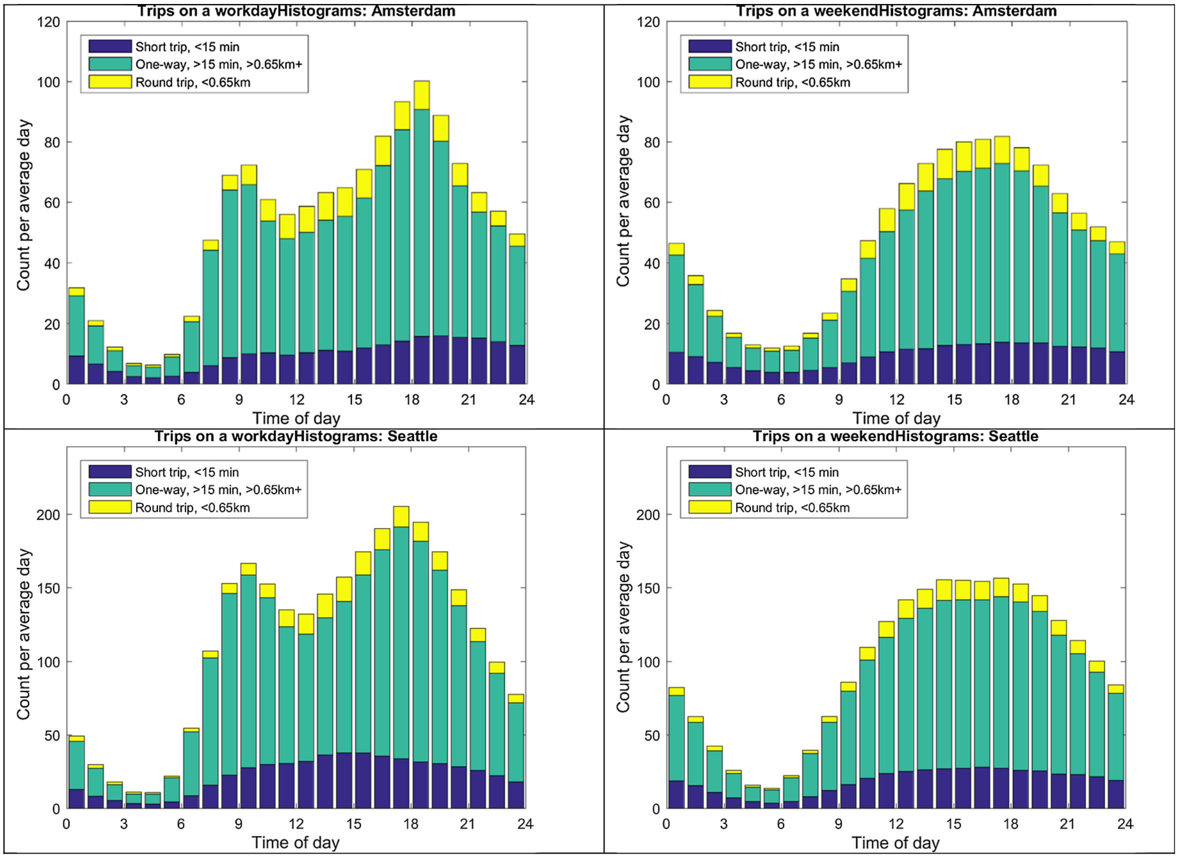

Fig. 2. Histogram over start of trips for Amsterdam (above) and Seattle (below) for workdays and weekends. The trips are divided into short trips (< 15 min rental time); One Way trips (rental time > 15 min and geo-distance > 0.65 km) and round trips (GEO-distance < 0.65 km and rental time > 15 min).

Table 3
Average number of trips during workdays and weekends with standard deviations in parenthesis and if there is a significant difference in number of days based on T-test with 95% level of significance.

City	Workdays	Weekends	Significant difference? (95%)
Amsterdam	1243 (613)	1133 (579)	Yes
Berlin	4731 (1168)	4829 (1123)	No
Cologne	1354 (369)	1419 (305)	No
Denver	875 (226)	593 (174)	Yes
Dusseldorf	697 (188)	650 (124)	No
Hamburg	6258 (1250)	6310 (1091)	No
Madrid	3921 (1551)	3089 (1257)	Yes
Munich	3158 (728)	3346 (691	No
San Diego	765 (191)	650 (147)	Yes
Seattle	2672 (493)	2276 (473)	Yes
Stockholm	589 (152)	546 (123)	No
Vienna	1603 (434)	1670 (244)	No

vehicles indicating that there is also a large overlap.

As for the other parameters we find that the rental duration has quite a large spread and that there is a statistically difference between ICE and BEV vehicles, with the expectation of Dusseldorf. In Hamburg and Vienna, the median rental duration is longer for BEVs than what it is for ICE vehicles. In the case of Stockholm, the difference is the greatest.

Looking at the two cities with only BEVs the numbers are similar to the other cities. In Amsterdam, the average distance per trip is 3.0 km with a standard deviation of 1.9 km. In Madrid, the average distance per trip is slightly lower, 2.7 km with a standard deviation of 1.4 km. The average number of trips, on the other hand, is higher for Madrid with an average of 9.5 trips per day (standard deviation 4.1 trips per day). Madrid is also the city with the highest utilization rate of 17% versus and average of 6% in 35 cities.

We find that there are differences in usage patterns between BEV and fossil vehicles in the cities. We do not know if the difference

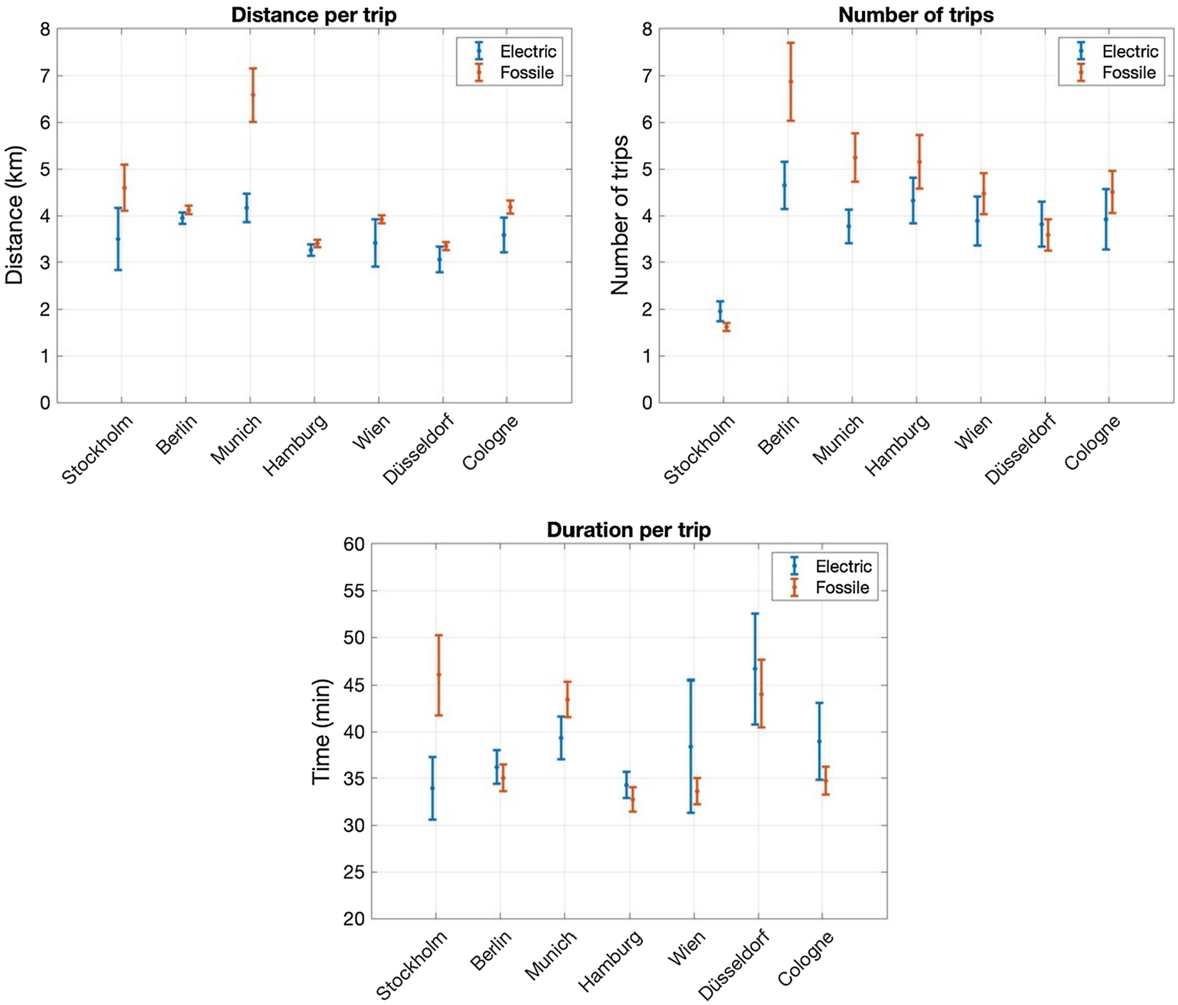

Fig. 3. Average distance and standard deviation for geo-distance per trip (top left) and number of trips per day per vehicle (top right); median and 1st and 3rd quartile for rental duration per trip (bottom), for 7 cities with both fossil fueled and EV.

is due to the preferences of the users or the fact that these vehicles are fewer. Charging may also make them less available. Some user studies have looked at preferences for BEVs. Wielinski et al. (2017) found in Montreal that there was no difference in preference for ICE over EVs for trips with a travel distance up to 24 km. Surveys and interviews with FFCS in Berlin and Munich also show that the users have a high acceptance of EVs and the main reason for not using it was that there was no car available (Mueller et al., 2015). Still, this is an area for further research to better understand the choice of vehicles, if it differs depending on the type of trip and what would make users even more prone to choose EVs. Studying the operators' perspective is also of interest: what guides the choice of vehicles from their perspective and what is needed for them to increase the share of EVs in their fleet.

The examples of Amsterdam and Madrid show, through a high utilization rate with a BEV only fleet, that BEVs can provide a similar service to fossil fueled vehicles. Policies and regulations from the cities are the reason for an all BEV fleet. In Madrid parking is free for BEVs implying large costs savings for the operators. The city of Amsterdam requires the operators to have only BEVs in order to be eligible for parking permits (Sprei et al., 2017). What might be a barrier is charging opportunities as was the case in San Diego where the lack of charging infrastructure stopped the shift to BEV (Saunders, 2018). The density and occurrence of charging infrastructure will affect users since it will determine if vehicles with enough range can be found. In general, the trips taken with the FFCS are well below the range of the vehicle, given that the vehicles are recharged regularly. The two cities with BEV only fleets have two different strategies for how to handle charging. In Amsterdam, it is solved through a widespread network of "slow" charging stations provided by the city. Thus the vehicles are recharged by the users themselves. In Madrid instead, the vehicles are charged by the FFCS operator at designated fast-charging stations.

6. Comparison with other modes of transport

In this section, we present the results from comparing the rental times for FFCS trips with the equivalent travel time with other

Table 4
Share of trips and average geo-distance of trips divided in the three different time slots.

City	Short trips (< 15 min)		Medium trips (15–30 min)		Long trips (30 min)	
	%	Geo distance (km)	%	Geo distance (km)	%	Geo distance (km)
Amsterdam	14	1.79	43	3.26	39	3.33
Berlin	13	1.76	41	3.52	42	4.46
Denver	26	1.80	42	2.79	27	2.71
Madrid	8	1.49	51	2.63	36	3.11
San Diego	25	2.10	38	3.68	32	3.73
Seattle	16	1.91	42	3.71	37	4.42
Stockholm	19	1.71	42	3.25	35	3.03

modes of transport. As noted in the method section rental time for FFCS includes reservation time, driving time and parking time. The free reservation time differs between cities and operators ranging from 15 min to 30 min. We thus compare travel times of alternative modes with both driving time and rental time to get a better understanding of differences in actual travel time. We also compare three different categories of trips: short (< 15 min), medium (15–30 min) and long trips (> 30 min). It should be reminded that we exclude round trips for this section. Table 4 shows that there is a clear distinction between the average geo-distance of the short trips and medium trips; while there is no major difference between the average in medium and long trips. Differentiating between the different duration gives us an opportunity to separate trips where reservation time most probably has a larger share of the rental time. A larger share of the long trips may include trip-chaining.

As can be seen in Table 4, short rentals include on average 19% of all rentals. This share is around 25% in Denver and San Diego, and 8% in Madrid. Medium rentals are the largest group and contribute to on average 43% of all rentals in the cities. The share of these trips is the largest in Madrid with 51%. The long rentals include on average 35% of all rentals in cities. In Denver and San Diego, the share is lower, i.e., 27% and 29% respectively.

6.1. *Compared to driving*

The expected travel time by car returned from Google Maps is compared with the FFCS rental time in order to estimate average "non-driving time", i.e., the reservation time, access time and parking time (see Fig. 1).

Looking at driving time per se we find that compared to the rental time there is less of a distribution. While the median rental time for all trips is around 27 min, driving time is much closer to 15 min. We do not find much difference in driving time between the medium and longer rental times, and the geo-distances are roughly the same for medium and long rentals (see Table 4). For the short trips the average driving time varies between 7 and 9 min between the cities.

If we instead focus on the difference between driving time and rental time for all the trips we find a small fraction of all trips for which the FFCS rental time is shorter than the Google maps driving time. These represent 1–5% of the trips in the studied cities (see Table 5). However, the median time difference is very small, i.e., one minute.

For trips that are faster by car, which is expected, we see that the median difference between rental time and driving time, does not vary that much between the cities and lies between 12 and 15 min (see Table 5). This is despite the fact that the free reservation time differs between European cities where it is 20 min and US cities where it is 30 min. Stockholm has the shortest free reservation time of 15 min.

Given the results from the median driving time in the different time slots, it is not surprising that the median time difference between driving time and rental time increases with the length of the rental time. For short trips, the median time difference is 4 min, for medium length trips the median is 11 min and for long trips it is 28 min. For long trips, Stockholm has the highest time difference, 30 min (see Table A1).

The observed longer rental time, especially for the long trips, can be explained by access time, reservation time, cruising for parking or the occurrence of trip-chaining. There is little empirical evidence on each of these parts however, we find some indication of their magnitude in the literature. Regarding access time, Wang et al. (2017) calculate an average access time of 5.5 min for Seattle. While not giving an estimate of access time (Becker et al., 2017a) conclude that FFCS users might be willing to walk longer compared to public transport for the higher utility they get by taking the car. Access time is also most probably included in the reservation time, i.e., users will first book the vehicles and then start walking towards it. For cruising for parking Van Ommeren et al. (2012) finds that there is little empirical data on how much time people spend cruising for parking in different cities. However, Shoup (2006) finds that it varies between 3.5 and 14 min, based on 16 studies from 1927 and 2001. We can thus expect actual travel time with FFCS can be roughly 5–20 min longer than the driving time.

6.2. *Compared to walking*

We now compare the rental time of FFCS with that of walking. As expected, for the majority of the trips, 84%, the rental time is shorter than the time it would take to walk the distance (Table 5). The time gain is between 18 min for Madrid and 36 min for San Diego. However, in 16% of the trips, on average, walking outperforms FFCS. This share varies from 11% in Seattle to 20% in Madrid and Stockholm. The time difference is 11 min on average which is similar to that of the driving. The time difference between walking

Table 5
Share of trips where rental time for FFCS is longer than the travel TIME per mode; median time difference for trips where rental time for FFCS is longer than the travel time per mode as well as median time difference for trips where rental time is shorter than the travel time per mode. All results presented for each mode and city.

City	Driving			Walking			Cycling			Public transport		
	% $T_{FFCS} > T_{driving}$	ΔT (min) $T_{FFCS} > T_{driving}$	ΔT (min) $T_{FFCS} < T_{driving}$	% $T_{FFCS} > T_{walking}$	ΔT (min) $T_{FFCS} > T_{walking}$	ΔT (min) $T_{FFCS} < T_{walking}$	% $T_{FFCS} > T_{cycling}$	ΔT (min) $T_{FFCS} > T_{cycling}$	ΔT (min) $T_{FFCS} < T_{cycling}$	% $T_{FFCS} > T_{PT}$	ΔT (min) $T_{FFCS} > T_{PT}$	ΔT (min) $T_{FFCS} < T_{PT}$
Amsterdam	95%	13	1	16%	12	26	81%	12	4	40%	10	8
Berlin	97%	13	1	13%	9	30	81%	11	4	60%	10	6
Denver	98%	12	1	15%	9	22	63%	10	5	42%	9	8
Madrid	99%	14	1	20%	7	18	94%	13	2	40%	7	8
San Diego	98%	12	1	14%	17	36	59%	11	8	38%	11	12
Seattle	99%	15	1	11%	8	35	59%	10	8	41%	9	10
Stockholm	96%	13	1	20%	16	26	73%	11	5	52%	12	8

and rental is the highest in San Diego and Stockholm, 17 min. Again one should remember that the rental time includes the reservation time; thus the actual time difference will probably be smaller.

In general, as the rental duration increases the share of walking trips that are shorter than the equivalent FFCS rental time increases as was the case for driving. This can partly be explained by the fact that longer rental time also implies longer reservation time. For the short rentals, walking is never faster. For medium length rentals, on average 9% of the FFCS trips have a longer rental time than walking time. Again Madrid stands out with the highest share, 14%, while Amsterdam has the lowest share of 7%. The share and time differences can be found in Table A1 in the Appendix A.

Roughly 10% of the medium length rental trips are on average 5 min longer than walking. If we instead look at the trips where FFCS rental time is shorter, we find that the time gain varies from 25 min in Denver to 43 min in San Diego.

For the longer rentals, on average 32% of the trips have longer rental time than walking time. Stockholm is the city with the highest share of such trips, i.e., 45%, while Seattle and Berlin, on the other hand, only have 20%. The median time difference for these trips is 18 min.

Concluding walking is slower for the majority of the trips, which is not surprising results, the time gain can roughly be around 30 min.

6.3. Compared to cycling

The majority of cycling trips, on average 73%, are shorter than their equivalent FFCS rental time in the studied cities. As can be seen in Table 5, Madrid has the highest share of trips, 94%, where cycling time is shorter than FFCS rental time, while Seattle has the lowest share with 59%. All of the observed European cities (Madrid, Berlin, Amsterdam and Stockholm) have a higher share of trips with shorter cycling time, on average 82%, compared to the US cities (Denver, San Diego and Seattle) with an average of 60%. This might be an indication of city planning and traffic in different cities. The median time difference does not vary that much between the cities, between 10 and 13 min, which is also fairly similar to the time difference compared to driving. For the trips in which the rental time is shorter than the cycling time, the time difference is not that large (between 2 and 8 min, see Table 5). The time gain might be larger due to the reservation time, but this still the results give an indication that for the majority of the trips there is no large time gain to use FFCS compared to biking.

Looking more specifically at the different time slots, we find that for short rental times (< 15 min) the share of trips where the cycling time is shorter varies from 30% in Denver to 80% in Madrid. The observed time difference for these trips is on average around 3 min, similar to the driving time difference of 4 min. Therefore, it is probable that the majority of cycling trips take a similar amount of time as their equivalent FFCS trips in this category.

For the medium length trips, the share of cycling trips that are faster is above 50%. This share is the highest, 92%, in Madrid and the lowest, 50%, in Denver. As for the short trips, the average time difference between cycling and rental time for medium length trips is similar to that of driving, 9 min and 11 min respectively. The time gain by cycling is fairly similar between the cities. The gain for trips where the FFCS rental is shorter is around 5 min for European cities and Denver while for the other two US cities it is at least 10 min.

The share of trips where cycling travel time is shorter than FFCS trips for the long rentals, is 90%, on average. For Madrid, all the trips in this category have a shorter cycling time than rental time. Seattle has the lowest share of such trips, 78%. For this category, the time gain for cycling is lower than the time difference for driving, 22 min versus 28 min.

For cycling, there is more evidence that there is no major time gain of using FFCS. For medium length trips, we find that at least half of the trips have a shorter cycling time than rental time. Also for the trips where FFCS rental is faster, the time gain is not that large.

6.4. Compared to public transport

The share of public transport trips being shorter than the FFCS rental time varies between the studied cities. As can be seen in Table 5, in most of them the share is roughly 40% while in Stockholm it is 52% and in Berlin 60%. The median time difference is around 10 min, slightly lower than that of driving and cycling. For a small share of trips, 5%, we find that the public transport travel time is between 20 and 30 min shorter than the rental time. What should be noted is the fact that travel time with public transport from Google Maps, while including walking time and waiting time for transfers, does not include the first waiting time. This means that we might be underestimating the actual travel time for public transport.

If we look at the trips where FFCS rental time is shorter, Table 5, we see that the median time difference is slightly lower for European cities. Berlin has the lowest time difference of 6 min, while Seattle and San Diego have a 10–12 min time gain. This can be due to a better public transportation system in the European cities. Taking into consideration reservation time and waiting time, the time gain with FFCS could be up to 20–30 min in some cases. Wang et al. (2017) find an average difference of travel time of over 20 min between FFCS and public transport in Seattle.

As with the previous modes, we now look into more detail into the three-time categories (see Table A1). For short rentals, only 10% of these trips have a shorter travel time by public transport than rental time and the time difference is only 2 min. Therefore, the majority of public transport are longer than FFCS trips for the short rentals. The median time gain for using FFCS instead of public transport is 8 min.

For the medium length rentals, the share of public transport trips that are shorter than the FFCS rental time is around 35%, on average. The average time difference for the cities is 6 min, which is shorter than driving time difference, 11 min. One can, therefore, presume that the majority of public transport trips are equal or longer than their equivalent FFCS trips in this category. As can be seen in Table A1, the median time gain for FFCS trips when public transport time is longer is 11 min for the US and 8 min for European cities. The actual time gain might be larger since this time difference does not take into consideration reservation time and waiting time for public transport.

For long rental times, the majority of the trips (on average 79%) have a shorter travel time with public transport than the rental time. The median time difference between public transport and FFCS rental time is 16 min which is smaller than driving time difference, 28 min, for this category of rentals. The discrepancy with driving time implies that even taking into consideration access time and parking time these trips, would on average be faster by public transport – even if the actual time difference then would be closer to just a few minutes. The biggest time difference is in Stockholm, 22 min, and the smallest is in Madrid, 11 min (Table A1). However, the time gain for FFCS is probably not that large, especially for a city like Stockholm where the average time difference in this category is larger than the free reservation time (15 min).

For public transport there are some trips were there might be time gain compared to FFCS, however, this would probably be quite small. The majority of the trips are either equal in length or faster with FFCS.

7. Discussion

We base our analysis on travel time derived from the vehicles' origin and destination without any direct information from the users. In this section, we discuss how time travel has been addressed in other studies and how other factors, such as travel costs may influence mode choice.

As discussed in the introduction travel time has not been analyzed in many FFCS studies. Becker et al. (2017b) find that 76% of their respondents state shorter travel time as a motivation for using FFCS. Another study from the same city, Basel, Switzerland, find that the median travel time of car-sharing was not substantially faster than public transport (Becker et al., 2017a). We find similar results. What may explain the discrepancy? First, users might only take into consideration driving time and do not count access time and parking time in their mental comparison; thus the users may underestimate the actual travel time by car. Second, perceived travel time and actual travel time might differ, i.e., 15 min in a car may seem shorter (or longer) than 15 min on a bicycle. Perceived travel time will depend on, e.g., the number of transfers, travel environment and expectations on the trips (Li, 2003). The perceived travel time in a FFCS vehicle might thus be lower than in another mode and therefore even for equal travel times, the travel time in a FFCS vehicle may be perceived as shorter. The role of time perception may be extra important when comparing with public transport. Transfers normally increase the perceived travel time. One question for further research could thus be if users of FFCS are more prone to substitute public transport trips with transfers than those with direct trips. Other factors that might also influence mode choice are attitudes toward flexibility and comfort (Johansson et al., 2006).

Wang et al. (2017) find that the users of Car2go are using less money per hours saved compared to usual travel time-saving costs in Seattle. However, if the user have a transit pass the result do not hold. In general, the price of a single trip by FFCS is higher than the price by other modes such as cycling and public transport. The prices for FFCS range from 0.21 Euro/min in Madrid to 0.54 Euro/min in Copenhagen. For a trip with 15 min travel time, the cost would thus range from 3.15 Euro to 8.1 Euro. When comparing the costs for public transport one should take into consideration that FFCS members are often also holders of transit passes (Martin and Shaheen, 2016).

Given that the time savings aren't always that large and that the costs per trip are relatively high, what other utility do FFCS give to the users? This should be better explored in surveys to understand under which circumstances users choose FFCS over another mode. What disutilities from the other mode are most discouraging and what utilities from FFCS are most important? For example how important are reliability and predictability of actual travel time? Are FFCS chosen when public transport is overcrowded? In the case of one-way car-sharing in Paris, the members had a negative perception of public transport (Louvet, 2014). Still, FFCS seems to foster a more public transport-oriented lifestyle (Becker et al., 2018; Shaheen and Cohen, 2013), thus better understanding what type of trips are more attractive with FFCS may be warranted. It should also be noted that all studies, including ours, are based on early adopters and thus usage patterns and choices might change when (and if) a larger share of the urban population chooses to adopt the services.

8. Summary and conclusions

In this paper, we have studied two elements that affect the role FFCS may play in a sustainable transportation system: mode displacement and electrification. Our analysis is based on travel times and usage patterns. Here we sum up our results and give some implications for other studies and policies.

FFCS are mainly used for one-way trips and the median rental time is close to 30 min. However, the actual driving time is closer to 15 min. The rest of the rental time consists of cruising for parking and free reservation time including access time. The free reservation time is 20 min in the observed European cities (except Stockholm with 15 min) and 30 min in the observed US cities. Still, we do not find any major variation on the time difference between driving time and rental time between these cities.

For the majority of the trips, 85%, there is roughly a 30 min gain for using FFCS compared to walking. The travel time for cycling is instead faster for the majority of the trips: 70% in the observed cities. In this case, we find a distinct difference between the European cities with a share of 80% and the US cities with a share of 60%. Comparing with public transport gives a more mixed picture. There are some trips where there might be a time gain using public transport but taking into account waiting time and free reservation time this might not be so big. For the majority of the trips, FFCS will be faster than public transport and the time gain will be between 10 min and 30 min.

Findings from our analysis show that there are differences in usage patterns between BEV and ICE vehicles in the mixed fleet. So while the trips are well below the range of the vehicles, there are indications that the BEVs are chosen for slightly shorter trips. Still, evidence from cities with a fully electric fleet show that these services can be electrified and reach high utilization levels. One major challenge for electrifying the fleets is to ensure that there are good charging opportunities.

Given the higher cost per trip compared to other modes and that there is not always a major time gain these services provide some extra utility to the users. Surveys and qualitative interviews could be more specific on identifying these and understanding under which circumstances these services are chosen over other modes. Further research is also needed to better understand the other time elements such as the time spent looking for parking, access to the vehicles and how important these issues are for users. Most simulation studies rely on assumptions of travel time and usage patterns, the results of our study can improve the accuracy of these models.

Local policy makers and urban planners can take actions to facilitate for FFCS to move in a sustainable direction. In order to reduce mode displacement, discrepancies in travel time between FFCS and other modes should not be too large. Travel time by public transport, which we often found to be longer than by FFCS, could be improved through, e.g., designate bus lanes. Even for active modes urban planning and infrastructure development will influence travel time. Regarding the electrification of the fleets we find that for both Madrid and Amsterdam local regulations such as free parking for BEV have been a major reasons for operators to have a BEV only fleet.

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Appendix A

See Table A1.

Table A1
with share of trips and median time difference for both trips where rental time is shorter and longer than travel time per mode and city, for short, medium and long trips.

City	Transport mode	Short trips (< 15 min)				Medium trips (15–30 min)				Long trips (> 30 min)			
		$T_{mode} < T_{FFCS}$		Tmode > TFFCS		$T_{mode} < T_{FFCS}$		$T_{mode} > T_{FFCS}$		$T_{mode} < T_{FFCS}$		$T_{mode} > T_{FFCS}$	
		Share	Median ΔT (min)	Share	Median ΔT (min)	Share	Median ΔT (min)	Share	Median ΔT (min)	Share	Median ΔT (min)	Share	Median ΔT (min)
Amsterdam	Cycling	58%	3	42%	−3	72%	8	28%	−5	98%	22	2%	−2
	Walking	0%	1	100%	−19	7%	4	93%	−30	32%	19	68%	−27
	Public transit	11%	2	89%	−8	33%	5	67%	−9	81%	16	19%	−6
	Driving	81%	3	19%	−1	96%	9	4%	−1	100%	27	0%	
Berlin	Cycling	67%	3	32%	−2	73%	9	27%	−5	92%	20	8%	−4
	Walking	1%	1	99%	−16	9%	4	91%	−31	20%	12	80%	−39
	Public transit	15%	2	85%	−6	47%	5	53%	−6	88%	15	12%	−4
	Driving	93%	4	7%	−1	97%	10	3%	−2	100%	26	0%	−1
Denver	Cycling	31%	2	69%	−4	62%	7	38%	−6	96%	20	4%	−3
	Walking	0%	1	100%	−20	10%	4	90%	−25	38%	13	62%	−22
	Public transit	8%	1	92%	−9	39%	5	61%	−9	84%	16	16%	−5
	Driving	93%	3	7%	−1	100%	12	0%	−2	100%	28	0%	
Madrid	Cycling	79%	4	21%	−2	92%	10	7%	−3	100%	22	0%	−2
	Walking	2%	1	98%	−12	14%	4	86%	−18	33%	13	67%	−20
	Public transit	2%	1	98%	−12	23%	4	77%	−8	74%	11	26%	−5
	Driving	93%	4	7%	−1	99%	11	1%	−1	100%	24	0%	
San Diego	Cycling	37%	3	63%	−7	53%	8	47%	−10	87%	23	13%	−7
	Walking	0%	1	100%	−24	8%	4	92%	−43	34%	29	66%	−42
	Public transit	8%	2	92%	−10	30%	5	70%	−14	71%	20	29%	−10
	Driving	94%	4	6%	−1	99%	12	1%	−1	100%	29	0%	
Seattle	Cycling	42%	3	58%	−5	50%	8	50%	−10	78%	17	22%	−7
	Walking	0%	1	100%	−19	8%	4	92%	−38	20%	12	80%	−46
	Public transit	11%	2	89%	−8	31%	6	69%	−11	68%	14	32%	−9
	Driving	94%	4	6%	−1	99%	11	1%	−1	100%	27	0%	
Stockholm	Cycling	55%	3	44%	−4	65%	8	35%	−6	94%	26	6%	−6
	Walking	1%	1	99%	−16	10%	4	90%	−31	45%	24	55%	−29
	Public transit	13%	2	87%	−7	41%	5	59%	−8	89%	22	11%	−5
	Driving	84%	3	16%	−1	98%	10	2%	−1	100%	30	0%	

Appendix B. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trd.2018.12.018.

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