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Analysis

What will be the environmental effects of new free-floating car-sharing systems? The case of car2go in Ulm

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ABSTRACT

The purpose of this paper is the discussion of the environmental effects of a free-floating car-sharing system operating in Ulm, Germany. The system, called car2go, allows users to take and leave vehicles at any point within the city limits. Thus opposed to traditional car-sharing, there are no fixed stations and in particular one-way trips of any length are possible without a booking requirement. Since this is the first free-floating system in operation, there is as yet no associated empirical research. Based on primary data from a survey, a model was developed to forecast the environmental impact of car2go. The prognosis considers the period of five years after the launch of car2go in 2009 and indicates a CO_2-reduction per average car2go-user. In addition, more than a quarter of the survey respondents stated that they may forgo a car purchase if car2go was offered permanently. By reaching a greater share of citizens than traditional systems, the results indicate that free-floating car-sharing systems could contribute to reducing private vehicle ownership in cities.

1. Introduction

This paper discusses the environmental effects of a new form of car-sharing, operating with a free-floating vehicle fleet. Traditional car-sharing systems are based on fixed stations, whereas a free-floating set-up allows users to start and end a vehicle hire at any point within a specified area, which therefore enables discretionary one-way usage. Further characteristics differentiating the system called car2go are the absence of a booking requirement, the absence of fixed costs and GPS-based real-time information on availability. The company car2go operates in Ulm, Germany since April 2009 and offers the identical system in Austin, Texas, US since May 2010. This article focuses on the case of car2go in Ulm.

Research on product-service systems in the mobility sector (Mont, 2004) benefits from starting with a consideration of long-term urbanisation trends and the resulting mobility-related challenges. These involve traffic congestion caused by moving cars(Button, 2002) and the provision of sufficient parking spaces required by standing cars (Grazi and van den Bergh, 2008) as well as negative externalities of vehicle emissions with a local and global impact (Meyer et al., 2007). In addition to these collective challenges focussed on cities, individuals also consider the social perception of the object car (Coad et al., 2009), with restrictions limiting the use of private vehicles quickly raising the question as to what extent they lower individual mobility options.

The literature regularly discusses car-sharing in the context of sustainable mobility (Köhler et al., 2009; Ornetzeder et al., 2008; Prettenthaler and Steininger, 1999), as finding response strategies to mobility-related problems grows in urgency over time. Between 1950 and 2050 the world population is expected to have tripled to quadrupled (UN, 2008), while in the same period the global urbanisation rate is expected to have risen from approximately 29% to 69% (UN, 2009).The world fleet of vehicles is growing even faster (OECD, 2000), as in 1950 there were 70 million cars, trucks and buses (WRI, 2010) whereas in 2010 there are already more than 700 million cars alone (UNEP, 2010). It is assumed that the total number of cars will triple between 2010 and 2050 (UNEP, 2010), basically because saturation levels are not reached until approximately 850 vehicles per 1000 inhabitants (IMF, 2005). Given these long-term trends, the analysis of any car-sharing system should be considered in the context of the potential to support sufficiency strategies (Alcott, 2008) by changing consumption decisions (Halme et al., 2004; Lintott, 1998; van den Bergh, 2008) within the mobility sector.

For traditional station-based car-sharing systems used by restricted milieus (Wilke, 2009a), the literature shows positive environmental effects (Shaheen and Cohen, 2007), including a reduction of total CO_2-emissions (Haefeli et al., 2006) and an individual reduction of vehicle-kilometres travelled (Shaheen et al., 2009) as well as a reduction in the average number of vehicles per household (Martin et al., 2010). However, these effects might not be replicated to a similar extent or could even be negative regarding fully flexible systems (Wilke and Bongardt, 2005; Wilke, 2009b) like car2go, as its free-floating fleet is a product–service system (Mont, 2004; Mont and Tukker, 2006; Mont and Plepys,

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2008; Schrader, 1999) incomparable to traditional car-sharing organisations. According to the German Association of CarSharing, an organisation representing approximately 90 of the 110 German car-sharing providers (German Association of CarSharing, 2010), car2go does not even count as car-sharing because its members are required to have a pricing structure based on a combination of time-related and distance-related components, and therefore car2go is only considered as being similar to car-sharing (German Association of CarSharing, 2009). However, while the constituent attributes of the term car-sharing are primarily a question of definition, this position does emphasise the disruptive differentiation between traditional car-sharers and car2go, because of which the transferability of the valuable existing car-sharing research to car2go is likely to be limited.

Without primary data, it can therefore not be known whether the users of car2go will increase their weighted average vehicle-kilometres travelled over time, or how they will adapt their average usage of public transportation. In addition, car2go's environmental effect will not only depend on the question, to what extent its average impact per user is similar to traditional car-sharing systems, but also on differences regarding the total customer base reached. This is because on any geographical- or time-scale, and independent of the environmental parameters considered, the overall impact of a car-sharing system equals the product of the number of its users multiplied by their weighted average individual impact (Schrader and Koch, 2001).

Within its first year of operation more than 17,000 car2go-members signed up in Ulm and the neighbouring town of Neu-Ulm, a combined operating area of 174,000 inhabitants, thus approximately 9.8% of the total population are registered. This figure would be lower when selecting more active users, depending on the chosen definition, but then the identical correction factor concerning the selection of active users would also need to be applied to traditional car-sharing organisations in order to compare identically constructed market penetration rates. Excluding car2go, there are currently 151,000 registered car-sharing users in Germany (German Association of CarSharing, 2010). Of the 82 million Germans, 40.4 million live in cities of more than 500 inhabitants per square kilometre (Federal Statistical Office, 2010), which is also the class of the population density of Ulm. Attributing the existing car-sharing users to this subpopulation, the corresponding market penetration is 0.37%. car2go's market penetration rate is therefore approximately 25 times higher than the weighted average market penetration of traditional car-sharing providers in Germany, a ratio which also results if the market penetration is calculated based on driving licence holders. In summary, a free-floating system has not previously been in operation by another car-sharing provider, and there are two new aspects for which there is currently no research: firstly, the average user impact resulting from the free-floating set-up and secondly, the larger scale of the customer base.

The present paper contributes to filling this empirical research gap by presenting the results of a quantitative survey, based on the research question: what will be the environmental effects of new free-floating car-sharing systems like car2go with respect to CO_2-emissions and static land consumption? To the best knowledge of the authors, a similar system is neither in operation, nor has there been one previously. A corresponding literature search did not reveal any results. Therefore, this research makes three contributions to a better understanding of new free-floating car-sharing systems. Firstly, through the assessment of the specific environmental impact of car2go in Ulm, that is based on a quantitative model. Secondly, through the structuring of generic research designs, and the subsequent deduction and explanation of the methodology applied in the presented survey. This contributes to the classification and comparability of the variety of heterogeneous approaches applied to car-sharing in general. Thirdly, through the discussion of implications of a potential widespread expansion of free-floating car-sharing systems, in particular regarding possible economies of scale and technological development.

Section 2 briefly explains the new system functionalities of car2go, in order to clarify the object of investigation. Section 3 defines the specific outcome variables (Section 3.1), explains the research design on a macro (Section 3.2) and a micro level (Sections 3.3 and 3.4), and describes the collection of the empirical data (Section 3.5). Section 4 presents the results by describing the obtained sample (Section 4.1), and the results regarding CO_2-emissions (Section 4.2) and static land consumption (Section 4.3). Section 5 discusses the results (Section 5.1) and extends the discussion to city characteristics (Section 5.2), further emission parameters affected (Section 5.3), and the role of technological development (Section 5.4). Section 6 concludes.

2. Operational Setting of car2go

car2go, offered to the public since April 2009, is fully flexible in a spatial, temporal and financial dimension. The free-floating fleet consists of 200 identical *smart fortwo cdi* cars which can be taken and left at any point within the city area. Thus, as opposed to traditional car-sharing systems, one-way journeys are permitted. Booking a vehicle in advance is possible but not compulsory, thus the cars may be taken spontaneously in the street. Real-time information on the position of available vehicles, together with their level of fuel as well as their inner and outer state of cleanliness, is available via smartphone applications, hotline or regular internet. Registered users can open any car2go with a radio frequency identification chip (RFID) glued on their driving licence. The car then requests the compulsory entry of a personal PIN plus the validation of its state of cleanliness. In the case of previously undetected damage, the car2go automatically calls the customer support. The entire communication with the system is carried out via an integrated touch-screen, combining all rental functionalities with the navigation system and in-car phone. Users are charged from the moment of logging in at a car2go, which is defined by swiping the driving licence with the personal RFID-chip at the car's reading device behind the windscreen. The universal gross price of 0.19 €/min applies to everyone without price discriminations based one date, time or user characteristics, and without a separate charge for the kilometres driven. Fixed costs, such as a booking fee, minimum hire length, minimum monthly usage or a monthly base fee, do not exist.

3. Method

3.1. Definition of Outcome Variables

What exactly is meant when speaking of the term *environmental effects*? While some studies on car-sharing emphasise the impact on total kilometres driven in private cars and car-sharing vehicles, other authors place greater weight on changing patterns of car ownership or the interdependence with local public transportation. Depending on which of these aspects of individual mobility are targeted, studies differ in two main methodological considerations: firstly, in the extent to which they cover and approach the overall modal split of car-sharing users, which is expected to shift due to individuals starting to car-share (Baum and Pesch, 1994; Haefeli et al., 2006). Secondly, in the parametrisation of the consequences of this behavioural change (Martin and Shaheen, 2010; Martin et al., 2010), though this usually just differs by linear mathematical transformations. For example, the parameter “total distance driven in cars” can linearly be transformed into energy equivalents like fuel consumption, joule or kilowatt hour, or just as well into more specific terms such as carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x), sulphur dioxide (SO_2) or particulates. Should the focus be on CO_2 or CO_2-equivalents because this parameter is omnipresent within current discussions about mobility systems? In addition, how should trade-offs be evaluated, for example regarding drivers switching from private cars with a high fuel consumption to more efficient car-sharing vehicles, subsequently driving more total kilometres in cars but emitting less CO_2 in doing so? Given the scope of interpretation of car-sharing effects, and the resulting challenges to define specific system boundaries and periods of analysis, potential car-sharing effects are systematised in Fig. 1, in order to give the discussion more structure.

From left to right, Fig. 1 shows three general categories into which car-sharing effects can be classified, then splits the environmental category into three generic process steps concerning the lifecycle of all mobility systems and subsequently describes relevant core parameters supported by examples. This logical tree shows the heterogeneity of car-sharing effects and at the same time the limitation of this research. The social and economic analysis is left to future research, and within the environmental category the focus is only on gaseous emissions and static land consumption, resulting from the operation of given mobility systems. Theoretically, a perfectly holistic assessment of a car-sharing system would cover all public and private mobility options by a lifecycle approach over a longer period of analysis. For example, if the introduction of any new car-sharing system was reducing the overall number of cars and if as a second consequence a significant number of people were switching from private vehicles to car-sharing in combination with public transportation, then more space would be required to increase the capacity of buses and tramways over time, once their occupancy rates grow too high. However, as this approach would have been complex regarding data requirements and assumptions about breaking down utilised resources, e.g. for public transportation infrastructure, this research focused specifically on only two parameters. Firstly, on the total CO_2-emissions from the operation of the collective local mobility systems. This emission parameter was chosen because of its relevance both on a local as well as on a global scale. Secondly, on static land consumption, that refers to the impact on the overall number of vehicles in the municipal area of Ulm. This parameter was chosen because even if car2go vehicles were running without any emissions, they would still require part of the limited parking space in the city, thus the net change of static land consumption constitutes a second relevant unit of analysis independent of any gaseous emissions. No quantitative assessment of car2go's impact concerning dynamic land consumption was carried out, as this would have required combining traffic statistics with real-time patterns of usage, which is data the authors have so far been unable to collect.

3.2. Research Design

Based on the previous definition of the two target parameters CO_2-emissions and total number of cars, the research design was constructed. The methodological approaches used in existing car-sharing studies are very diverse, both within the English (Cervero et al., 2007; Martin et al., 2010) and the German (Haefeli et al., 2006; Wilke et al., 2007) literature. On an abstract level, whenever assessing an effect of car-sharing, two situations are compared, whereby a *base*

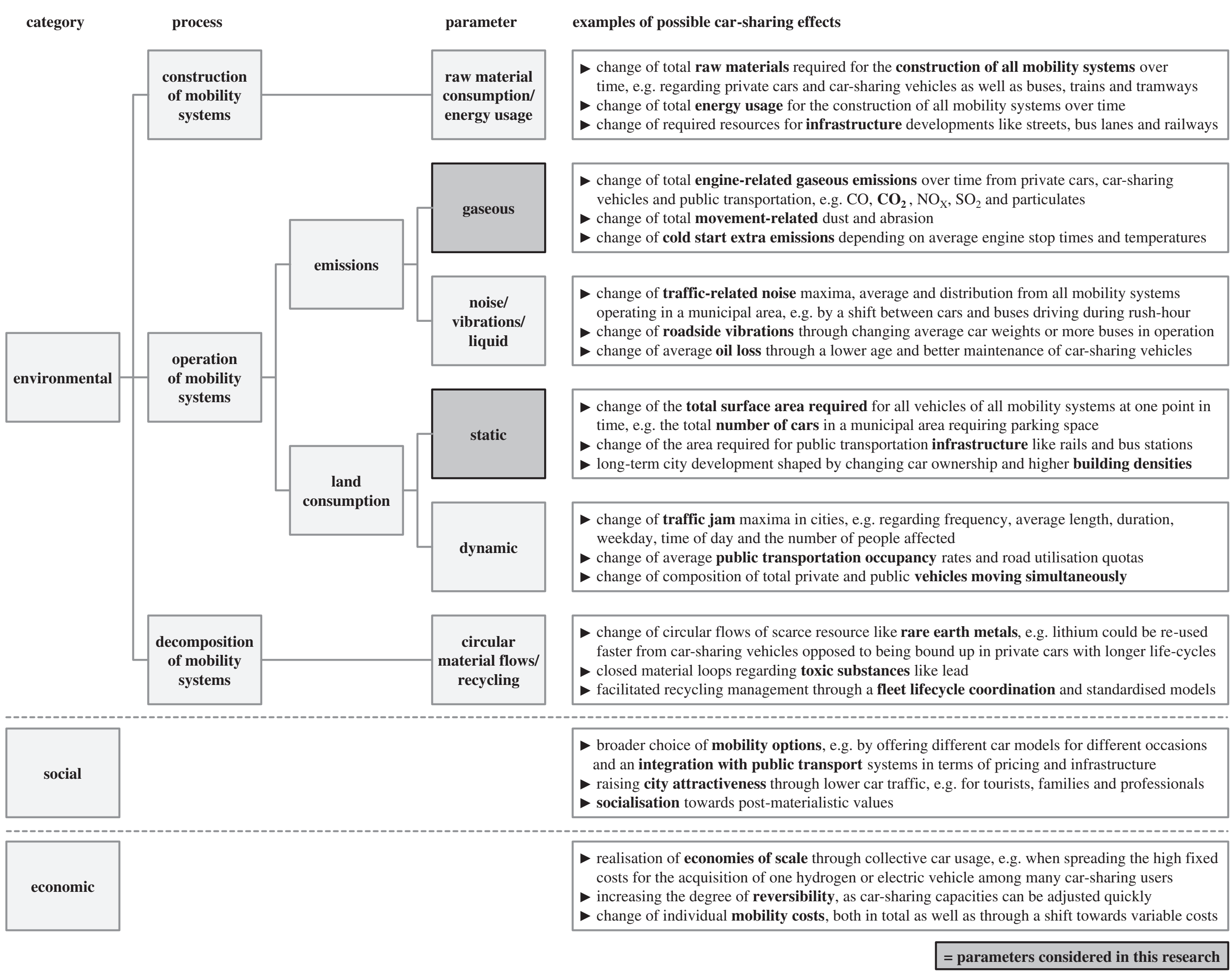

Fig. 1. Systematisation of car-sharing effects in the context of collective mobility systems over time.

situation is transformed into a *changed situation* by people starting to use car-sharing. The discrepancy between these two situations constitutes the *effect*, which, independent of the targeted parameters and periods of analysis, could be positive or negative. In many research designs, the changed situation is posterior on a timescale, but this is not necessarily the case, as the new situation could also be hypothetical but referred to today (e.g. applied in Haefeli et al., 2006). A comprehensive overview of existing car-sharing studies can be found in several articles by Shaheen (e.g. Shaheen and Cohen, 2007; Shaheen et al., 2009). Based on a literature review, four generic research designs were identified by the authors of the present article, into which impact assessments of car-sharing or other mobility systems can be classified. This classification is given in Fig. 2, which also includes one exemplary car-sharing study for each generic research design.

From top to bottom, Fig. 2 shows that the data required to make a comparison can generally be captured either by a longitudinal or a cross-sectional analysis, the latter offering the generic options to compare the status quo with the future, the past or a hypothetical scenario. The research designs(1 = longitudinal) and (3 = past) lead to results based on completed impacts, whereas the designs (2 = future) and (4 = hypothetical) lead to a potential impact by projecting a future behaviour and a hypothetical scenario of today, respectively. As the data for this first evaluation was collected shortly after car2go's public launch, (1 = longitudinal) was not applicable based on this single data collection and (3 = past) would have restricted the survey to early adopters with limited user experience. If (4 = hypothetical) had been applied to users, the results would have been also restricted to early adopters with limited experience. Theoretically, (4 = hypothetical) could be asked with a reversed logic to non-users, but to the knowledge of the authors this variant has never been applied in any existing car-sharing study and it would also be more complicated for interviewees as opposed to thinking about change over time as in (2 = future). Therefore, the generic research design (2 = future) was selected for this research.

With the survey, the current mobility patterns of the interviewees were matched against their answers to scenario questions, based on the following three stated assumptions: (a1) car2go will be in operation continuously for five years after its public launch in 2009, (a2) usually a car2go-vehicle can be reached within walking distance, and (a3) car2go will be offered in Ulm permanently beyond 2014. The scenario-year of 2014 was chosen because it is long enough that the majority of private car owners have to decide on a replacement purchase, as the average German vehicle age is 8.5 years (German Association of the Automotive Industry, 2009). On the other hand, a later reference year seemed to be speculative concerning the technological progress of motors, the structural change of the city and public transportation systems, as well as the potential change of cultural attitudes towards private vehicle ownership and car-sharing. In addition, a significantly longer time horizon would require the interviewees to consider decisions over several usage periods of more than one potential private vehicle, which appeared to be too complex to ask.

3.3. Parametrisation

Based on the specification of the target parameters CO_2-emissions and static land consumption (Section 3.1), and the choice of the applied research design to assess car2go's effect on these parameters (Section 3.2), the necessary variables were defined for the calculation of the impact, which are displayed in Table 1.

From top to bottom, Table 1 shows the group of individually determined variables, the group of fixed external variables and the group of calculated variables. The survey considered four motorised mobility options. Firstly, public transportation (KM_pub_2009) was captured by asking how many kilometres the respondents cover by bus and rail. Secondly, car2go (KM_c2g_2009) was captured by asking how many kilometres the respondents already cover by this car-sharing system. Thirdly, cars borrowed privately from friends and family members together with rental cars (KM_borr_2009) was captured by asking how many total kilometres the respondents cover with these vehicles. Fourthly, privately owned vehicles belonging to the respondent (KM_priv_2009) was captured by asking for the kilometres driven in their own cars. Concerning privately owned vehicles, the type of fuel (FUELTYPE_priv) and the fuel consumption (FUELCONS_priv) was also requested. The respondents were then asked to consider the scenario that car2go was offered permanently in the city during the next five years, and that usually they could reach the next car2go-vehicle within walking distance. Given this scenario, they were then asked how they will adapt their usage of public transportation (PUBCHANGE_delta), and what percentage of their current kilometres driven as own-vehicle drivers they will substitute by car2go (PRIVCHANGE_delta). In addition, the willingness to forgo

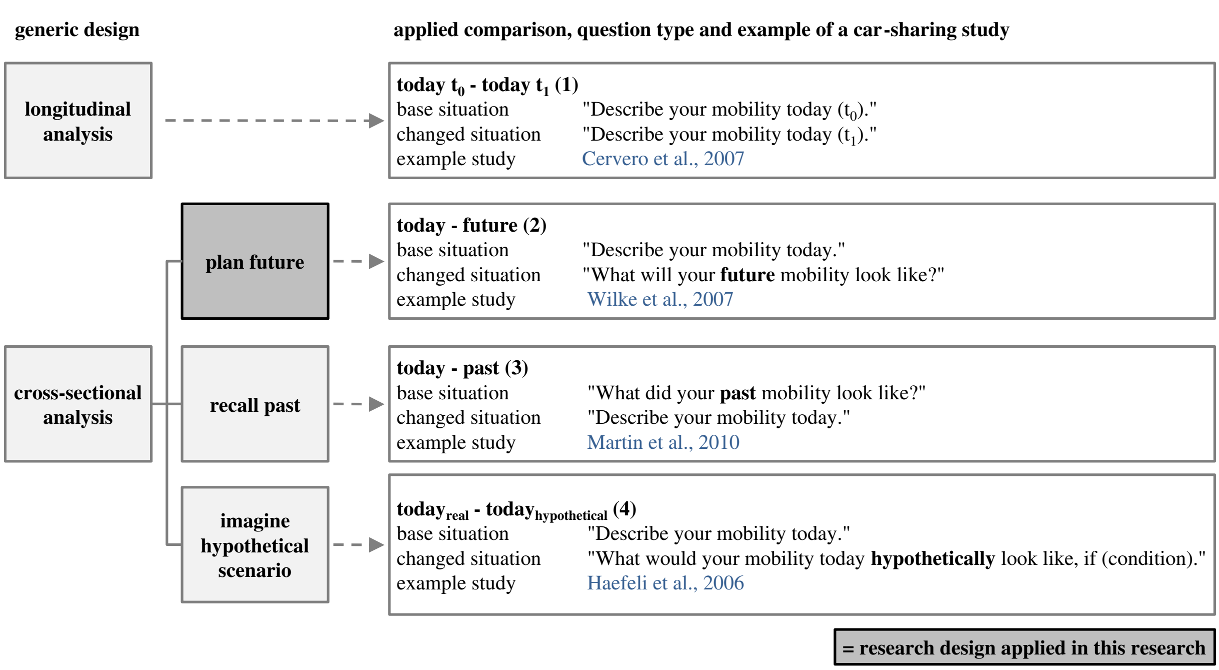

Fig. 2. Categorisation of generic research designs and applied comparison.

Table 1
Internal and external variables utilised in the quantitative model.

Variable name	Variable unit	Variable explanation	Type[a]
KM_pub_2009	[km/year]	Kilometres driven with public transportation per year	i
KM_c2g_2009	[km/year]	Kilometres driven with car2go per year	i
KM_borr_2009	[km/year]	Kilometres driven with cars borrowed from friends, family members and car rentals per year	i
KM_priv_2009	[km/year]	Kilometres driven with cars privately owned by the respondent per year	i
FUELTYPE_priv	[1 = petrol; 2 = diesel]	Type of fuel of privately owned car; if several cars are owned the fuel type of the car most driven	i
FUELCONS_priv	[l/100 km]	Fuel consumption of privately owned car; if several cars are owned the average fuel consumption	i
PUBCHANGE_delta	[x2–x0 step scale]	Change of individual public transportation usage until 2014 as a result of car2go	i
PRIVCHANGE_delta	[% of 0–100 range]	Substitution of kilometres driven with privately owned and borrowed cars by car2go until 2014	i
SELL_priv	[1–5 Likert scale]	Willingness to refrain from buying a private car because of the availability of car2go	i
SELL_borr	[1–5 Likert scale]	Likelihood of a currently borrowed car being dispensed with because of the availability of car2go	i
FUELCONS_c2g	[l/100 km]	Fuel consumption of car2go	e
CO2_REGULAR	[kg CO_2/l]	Amount of CO_2 emitted from the consumption of one litre of petrol in a car motor	e
CO2_DIESEL	[kg CO_2/l]	Amount of CO_2 emitted from the consumption of one litre of diesel in a car motor	e
CO2_PUB	[kg CO_2/pkm]	Amount of CO_2 emitted per passenger-kilometre of public transportation in Ulm/Neu-Ulm	e
CO2_BOR	[kg CO_2/km]	Amount of CO_2 emitted per kilometre driven with a car borrowed from friends, family members and car rentals	e
mult_c2g	Not applicable	Variable to simulate an additional increase in the total kilometres driven with car2go; simultaneously applied to all users	e
KM_total_2009	[km/year]	Total kilometres travelled with all considered local transportation options in 2009	c
KM_total_2014	[km/year]	Total kilometres travelled with all considered local transportation options in 2014	c
EM_pub_2009	[kg CO_2/year]	CO_2 emissions per year from the use of public transportation in 2009	c
EM_c2g_2009	[kg CO_2/year]	CO_2 emissions per year from the use of car2go in 2009	c
EM_borr_2009	[kg CO_2/year]	CO_2 emissions per year from the use of cars borrowed from friends, family members and car rentals in 2009	c
EM_priv_2009	[kg CO_2/year]	CO_2 emissions per year from the use of privately owned cars in 2009	c
EM_total_2009	[kg CO_2/year]	Total mobility-related CO_2 emissions in 2009	c
EM_pub_2014	[kg CO_2/year]	CO_2 emissions per year from the use of public transportation in 2014	c
EM_c2g_2014	[kg CO_2/year]	CO_2 emissions per year from the use of car2go in 2014	c
EM_borr_2014	[kg CO_2/year]	CO_2 emissions per year from the use of cars borrowed from friends, family members and car rentals in 2014	c
EM_priv_2014	[kg CO_2/year]	CO_2 emissions per year from the use of privately owned cars in 2014	c
EM_total_2014	[kg CO_2/year]	Total mobility-related CO_2 emissions in 2014	c
EM_delta_abs	[kg CO_2/year]	The difference of mobility-related CO_2 emissions in 2014 compared to 2009; absolute value per year	c
EM_delta_rel	[%]	The difference of mobility-related CO_2 emissions in 2014 compared to 2009; percentage	c

[a] i = individually determined variable stated by the participants of the survey; e = external variable with a fixed value applied identically to all users; c = calculated variable.

a vehicle purchase based on the given scenario was captured (SELL_priv), as well as the likelihood of a currently borrowed car being dispensed with because of car2go (SELL_borr). Trips with taxis were excluded because of their low weight of 0.2% in the average modal split in the federal state of the considered car2go-location (German Taxi and Rental Car Association, 2009; infas and DLR, 2010). In addition to the necessary external variables concerning CO_2-emission, a dummy variable was included to enable the simulation of how much the results would change if car2go-users drove more than forecasted by their answers in the survey (mult_c2g).

3.4. External Variables and Calculations

The distances covered by the four mobility options combined with the variables fuel type, fuel consumption and the external variables are used to calculate the emission change. The fuel consumption by car2go (FUELCONS_c2g) and the variable simulating additional increases in the total kilometres driven with car2go (mult_c2g) are varied in different scenarios as discussed in Section 4. For regular petrol with a weight of approximately 0.75 kg/l depending on pressure and temperature, the value CO2_REGULAR = 2.37 kg CO_2/l is used. For diesel, whose lower consumption rate results from the conversely higher energy density and a weight of approximately 0.83 kg/l, the value CO2_DIESEL = 2.65 kg CO_2/l is used. These conversion rates result from fuel reacting with a multiple proportion of oxygen when burned in combustion engines and refer to the European standard procedure 80/1268/EWG as amended in 93/116/EG (Federal Motor Transport Authority, 2009).The resulting values are fully attributed to a single driver without considering co-drivers, as the German average car occupation rate of 1.2 (Association of German Transport Companies, 2003)to 1.5 (Federal Environment Agency, 2010) passengers does not apply as a restriction for the two-seaters of car2go. This contributes to a more conservative assessment of car2go, as the inclusion of co-drivers would reduce the emissions per passenger-kilometre.

Regarding CO_2 emitted from public transport, there is a variation depending on the type of public transportation and passenger occupancy rates, with light rail traffic having the highest and motor-coaches having the lowest emissions (Federal Environment Agency, 2007). For the specific case of Ulm, under consideration of the domination of urban buses, the value CO2_PUB = 0.075 kg CO_2/pkm (Federal Environment Agency, 2009a, 2010) is applied.

Regarding CO_2 emitted from the average borrowed car, it needs to be considered that in Baden-Württemberg, the federal state of the analysed car2go-city, 70.5% of all registered cars run on regular fuel, 28.9% run on diesel and 0.6% on other powertrains (Federal Motor Transport Authority, 2010). Taking the ratio of regular fuel to diesel cars in the state to weight the average German CO_2-emissions of both types of cars, which are 0.184 kg CO_2/km for regular fuel and 0.174 kg CO_2/km for diesel (IFEU, 2010), results in 0.181 kg CO_2/km emitted from the average car in Baden-Württemberg. However, compared to car owners driving their own vehicle, drivers of borrowed cars will on average be less experienced in shifting optimally and avoiding high engine revs because of not knowing the car as well as an owner. In addition, in some cases there will be no monetary compensation mechanism as an incentive to save fuel, and drivers of borrowed cars are also less likely to drive long distances. Therefore, the higher value of CO2_BOR = 0.190 kg CO_2/km is used in the model.

With these external variables utilised for all respondents and the individually determined variables from the survey, the particular emissions per mobility option are calculated as displayed in Table 2.

From top to bottom, Table 2 displays the calculations for the emissions in 2009, in 2014 and the differences between these two years. The variable mult_c2g (Section 3.3) was included to enable a sensitivity test of the results to a potentially induced traffic. When mult_c2g = 1.0, the overall passenger kilometres are kept constant while mult_c2g > 1.0 simulates additional traffic, assuming that the survey respondents have underestimated their future car2go usage. At the same time, the substitution approach ensures that KM_total_2009 and KM_total_2014 only deviate via mult_c2g, as opposed to uncontrolled deviations in both

Table 2
Formulas of calculated emissions.

Variable name	Calculation
EM_pub_2009	KM_pub_2009 * CO2_PUB
EM_c2g_2009	KM_c2g_2009 / 100 * FUELCONS_c2g * CO2_DIESEL
EM_borr_2009	KM_borr_2009 * CO2_BOR
EM_priv_2009	KM_priv_2009 / 100 * FUELCONS_priv * (FUELTYPE_priv of CO2_REGULAR or CO2_DIESEL)
EM_total_2009	EM_pub_2009 + EM_c2g_2009 + EM_borr_2009 + EM_priv_2009
EM_pub_2014[a]	KM_pub_2009 * CO2_PUB * PUBCHANGE_delta
EM_c2g_2014[a,b,c]	mult_c2g * [KM_c2g_2009 + (1 − PUBCHANGE_delta) * KM_pub_2009 + PRIVCHANGE_delta / 100 * (KM_priv_2009 + KM_borr_2009)] / 100 * FUELCONS_c2g * CO2_DIESEL
EM_borr_2014[b]	KM_borr_2009 * (100 − PRIVCHANGE_delta) / 100 * CO2_BOR
EM_priv_2014[b]	KM_priv_2009 * [(100 − PRIVCHANGE_delta) / 100] / 100 * FUELCONS_priv * (FUELTYPE_priv of CO2_REGULAR or CO2_DIESEL)
EM_total_2014	EM_pub_2014 + EM_c2g_2014 + EM_borr_2014 + EM_priv_2014
EM_delta_abs[d]	EM_total_2009 − EM_total_2014
EM_delta_rel[d]	(EM_total_2009 − EM_total_2014) / EM_total_2009

[a] PUBCHANGE_delta: change in public transportation usage is fully attributed to car2go. Example: a reduction of KM_pub_2009 by 10% = 300 km would add 300 km to car2go in 2014.

[b] PRIVCHANGE_delta: substitution of KM_borr_2009 + KM_priv_2009 is fully attributed to car2go based on the same total. Example: 10% of 10000 km substituted adds 1000 km to car2go in 2014.

[c] KM_total_2009 = KM_total_2014 when mult_c2g = 1.0, adding up all four transportation modes.

[d] Result does not include the additional fleet effect or technological progress of any mobility system.

directions which can result from participants stating absolute future, past or hypothetical values in cross-sectional research designs. The changing overall number of cars in Ulm is analysed separately, comparing the car2go fleet size to the expected private vehicle reduction using SELL_priv and SELL_borr, as it is more meaningfully expressed on an aggregated level than allocated to car2go users.

3.5. Collection of Empirical Data

The dataset for this article was generated by personal interviews conducted in 2009, based on a pre-tested closed questionnaire. Pedestrians were approached in the municipal area of Ulm and asked if they would participate in an anonymous survey about their mobility behaviour, and if they agreed the interviewers started the survey on the spot. All interviews followed an identical and predefined set-up, whereby variations where possible based on previous answers during the interview. For example, a participant stating not to possess a private car jumped the subsequent question block about specific vehicle attributes. Depending on the routing, the participants were asked between 45 and 66 questions. The interviewers noted down the answers on printed versions of the questionnaires using clipboards, whereby the majority of questions allowed only a single choice on closed answer scales. Random sampling was used at the beginning of the field-time, but as the interviewers entered the completed paper questionnaires regularly in an identical web interface to enable a control of the data collection, the information from the accumulated dataset could be used to improve the representativeness of the sample. For example, after one week of field-time the accumulated dataset showed that more older participants were required in the sample, thus the interviewers approached more elderly people to fill this gap. Individuals were screened out and the interviews aborted when respondents did not fulfil the necessary conditions of either living in the area of Ulm and being in the possession of a driving licence for cars, or being an already registered member of car2go. This selection ensured that only car driving licence holders were included in the sample, as only this subpopulation comes into consideration to change its mobility behaviour by starting to use car2go.

4. Results

4.1. Sample Description

A total of 383 people were interviewed during the period of June–July 2009, of which 308 provided all the required information to calculate car2go's expected impact on their individual mobility behaviour. For example, participants who could not estimate their kilometres driven with public transportation were excluded from the sample because of incomplete variables. All figures in this article refer to the cleaned sample of 308 interviews, which took on average 14 min. The sample included participants living in 16 of the 18 urban districts of Ulm and in the directly neighbouring town of Neu-Ulm, which represents 98.3% of the combined municipal population. The respondents from the seven largest city districts of Ulm, which account for 58% of the combined municipal population (City of Ulm, 2009; Regional Statistical Office of Bavaria, 2010), were represented by 55% in the cleaned sample. As pedestrians were asked to participate in the survey, interviews were distributed across all times to avoid a bias resulting from the interview time. 14% of the interviews took place between 06:00 am and 11:59 am, 59% between 12:00 pm and 05:59 pm and 27% between 06:00 pm and 11:59 pm. The demographic structure of the sample is displayed in Table 3.

From left to right in Table 3, the column "Impacted" shows the attributes of the 256 participates who stated that they will start using car2go, which allowed the calculation of the resulting impact. The column "Non-impacted" shows the attributes of the 52 respondents saying they will not use car2go. The demographics of the "Total sample" of all 308 respondents in the cleaned sample and reference values from the "Population mean" are given in the other two columns. Comparing the columns "Impacted" and "Non-impacted" indicates that male, younger and higher educated participants are more likely to start using car2go compared to the average sample, whereas the net household income is almost identical between the two groups.

Table 3
Demographics.

	Impacted	Non-impacted	Total sample	Population mean
Gender	N = 256	N = 52	N = 308	[a]
Male	62.5%	40.4%	58.8%	49.2%
Female	37.5%	59.6%	41.2%	50.8%
Age	N = 255	N = 52	N = 307	[a]
Mean	33.7	41.7	35.1	41.4
Standard deviation	13.2	15.4	13.9	22.4
Education	N = 252	N = 52	N = 304	[b]
No school graduation certificate	0.0%	0.0%	0.0%	2.6%
Basic secondary school (9 total years in school)	7.1%	13.5%	8.2%	44.1%
Middle secondary school (10 total years in school)	22.6%	26.9%	23.4%	24.5%
Higher secondary school (13 total years in school; incl. graduate degrees)	70.2%	59.6%	68.4%	28.7%
Net household income per month	N = 229	N = 49	N = 278	[c]
Mean (€)	2436	2459	2440	2936
Standard deviation	958	1025	968	2445

[a] Reference values referring to Ulm city (Regional Statistical Office of Baden-Württemberg, 2009).

[b] No local data available; reference values referring to the average German city of between 100,000 and 500,000 inhabitants (Federal Statistical Office, 2002).

[c] No local data available; reference values referring to the average net household income per month in Baden-Württemberg (Regional Statistical Office of Baden-Württemberg, 2010a).

4.2. Car2go's Impact on Local CO_2-Emissions

With the survey data and external variables (Table 1), three scenarios were calculated (Table 2) by simultaneously varying mult_c2g and FUELCONS_c2g. The best case represents the direct survey answers using the manufacturer's official fuel consumption for car2go vehicles of 3.4 l/100 km. The most likely case uses a fuel consumption of 3.6 l/100 km and simultaneously assumes a total of 15% more car2go-kilometres driven by setting mult_c2g = 1.15. The worst case assumes a car2go fuel consumption of 3.9 l/100 km and 30% more car2go-kilometres driven. Table 4 shows the results for each of these three cases.

The first row of Table 4 shows the total CO_2-emissions from all transportation modes in 2009. The values between the three cases differ as a result of the varied fuel consumption for car2go. The next four rows show the single CO_2-changes per mode of transportation between 2009 and 2014. For car2go, the CO_2-emissions vary as a result of the simultaneous increase of mult_c2g and FUELCONS_c2g, which does not affect the emission values of the other modes of transportation. The net change is calculated in the final row, which shows that even in the worst case the result is a CO_2-reduction as a consequence of the launch of car2go. All figures are weighted average values for the 256 respondents of the cleaned sample who stated they will use car2go, whereas the 52 respondents saying that they will not use car2go (Table 3) have a zero emission change and are therefore excluded in this calculation.

Of the 256 respondents who stated they will use car2go (Table 4), 227 individuals or 89% have an individual CO_2-reduction in the best case, 83% in the most likely case and 77% in the worst case. However, the unweighted percentages of individual positive and negative CO_2-changes are not relevant for the weighted overall effect, as for example one large individual change can outweigh the sum of several small reversed changes of other users (Martin and Shaheen, 2010).

To test the results for sensitivity to a potentially induced traffic, a goal seek analysis was carried out in order to determine the break-even value of mult_c2g which would lead to a weighted average emission-change of zero. These are the values mult_c2g = 1.90 in the best case, mult_c2g = 1.80 in the most likely case and mult_c2g = 1.67 in the worst case. This means that even when assuming the highest car2go fuel consumption of FUELCONS_c2g = 3.9 l/100 km, all respondents could drive up to 167% of their total car2go-kilometres forecasted by the survey to maintain an overall CO_2-reduction.

4.3. Car2go's Impact on the Total Number of Cars

While the results of the previous section only refer to car2go's effect regarding one single specific gaseous emission and only from the operation of the collective mobility systems, in this section car2go's impact on static land consumption is discussed (Fig. 1). The impact on the area required by public transportation could be considered (Section 3.1), but as this effect is unlikely to be significant in Ulm in the period under review until 2014, vehicles other than cars are excluded from the analysis.

Table 4
Forecast of changing emission effects per average car2go user [kg CO_2/year] (N = 256).

	Best case	Most likely case	Worst case
Total emissions in 2009 (EM_total_2009)	2786	2787	2790
CO_2 car2go	+318	+392	+484
CO_2 public transportation	−16	−16	−16
CO_2 borrowed car	−149	−149	−149
CO_2 private car	−466	−466	−466
Total emissions in 2014 (EM_total_2014)[a]	2474	2549	2644
Net change (EM_delta_abs)	−312	−238	−146

[a] Calculated on exact figures without rounding.

As a further step to reduce complexity, the assumption is made that the change in the total number of cars in operation in Ulm is linear to the overall impact on static land consumption. This is a simplification, as the average weight of new cars in Germany has increased by roughly 10% between 2000 and 2007 (Federal Motor Transport Authority, 2007), and while the two-seater car2go has a kerb weight of 770 kg (Smart, 2010), the average new German car has a kerb weight of 1445 kg (Federal Motor Transport Authority, 2007). In terms of vehicle length, a car2go is 2.7 m long (Smart, 2010) as opposed to the German average car of approximately 4.7 m (Dunker et al., 2005), thus roughly three car2go-vehicles can be parked in the space of two average cars, depending on the distances between the parked cars and their alignment. However, it is assumed that all private and car-sharing vehicles require an identical ground area to park.

With the launch of car2go, 200 cars were added to the municipal area, and this fleet will be increased to 300 vehicles in 2011. In order to estimate the opposite effect of a private vehicle reduction, two questions were included in the survey, which are indicated in Table 5.

Table 5 shows that 29% of the respondents (strongly) agreed with the first statement, adding up the percentages of columns 1 and 2. Regarding the second statement, the corresponding number is 19%. Due to an intention-behaviour gap, it is assumed that only one third of the respondents (strongly) agreeing with the first statement will reduce their car ownership by selling or not acquiring a car, which equals 9.7% of the total respondents. As the decision to dispense with a borrowed car does not directly depend on the respondents and might in addition have referred to cars already covered by the first statement attributed to a second person, it is assumed that only one fifth of the respondents (strongly) agreeing to the second statement will represent an additional realised car reduction, which equals another 3.8% of the total respondents. In total, the authors expect 13.5% of the 17,000 car2go-members to reduce their car ownership, equalling 2295 cars to be dispensed with between 2009 and 2014 as a consequence of car2go, which corresponds to a net reduction of 1995 cars realised up to 2014.

5. Discussion

5.1. Leverage on Local CO_2-Emissions

The results indicate that the weighted average car2go-user will emit less CO_2 by starting to use car2go, whereby the applied model in this article forecasts an average reduction of −312 to −146 kg CO_2/year (Table 4). Studies on traditional car-sharing systems have indicated reductions in a comparable range, for example −200 kg CO_2/year (Haefeli et al., 2006) or −142 kg CO_2-equivalents/year (Wilke et al., 2007) per weighted average car-sharing user. A study calculating the effect on a household level resulted in an observed impact of −580 kg CO_2-equivalents/year, which when divided by the average household size of 2.5 in the considered area corresponds to −232 kg CO_2/year per person (Martin and Shaheen, 2010). However, even though the results

Table 5
Potential to reduce private vehicle ownership.

	Applies strongly				Does not apply at all
	1	2	3	4	5
If car2go proves itself in the next 5 years in Ulm, I could image forgoing the purchase of a car or of a replacement car in the future. (n = 307)	14%	15%	14%	11%	46%
If car2go proves itself in the next 5 years in Ulm, a car which I currently borrow is likely to be dispensed with, for example by a friend or family member. (n = 294)	8%	11%	14%	12%	55%

for car2go are similar to studies on traditional car-sharing systems concerning the effect per average car-sharing user, the overall emission reduction, resulting from the average impact multiplied by the customer base, will be scaled up by car2go's market penetration, which is multiple times higher compared to traditional station-based systems.

This result needs to be reflected in two ways. It is a conservative estimation, as no technological efficiency improvements over time were included in the forecast. In addition, 17,000 users were already reached within car2go's first year of operation and additional customers will register over the next five years. The other way to reflect the result is to see it in the context of the magnitude of car2go's emissions in relation to other mobility systems. car2go's fuel consumption of 3.6 l/100 km assumed in the most likely case (Section 4.2) corresponds to 0.095 kg CO_2/km. This is 51% of the German average real-world car emission of approximately 0.185 kg CO_2/km resulting from an average fuel consumption of 7.4 l/100 km (Federal Environment Agency, 2009b; Shell, 2009) and 127% of the value for local public transportation, which is CO2_PUB = 0.075 kg CO_2/pkm. Public transportation on full capacity utilisation will always beat individual transportation in terms of emissions, but the difference between the emissions of car2go and public transport is small enough to rethink the paradigm that public transportation is invariably superior to cars in environmental terms.

5.2. Importance of City Characteristics

More than a quarter of the respondents of the survey stated that they could imagine forgoing a car purchase because of car2go, and even when assuming a large intention-behaviour gap, the overall number of cars is likely to fall in Ulm through car2go's launch (Table 5). In addition, the average annual mileage of cars in Baden-Württemberg, the federal state in which the city of Ulm is located, has been falling continuously since reaching a peak in 1999, with a drop from 13,940 km/year in 1999 to 12,640 km/year in 2007 (Regional Statistical Office of Baden-Württemberg, 2010b), primarily caused by households acquiring second and third cars. Also, the ageing process of the society will, as a trend, reduce the average annual mileage further (Büringer, 2007). This leads to higher marginal costs of driving an own car and thereby increases the incentive to substitute private cars through car2go and public transportation. However, car2go's potential to replace private vehicles will be limited to cars being driven primarily in the area of Ulm, firstly because the two-seater has a low maximum speed of 135 km/h (Smart, 2010) and comparatively limited space for luggage, and secondly, because longer rentals for trips outside the city area become comparably more expensive than rental cars or railway.

The discussion of the impact of this first free-floating system should, however, not be limited to a short-term perspective on only a single medium-sized city in Germany. For example Austin, Texas, US, which started as the second city with car2go in public operation in May 2010, would need to be analysed in a different context than Ulm, in particular regarding the existing infrastructure, mobility patterns and supportive policies (Shaheen et al., 2006). In the US, the average resident travels about 30,000 km per year in total by all modes of transportation (OECD, 2000), which is roughly double the distance travelled by the average German by all modes of transportation (Federal Ministry of Transport, Building and Urban Development, 2009). Car usage dominates the modal split in both countries, which results in approximately 40% of all US oil being consumed by passenger vehicles (EPA, 2004) and in addition, average emissions per passenger-kilometre from buses are higher in the US due to lower load factors (Kahn Ribeiro et al., 2007). The petrol motor of the car2go-vehicles in Austin is stronger than the diesel motor of the car2go-vehicles in Ulm, but this has to be considered in the context of the average real-world US vehicle fuel consumption of approximately 11.2 l/100 km, which corresponds to 0.262 kg CO_2/km (EPA, 2009). Even though the US Environmental Protection Agency calculates with other transformation rates with respect to CO_2 per litre petrol or diesel compared to the European standard (EPA, 2005a, 2005b), and even though the underlying definitions of the object car are not exactly identical, the bottom line is that analogous to Germany, in the US car2go-vehicles also emit less CO_2-emissions compared to the respective national average. However, in absolute terms, the substitution of one average national car through car2go would save more CO_2-emissions in the US than in Germany.

5.3. Further Emission Parameters Affected

This research focused on CO_2-emissions, but for other cities different parameters might be more relevant than the local or global externalities of this single gas. For example, congestion charges in various countries have been introduced primarily as an effort to combat increasing city traffic with respect to the resulting traffic jams and parking space shortages. If the latter problem was dominating, a position inevitably requiring an evaluation of the emission externalities and a judgement about underlying responsibility (Button, 2002), the priority of car-sharing research should be on vehicle size and occupation rates instead of CO_2. For example, in China the total number of private cars approximately tripled between 2000 and 2005 (Han and Hayashi, 2008) and the rapid urbanisation continues (Yu and Wen, 2010), a growth which has already reached the physical capacities of cities to provide sufficient parking spaces. This in turn is directly linked to emissions, as drivers searching for a parking space were found to account for more than 10% of all cruising traffic in several cities (Shoup, 2006), causing proportionally higher total emissions. As the vehicles of car2go are used alternately between users, as the free-floating set-up avoids unnecessary return trips and as car2go offers reserved parking spaces scattered across the city, the emissions from cruising for parking are directly reduced through car2go's organisational setting.

Also regarding other gaseous emissions than CO_2, there could be specific car-sharing effects worth investigating. For example, the efficiency of modern catalytic converters is high enough that regarding specific emissions like NO_x, it becomes difficult to detect them in the exhaust air, but this requires the catalyst to be sufficiently hot (Favez et al., 2009). As a large part of several gaseous emissions is emitted during the first kilometres after a cold start, the alternate usage of car-sharing vehicles could reduce specific emissions per average kilometre travelled for two reasons. Firstly, because the fuel consumption of cars is considerably higher during the first kilometres with a cold motor, and in addition, cold lubricants lead to a higher abrasion which reduces the total life expectancy of vehicles. Secondly, with respect to emissions like carbon monoxide or hydrocarbons, one cold start equals driving up to several thousand kilometres with a hot motor, depending on outside temperatures and humidity (Weilenmann et al., 2009). For example in Switzerland, based on real-world car usage patterns with an average trip length of 18 km, it is assumed that almost the entire emissions of carbon monoxide and hydrocarbons result from cold start extra emissions (Weilenmann et al., 2009). Thus, should the average cooling periods between the car2go-users be sufficiently short, a significant amount of emissions could be saved compared to an alternative higher usage of private cars for individual short trips. However, if the average motor cooling periods are too long, the induced short trips with car2go could be responsible for a multiplication of several gaseous emissions other than CO_2.

5.4. Technological Development

Independent of any current emission impact, the development of a free-floating system without a booking requirement or fixed stations, will trigger technological innovations. This regards hardware, like the integrated touch-screen combining all rental functionalities, as well as software, like fleet maintenance algorithms. Both types of technological progress could contribute to decreasing emissions in the future. For example, if at any point in the future we wanted the citizens of global megacities to live primarily without private vehicles, to travel with high-speed trains between hubs and to satisfy their local mobility demand (Curtis, 2003) by public transportation fully integrated with free-floating shared cars running on renewable energy, the required system transformation can only be realised once the complex organisational problems resulting from free-floating fleets are solved. Taking the first step of developing the know-how required to manage free-floating systems earlier using fuel motors, will enable free-floating mobility solutions based on renewable energy to be implemented faster once their capacity has grown sufficiently. Thus theoretically, future emission savings resulting from an earlier system transformation through technology could be incorporated in emission analyses of today.

Irrespective of the progress in engine technologies, the high number of users reached by car2go also creates a potential for innovations depending on *large-scale usage*. Firstly, car-sharing specific vehicles could be produced as being optimised for city usage with a higher robustness and equipped with additional technology to facilitate shared use. For example, user-specific information could be retrievable from the integrated touch-screens, supporting the integration of information technology and mobility systems. With increasing bandwidths and falling costs for data transfer, why should a car not be able to show available connections with public transport and directly offer the option to book a connecting ticket? Secondly, large-scale usage also offers the possibility to implement mechanisms to reward efficient driving. A significant amount of any energy carrier consumed by a vehicle, e.g. petrol, hydrogen or electricity, depends on the individual driving style. Already today, insurances offer pricing schemes depending on the style of driving, and why should the efficient driving of car-sharing vehicles not be rewarded once technologically feasible? Thirdly, large-scale car-sharing usage could support the integrated development of infrastructure and mobility systems (Camagni et al., 2002). Already today, some cities offer new citizens monetary incentives to use car-sharing, and a market penetration of any provider as high as the one of car2go in Ulm could influence the long-term development of a city, in particular in new development areas where building less parking spaces per new building could be sufficient.

car2go became realised because an automobile manufacturer started to invest resources in a system based *mobility on demand* instead of selling cars to private drivers. Is this a first sign of a system transformation towards a post-materialistic mobility sector? If sufficiently large numbers of users were reached by new free-floating systems technically enabling shared car usage similar to private car usage within cities, this could help in overcoming the technological lock-in (Sanne, 2002) based on the widespread possession of private cars. In addition, it could also reduce the fleet growth in emerging economies that are following the same consumption patterns of industrialised countries (Mont, 2004).

6. Conclusion

The aim of this research was to forecast the environmental impact of a free-floating car-sharing system based on the calculation of three scenarios. The results were calculated using primary data from a quantitative survey and indicate an improvement in terms of CO_2-emissions per average car2go-user even in the considered worst case. In addition, the data indicates that static land consumption will be reduced through a reduction of the total number of vehicles in the city. The impact forecasted per average user is similar compared to traditional car-sharing systems based on fixed stations, yet car2go's higher market penetration will scale up the aggregated effect. Therefore, free-floating fleets could reduce car ownership in cities. In the case of car2go in Ulm, the magnitude of the vehicle reduction predicted by this research should be verifiable by the development of the official car registration numbers until 2014. As there was no previous empirical research on a free-floating system, the forecast should not be overrated until validated by a triangulation using retrospective data. Also, beyond the local impact in Ulm, the more decisive question is which impact free-floating systems could have in general if they were deployed in metropolises multiple times larger.

This research has limitations. Firstly, no annual mobility cycles are analysed. Users could vary their modal split depending on the season and as *year* is used as the temporal unit of analysis, this aspect is not considered. Secondly, the CO_2-assessment only refers to the operation of given mobility systems but does not include infrastructure construction and maintenance, which would be covered by a holistic LCA. Thirdly, no rebound effect (de Haan et al., 2006) and time use analysis (Jalas, 2002) is included.

Further research would benefit from a consistent methodology to improve the comparability of empirical studies, especially if longitudinal data is gathered over several years. This will require the explicit description of calculations and external model values, information currently not described in most studies on car-sharing. Also, the sensitivity of results to model variations is mostly not tested, yet solution spaces and sensitivities to varied parameters might provide more insight than singular values. In addition, further research on the intertemporal causalities behind changing mobility behaviour would be valuable, for example regarding the question whether people dispense with private vehicles independently and before they start car-sharing or if they first try car-sharing, which as a consequence convinces them that not possessing a private vehicle does not equal giving up comfort.

It needs to be emphasised that any car-sharing system should be developed complementarily to public transportation, as only *integrated mobility systems* satisfy the variety of individual transportation needs, which is a necessary condition for a large-scale reduction of private vehicle usage. In Ulm, the network plans of the local public transportation provider already display car2go parking spots, and in turn car2go-vehicles contain a map showing the central public transportation lines. These are first small steps towards an integration of *public -private transportation* transportation into traditional *public–collective transportation*, but a fully integrated mobility network will require a more extensive cooperation in terms of pricing and infrastructure.

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