Quantifying material and carbon reduction in circular consumption: solving selected methodological and data challenges while accounting for rebound effects

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Chapter 2

Does car sharing reduce greenhouse gas emissions? Assessing the modal shift and lifetime shift rebound effects from a life cycle perspective

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Abstract:

Car-sharing platforms provide access to a shared rather than a private fleet of automobiles distributed in the region. Participation in such services induces changes in mobility behaviour as well as vehicle ownership patterns that could have positive environmental impacts. This study contributes to the understanding of the total mobility-related greenhouse gas emissions reduction related to business-to-consumer car-sharing participation. A comprehensive model which takes into account distances travelled annually by the major urban transport modes as well as their life-cycle emissions factors is proposed, and the before-and-after analysis is conducted for an average car-sharing member in three geographical cases (Netherlands, San Francisco, Calgary). In addition to non-operational emissions for all the transport modes involved, this approach considers the rebound effects associated with the modal shift effect (substituting driving distances with alternative modes) and the lifetime shift effect for the shared automobiles, phenomena which have been barely analysed in the previous studies. As a result, in contrast to the previous impact assessments in the field, a significantly more modest reduction of the annual total mobility-related life-cycle greenhouse gas emissions caused by car-sharing participation has been estimated, 3-18% for three geographical case studies investigated (versus up to 67% estimated previously). This suggests the significance of the newly considered effects and provides with the practical implications for improved assessments in the future.

2.1. Introduction

Our planet faces increasing environmental risks imposed by growing rates of greenhouse gas (GHG) emissions toward the atmosphere (Le Quéré et al., 2018). The transportation sector plays a significant role in these greenhouse gas contributions, producing approximately 23% of the global direct CO2 emissions in 2010. In developed economies these contributions are driven by road transportation and become even more significant, reaching circa 30% of their national total (Sims et al., 2014).

There are various approaches to lowering GHG emissions of the mobility sector, and they can be roughly grouped in four categories: technical, such as the development of electric vehicles (EV); legislative, such as introduction of a carbon or fuel tax; infrastructural, such as the development of an extensive urban cycling infrastructure; and behavioural, such as promoting vehicle and ride-sharing (Temenos et al., 2017). Car sharing (CS) is a vehicle access scheme, usually delivered by a digital platform, which allows and facilitates communal (shared) rather than private access to a pool of vehicles distributed in the city (for a personal use) by a provider such as Car2Go or Zipcar. This should not be confused with ride-sharing (carpooling) services such as BlaBlaCar, where strangers simultaneously share rides in the same direction or on-demand ride-hailing services such as Uber or Lyft (Frenken et al., 2015). In these terms, CS primarily induces behavioural aspects of change.

Recently, CS has gained traction in the urban areas of the developed world, with North America showing a 25% average compound annual member growth rate from 2010 to 2016 (Shaheen, Cohen, et al., 2018). It has been shown that consumers' image of CS is "greener" than owning a car (Hartl et al., 2018) and that, among others, environmental motives drive the intention to participate in CS (Mattia et al., 2019).

Car-sharing platforms vary significantly in terms of the trip patterns performed by their users, the ownership models, and the stakeholders involved. Nevertheless, members of all types of CS expose two important behavioural effects: 1) change in distances travelled by various modes of transport including their personal vehicles, and 2) change in the vehicle ownership or access patterns (Martin et al., 2010; Martin & Shaheen, 2011; Mitropoulos & Prevedouros, 2014; Namazu & Dowlatabadi, 2018; Nijland & van Meerkerk, 2017; Shaheen, Martin, et al., 2018). Such effects could have a strong impact on the GHG emissions related to transportation habits in total. While such sharing practices are frequently advertised and perceived as being inherently more sustainable over private ownership, various rebound effects that could limit these benefits are addressed in this research (Frenken & Schor, 2017; Schor, 2014).

The central aim of this study is to address the effects of CS participation on the transportation habits of an average service user in addition to the corresponding change in total mobility-related GHG emissions. This is achieved via a before-and-after participation comparison combined with a Life Cycle Analysis (LCA) based perspective. Contrary to most existing studies on business-to-consumer (B2C) CS (Cervero et al., 2007; Martin & Shaheen, 2011, 2016; Nijland & van Meerkerk, 2017), this study accounts for GHG emissions related to the modal-shift effect based on real distances travelled by all the modes of transport. This study, thus, accounts for the increased use of alternative transport modes caused by a decrease in car use. It further includes the non-operational emissions (manufacturing, infrastructure) of all the modes of transport used by the service participants. Finally, our study incorporates the automobile lifetime shift effect induced by sharing, i.e. an unexpected preservation of the manufacturing rates after changes in resource access patterns (sharing) caused by changing intensities of usage – a rebound effect which has been rarely addressed in previous studies. Our study focuses only on the B2C platforms as the impacts of peer-to-peer (P2P) car-sharing platforms on travel behaviour have yet to be statistically quantified.

2.2. Materials and methods

2.2.1 Research design

This study considers GHG emissions from the urban mobility sector, expressed in carbon dioxide equivalent (CO2-eq) mass. To estimate such environmental impacts, a before-and-after analysis was conducted comparing total mobility-related emissions of an average CS member for one year before and one year after the start of their car-sharing participation. In this study, these are estimated based on the annual distances travelled by different transport modes (section 2.2.2) and their corresponding per-kilometre travelled cradle-to-grave life-cycle emissions factors (section 2.2.3). For CS mode, the emissions factor was derived from private vehicle's emissions factor assuming three proposed scenarios for the lifetime mileage (LTM) of shared vehicles (sections 2.2.3-2.2.4).

After estimating possible lifetime mileage scenarios for CS vehicles, collecting life-cycle emissions factors for various modes and regions, as well as projecting annual before-and-after distances for all the modes for three case studies, the total annual emissions reductions induced by CS participation were estimated comparing before and after annual mobility profiles for a given case study using the following model, see Eq. (1).

$$\mathrm{e_{annual}} = \mathrm{e_{PKT_{car}}} * \mathrm{VKT_{car}} + \mathrm{e_{PKT_{cs}}} * \mathrm{VKT_{cs}} + \mathrm{e_{PKT_{bus}}} * \mathrm{VKT_{bus}} + \mathrm{e_{PKT_{rail}}} * \mathrm{VKT_{rail}} + \mathrm{e}_{\mathrm{PKT}_{cycl}} * \mathrm{VKT_{cycle}} + \mathrm{e}_{\mathrm{PKT}_{other}} * \mathrm{VKT_{other}} \quad (1)$$

Here, $\mathrm{VKT_{mode}}$ is the total annual distance travelled by the mode (vehicle kilometres travelled) and $\mathrm{e_{PKT_{mode}}}$ is the corresponding per-passenger kilometre travelled (PKT) life-cycle emission factor.

A general overview portraying the methodological steps followed in this assessment is portrayed in Figure 2.1. Our model and the related data have been compiled into a graphical user interface for the use of scientific purposes. These are available at the Mobility Emissions Calculator (https://doi.org/10.5281/zenodo.3385074).

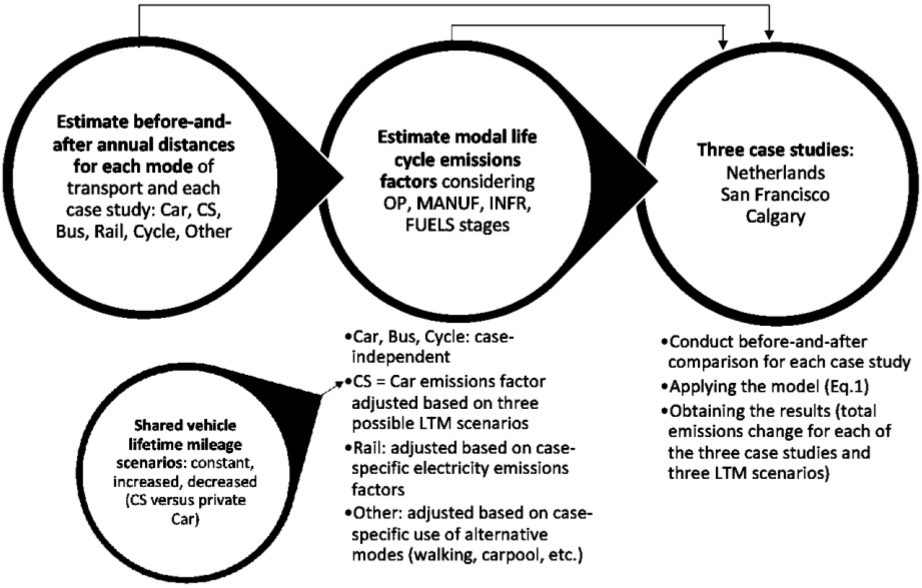

Figure 2.1 General overview of the methodological steps conducted in this study. Life-cycle stages: manufacturing (MANUF), infrastructure (INFR), fuels (FUELS), use (OP).

2.2.2 Before-and-after modal distances

Three case studies are presented in Section 2.3 of this study: San Francisco (City CarShare service), Calgary (Car2Go service), Netherlands (all the services). These case studies were chosen as they represent the only platforms and regions for which actual individual before-and-after modal distances for CS users were found to have been surveyed in previous studies (Cervero & Tsai, 2004; Martin & Shaheen, 2016; Nijland & van Meerkerk, 2017). Car2Go data exists for another four cities in North America; however, they have not been considered here as the annual distances driven per Car2Go customer and the reduction of such do not differ significantly between those cities and Calgary (Martin & Shaheen, 2016).

For each case study, we compare two average CS member's mobility profiles: annual modal distances before and after the start of B2C car-sharing participation in the urban area under consideration. These profiles consist of all the distances travelled by the 5 base modes and an additional other mode (see Eq.1): private car, car sharing (CS), bus, light rail (tram or metro, rail), cycling (cycle). Here, before-and-after distances travelled by the transport modes have been estimated based on regional transportation statistics and surveys reporting changes in distances travelled by average CS members for each of the three case studies under consideration. The distances for the complementary ‘other’, ‘walking’, and ‘carpooling’ modes have been reported previously for some cases and aggregated under the other category in the results of this study for uniformity. In all cases, the modal distances are assumed to be co-dependent, such that an annual reduction in one mode of transport will trigger alternative modes of transport. Accordingly, the total annual before and after distances travelled are assumed to differ insignificantly as only these CS participants who do not encounter major life events are considered (Nijland & van Meerkerk, 2017), and the total mobility demand is assumed unchanged.

2.2.3 Modal life-cycle emissions factors

LCAs allow for evaluating comprehensive environmental impacts (natural resource depletion or global warming potential, etc) of a particular product or service considering all the phases of its life cycle (Finnveden et al., 2009). Within the scope of this study, four stages of vehicle life (for each mode independently) were considered (Eq. 2): vehicle manufacturing (MANUF), infrastructure construction and operation (INFR), fuels production (FUELS), vehicle operation or use (OP) (Figure 2.2). For each mode’s vehicle, the four stages evaluated in this study together contribute at least 90% of the total cradle-to-grave GHG emissions reported by Chester (2008). End-of-life phase was not considered.

In the scope of this study, the per-PKT emission factors for each mode are defined as:

$$\mathrm{e_{PKT}} = \frac{\mathrm{E_{INFR}} + \mathrm{E_{MANUF}} + \mathrm{E_{FUELS}} + \mathrm{E_{OP}}}{\mathrm{LTM} * \mathrm{occup}} \qquad (2)$$

Here, $\mathrm{E_{stage}}$ is the total lifetime emissions related to a particular life-cycle stage of one vehicle of a specific mode of transport. Life-cycle emission factors for a private sedan gasoline vehicle, gasoline bus, and urban rail (tram or metro) were taken from a study in the United States of America (Chester, 2008) for the four life stages assessed in this study (see Eq. 2 and Appendix A in the Supplementary materials of this chapter for a detailed description of the stages). Along the study, emissions factors for rail were adjusted according to the local energy grid using corresponding electricity life-cycle emission factors (Appendix B). Life-cycle emissions related to cycling (excluding infrastructure-related emissions) were taken from the European Cyclists' Federation’s report (Blondel et al., 2011). Manufacturing-related emissions related to cycling as well as emissions from walking were assumed to be zero.

In general, the CS mode’s emissions factor was considered to be analogous to that of the private car (including average occupancy), but accounting for the effects of different driving intensity on the CS vehicles’ end of life total mileage (see Eq. 2). Increased access to the same vehicle facilitated by CS services could sharply affect the LTM of that vehicle, which is not usually the case for public transportation. In turn, this could affect the per-PKT emissions of shared cars compared to private cars (see Eq. 2). Hence, three possible scenarios for the LTM of CS vehicles are considered (see Section 2.2.4). Nevertheless, the additional car-sharing related infrastructure emissions were not considered (additional car-sharing stations, web-platform, etc.).

Total life-cycle emissions per-PKT for five base modes, including three possible lifetime mileage scenarios for CS vehicles, are given under Figure 2.2. Emissions factors for case-specific complementary modes (e.g. carpooling, other) were estimated based on the five base modes (see Appendix C).

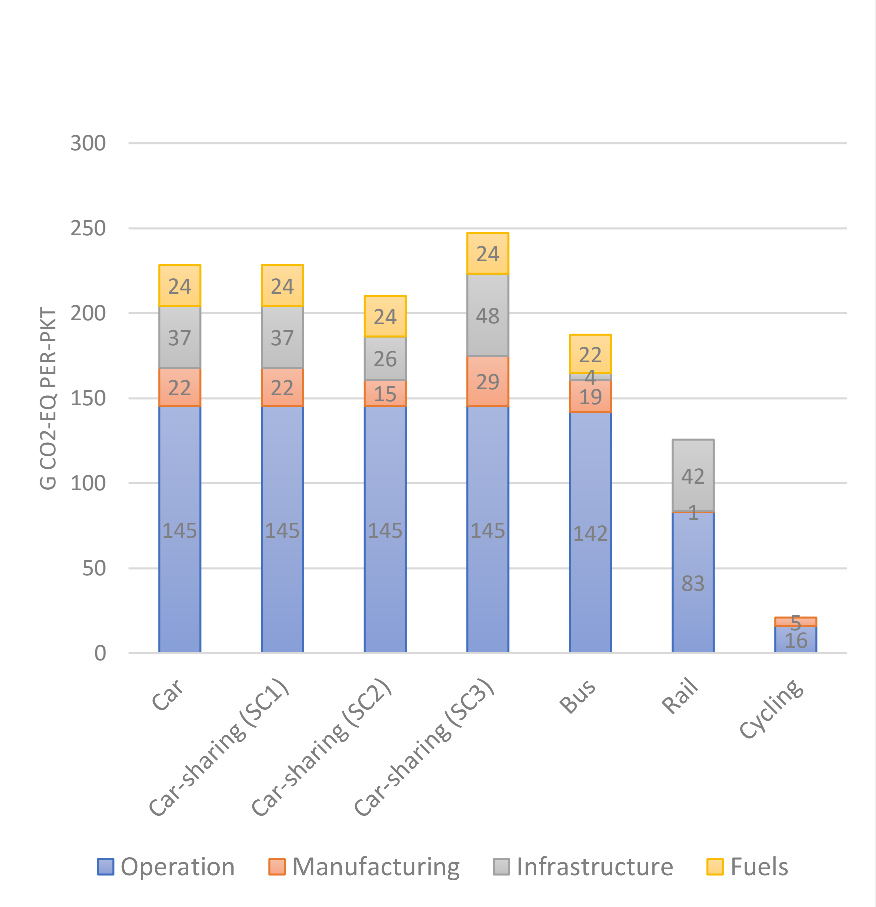

Figure 2.2 Transport modes' emissions factors. Per-passenger kilometre travelled (PKT) emissions (g CO2-eq / km) for various modes of transport based on four selected life stages. Includes three possible car-sharing fleet lifetime mileage (LTM) scenarios (SC1-SC3). Electricity emissions factors for Massachusetts, USA has been considered. Data sources: (Blondel et al., 2011; Chester, 2008)

2.2.4 Shared vehicle LTM scenarios

Several studies have suggested faster wear and tear and replacement of shared versus privately owned vehicles (Chen & Kockelman, 2016; Meijkamp, 1998). Yet, given that shared vehicles are usually sold into the second-hand market and continue their lives as regular personal cars, LTMs for CS are difficult to assess (Meijkamp, 1998). So far, no data has been published on the lifetime mileage of vehicles taking part in car-sharing services. Moreover, based on the methodology from Dun et al. (2015), we have conducted logit regression analysis and observed that both LTM of the vehicle and its lifetime (LT) do not predict its end-of-life, see Appendix D of the corresponding

Supplementary materials section. Due to the lack of data, this study addresses several possible scenarios for the lifetime mileage (LTM) of CS vehicles (Table 2.1).

Table 2.1 Overview of the three proposed scenarios for car-sharing vehicle lifetime mileage given various evidence for the annual mileage

Scenario number	Scenario	Evidence	Age (years)	Annual Mileage (km)	LTM_{cs} (km)
1	$LTM_{cs} \approx LTM_{car}$	None	15	16 000	240 000
2	$LTM_{cs} \gg LTM_{car}$	Scarce	12	29 000	348 000
3	$LTM_{cs} \ll LTM_{car}$	Yes	15	12 200	180 000

For a meaningful comparison between the scenarios, base lifetime and annual mileage for a private vehicle are set to 15 years and 16000 km accordingly as an average of values from existing sources (see Appendix G of the supplementary).

Scenario 1: Vehicles which participated in car-sharing (at least part of their lifetime) do not have a significantly different LTM_{cs} compared to an average private vehicle. This could be the case if these vehicles are not used significantly differently during their car-sharing period, and their average LT stays the same as well. Alternatively, this could be the case if the lifetime decreases (because of the wear and tear) while the mileage increases (because of the higher use intensity) remaining a strong determinant of the vehicle's end-of-life. So far, no literature evidence has been found to support this scenario.

Scenario 2: Average lifetime mileage increases for the car-sharing vehicles due to their more intensified use. This will be the case if the annual mileage increase outweighs the vehicle's shrinking lifetime. Several studies support this scenario. Meijkamp (1998) suggested that intensified car-sharing use does not allow such age-related causes as corrosion to affect a vehicle's lifetime as fast as its wear and tear, and, as a result, the vehicle reaches its lifetime mileage potential more freely. Further, significantly higher annual mileages (29000 km versus 18000 km for a private vehicle) have been suggested for car-sharing vehicles. However, this data has not been verified by other studies (Mitropoulos & Prevedouros, 2014). A three-year shorter LT has been assumed for this scenario.

Scenario 3: CS vehicles are prone to even lower LTM than their private counterparts. This could be the case if their LT stays the same while annual usage drops because of the CS platform logistics or more driving-conscious CS members being exposed to more explicit participation costs. Moreover, it could be speculated that car-sharing vehicles have a significantly lower lifetime as they are sold to the second-hand market much faster, in around 2 year (Mitropoulos & Prevedouros, 2014), and that this could lower their LTM as well. The first hypothesis was supported after aggregating usage data of the free-floating Car2Go car-sharing service from several North American cities (*Car2Go: Press Release*, 2018; Martin & Shaheen, 2016) and the CS fleet sizes of these (*Car2Go: Pioneer And Market Leader In Free-Floating Carsharing*, 2017). This results in relatively lower annual distances of 12200 km (see Appendix E of the supplementary). This scenario follows the results of (Weymar & Finkbeiner, 2016) who argued that smaller automobiles of the lower class (usually the case in the CS fleet), should be assigned lower LTM of around 170000 km.

2.3. Case studies

Before-and after analyses has been conducted separately for three cases: CS members in the Netherlands, City CarShare service in San Francisco, and Car2Go service in Calgary, Canada. For specific calculations applied to the various regions see Appendix C in the Supplementary materials.

2.3.1 Netherlands

Nijland and van Meerkerk (2017) showed that the average Dutch car-sharing participant (B2C and P2P platforms averaged) in total drives 1750 km/year less after starting to participate in CS services (7460 instead of 9220) and that 1850 km of that new total driving (private and shared) is done in a shared vehicle. In addition, authors surveyed participants on how their CS-related vehicle kilometres travelled (VKT) would be travelled otherwise, in the absence of the service. The reported car-sharing substitution profile is provided in Table E.1 of the supplementary.

This data along with the total annual distance of 11,000 km reported for an average Dutch citizen (Statistics Netherlands, 2016) allows to estimate the change between annual distances for different transport modes (see Appendix C for details). Given these modal distances and the corresponding emissions factors, annual GHG emissions can be estimated (see Table 2.2).

Table 2.2 Estimation of the total 'before' and 'after' annual distances travelled by car-sharing members. Emissions factor of CS is set as a range as it depends on one of the three LTM scenarios. Italic font for distances signifies those from the original sources rather than estimated here (Nijland & van Meerkerk, 2017)

	Before CS (km)	After CS (km)	per-PKT (g CO_2-eq)
CS	*0*	*1850*	210-247
Car	*9220*	*5610*	228
Train	1431	3069	101
Bus	140	299	187
Bicycle	105	225	20
Carpooling	35	75	144
Other	70	150	75
Total	11000	11278	

2.3.2 San Francisco (City CarShare)

Cervero and Tsai (2004) surveyed station-based car-sharing service members in San Francisco and showed that between 2003 and 2005 their daily car-VKT decreased by 38%. Similar to other studies, the authors did not survey the exact change in the distances travelled by various modes; however, they reported around 1609 km of annual car-sharing mileage, constituting 10.1% of the total annual travel distance. In addition to that, the authors’ adjacent study reported that rail distances travelled by the CarShare members constituted 33.5% of the total distances travelled, and they surveyed members on the alternative mode choice in the absence of the CS service (Cervero et al., 2007). This data allows to estimate before-and-after annual distances for various modes for this case study (see Appendix C). Table 2.3 shows these modal distances and the corresponding emissions factors.

Table 2.3 Before-and-after annual modal distances estimation and emissions comparisons for an average City CarShare member. Emissions factor of CS is set as a range as it depends on one of the three LTM cases. Italic font for distances signifies those from the original sources rather than estimated here. Sources: (Cervero et al., 2007; Cervero & Tsai, 2004)

	Before CS (km)	After CS (km)	per-PKT (g CO_2-eq)
CS	*0*	*1609*	210-247
Car	9774	4451	228
Train	1905	*5257*	84
Bus	1905	2331	187
Bicycle	519	636	20
Walking	919	1125	0
Other	426	522	125
Total	15448	*15931*	

2.3.3 Calgary (Car2Go)

The final case study investigated is based on an existing study of the environmental impacts of a free-floating Car2Go service in five North American cities (Martin & Shaheen, 2016). The authors reported 12,429 VKT driven annually on average by a Car2Go member before car-sharing participation and an average 122 km of annual car-sharing distances for current members in Calgary, Canada. Moreover, an average decrease of 898 km in private vehicle driving was estimated. Such data along with the existing official figures on a complete modal breakdown in Calgary (Behan & Lea, 2014) allow to estimate before-and-after distances for the rest of the modes for this case study (see Appendix C). Table 2.4 lists the distances projected for all the modes and their corresponding per-PKT emission factors. Contrary to the first two cases where all three LTM scenarios have been considered, here, CS emissions factor corresponds to the reduced LTM Scenario 3 only as it has been specifically estimated for Car2Go fleet (see Appendix E of the supplementary).

Table 2.4 Before-and-after annual distances and emissions estimated for an average Car2Go member in Calgary. Italic font for distances signifies those from the original sources rather than estimated here. Sources: (Martin & Shaheen, 2016)

	Before CS (km)	After CS (km)	per-PKT (g CO_2-eq)
CS	*0*	*122*	247
Car	*12429*	*11531*	228
Train	1370	1644	137
Bus	1370	1644	187
Bicycle	571	685	20
Walking	571	685	0
Total	16311	16311	

2.4. Results

Three case studies have been considered: a mix of platforms in the Netherlands, City CarShare platform in San Francisco, and Car2Go in Calgary. The effect of reduction in total annual urban mobility related GHG emissions caused by participation in the local CS services has been estimated (Figure 2.3). Pre-CS participation total emissions of the average CS member are compared with the 'after' total emissions to estimate the impact of the platform in the region of application. Complementary transport modes reported within each case study (carpooling, walking, other) have all been aggregated into the 'other' mode, in addition to the five base modes, for a proper comparison.

For the Netherlands, while the reduction in private driving is the strongest single contributor to the change in total emissions (-823 kg CO_2-eq), emissions caused by increase in CS driving and other modes moderate the total change significantly. A total annual decrease in 150-219 kg of CO_2-eq is estimated (depending on the car-sharing LTM scenario), 186 kg of CO_2-eq for the unchanged (middle) LTM scenario. This translates into a 7-10% reduction of the total annual mobility-related emissions because of CS participation. Similar to the Netherlands case, emissions in the San Francisco case study went down because the decrease in driving outweighed the increase of emissions caused by more intensified public transport use. A total decrease of 440 – 500 kg of CO_2-eq per member (470 for the middle CS LTM scenario) accounted for a 16-18% decrease relative to the pre-CS participation emissions. For the Calgary case study, we estimate an annual reduction per-member of 84 kg of CO_2-eq. According to Martin's study, 84 kg of CO_2-eq translates into a 3% reduction of the total transportation-related emissions induced by Car2Go participation of an average member.

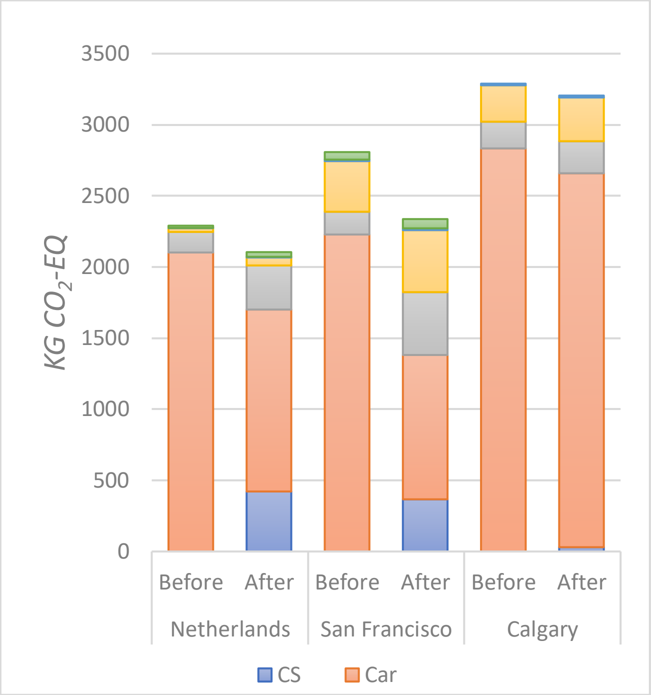

Figure 2.3 Effects of CS on total mobility-related GHG emissions (before-and-after analysis). Cumulative effect of CS participation on the total mobility-related GHG emissions (kg CO2-eq) for three case studies for the unchanged (constant) LTM scenario. Before-and-after analysis is based on the projected annual distances for five different transport modes, plus the aggregated 'other' mode for uniformity.

Comparison with the previous results for each region is given in Table 2.5. Previous CS environmental assessments (Martin & Shaheen, 2016; Nijland & van Meerkerk, 2017) concluded that greater emissions reduction takes place during CS than what our LCA-based model , Eq.(1), proposes for the same cases.

Table 2.5 Comparison of the new results with the previous three car-sharing environmental impacts analysis (ranges are based on three LTM scenarios, for Car2Go only decreased 3rd LTM scenario is considered).

Case study	Main Data Source	Prev. results (use phase oriented)	Our results (LCA-based)	
		Annual emissions reduction (kg CO_2-eq)	Annual emissions reduction (kg CO_2-eq)	Annual emissions reduction (rate)
Netherlands	Nijland & van Meerkerk, 2017	-236 to -392	-150 to -219	7 – 10 %
San Francisco	Cervero & Tsai, 2007	N/A	-440 to -500	16 – 18 %
Calgary	Martin & Shaheen, 2016	-120	-84	3%

As a result, based on the regional mobility statistics and existing behavioral surveys, it is estimated that, depending on the regional implication of the CS service, cumulative decrease rate of life-cycle mobility-related GHG emissions varies between 3-18%.

2.5. Discussion

2.5.1 Comparison of the results

CS has been previously evaluated to incur GHG emissions savings induced by participation in such services (Martin & Shaheen, 2016; Nijland & van Meerkerk, 2017). However, these studies did not take into account the rebound effects of using other forms of mobility while decreasing driving and of the possibly shifting lifetime (or lifetime mileage) of the shared vehicles. In all 3 regional studies, comparing the annual distances travelled by urban modes of transport (before and after the start of CS participation) and applying life-cycle rather than use-related emissions factors, we have found that these rebound effects along with the LCA-based perspective significantly decrease the GHG emission savings presented in previous work (Table 2.5).

Furthermore, comparing our results with two existing LCA-based research on environmental impacts of CS, even more significant difference between the results is observed (Table 2.6). Chen & Kockelman (2016) concluded that an average 50% GHG emissions reduction may occur under CS participation, whereas Ding et al. (2019) predicted up to 37% global warming potential (GWP) reduction due to short-term replacement of private cars.

Table 2.6 Comparison of the new results with the previous LCA-based studies on environmental impacts of car sharing. EoL = end of life

LCA-based study	Reduction in GHG reported	Life Cycle Inventory	Modal shift/lifetime effects considered
this	3 - 18 %	Excludes the EoL phase	+/+
Ding et al., 2019	1 - 37 %	Excludes the infrastructure and EoL phases for all and the manufacturing phase for public modes. Combines with electric vehicles and carpooling effects.	-/+
Chen and Kockelman, 2016	33 - 67 %	Meta-analysis – combines and averages existing results	-/-

While our findings of 3-18% reduction reported here are significantly lower, they can be attributed to the simultaneous treatment of three important phenomena induced by car-sharing behaviour at least one of which has not be addressed in the listed studies: the modal shift effect, non-operational emissions related to mobility, and the shared vehicle lifetime effect.

2.5.2 Modal shift effect

Most of the existing studies focused exclusively on the change in driving in their assessment of the environmental impacts. Cervero et al. (2007) surveyed station-based car-sharing service members in San Francisco and showed that between 2003 and 2005 their daily car-VKT decreased by 38%.

Similarly, a 2010 report concluded with an impressive decrease in GHG emissions based exclusively on the average 31% decrease in driving and impressive replacement of each 15 personal cars by only one car-sharing vehicle (Frost & Sullivan, 2010). Other studies surveyed Car2Go users by asking them if they changed their usage of other modes of transport after they started using the car-sharing platform (Martin & Shaheen, 2011, 2016). While behavioural changes in VKT driven after car-sharing participation were measured in cardinal values (exact distances), the answers proposed for other modes were based on the ordinal scale (no change, increased, decreased). The authors have found that there was no significant reported change in public transport use on average and accounted for no significant effects of such. On the contrary, real distances travelled by other modes of transport before they had been replaced by car-sharing kilometres have been assessed by Nijland and van Meerkerk (2017), see Table E.1 of the supplementary; however, their study does not take into account that the reported annual decrease in 1,750 kilometres driven by CS members could be replaced by distances travelled by other modes. The LCA study by Chen & Kockelman (2016) is a meta-analysis and is based on most of the aforementioned assessments. A study by Grischkat et al. (2014) admits and incorporates the modal shift effect while assessing the GHG reduction potential of alternative mobility services. However, a general population of Germany rather than actual CS users are surveyed to estimate potential (expected) rather than actual changes in distances travelled. Similarly, a study by Rabbitt and Ghosh (2016) estimates GHG emissions reduction based on a hypothetical rather than actual change in distances travelled. A study by Scarinci et al. (2017) quantifies the impacts of the modal shift effect induced by CS participation similarly to our approach. However, the nature and the source of the data on the before-and-after modal distances could never be verified.

Thus, our study, contrary to most of the previous assessments, assumes and accounts for a simultaneous increase in actual distances travelled by the alternative modes by CS users in the considered case-studies, which could explain more conservative results observed here. To illustrate the cumulative impact introduced by the modal shift effect, we compare our results (middle LTM scenario) for the three case studies against an assumption where non-driving transportations modes are not considered (Table 2.7). It is evident that the distance-based modal shift effect considered in this study significantly influences the estimation of the total annual impacts of CS participation and should be considered in the future studies.

Table 2.7 Comparison of the resulting annual GHG emissions reduction with such in our study if the modal shift effect would not be taken into account (for three case studies)

Case study	Annual emissions reduction driving modes only (kg CO_2-eq)	Annual emissions reduction w/o modal shift (kg CO_2-eq)
Netherlands	-186	-401
San Francisco	-471	-847
Calgary	-84	-175

2.5.3 Non-operational emissions and the lifetime shift effect

Non-operational stages (vehicle manufacturing, transportation infrastructure, etc.) of a vehicle's life contribute significantly to the total GHG emissions related to transportation (Chester & Horvath, 2009). However, most car-sharing studies do not take the GHG emissions of these stages for all the modes of transport accessed by the respondents and focus mainly on the lower car manufacturing from fewer owned cars (Ding et al., 2019; Jung & Koo, 2018; Nijland & van Meerkerk, 2017). Moreover, Nijland and van Meerkerk (2017) attributed all the shed vehicles (sold before the car-sharing membership) to the decrease in manufacturing emissions. On the contrary, our study takes into account that the majority of shed vehicles (sold during CS participation) by new CS members were actually close to their end of life (EoL) already (Martin et al., 2010). Hence, comprehensive treatment of the non-operational emissions for all the modes on a per-use (km) basis proposed here could explain lower emissions reduction rate obtained as well. The model presented in this study automatically assumes that along with those of the private cars, participants are similarly responsible for some portion of the non-operational GHG emissions behind other (public or shared) modes of transportation that they use and whose infrastructure they collectively 'own' and stimulate. The exact non-operational portion of emissions is driven by vehicle's LTM.

Exclusively positive environmental impacts induced by a more frequent shared vehicle replacement have been suggested (Chen & Kockelman, 2016; Meijkamp, 1998) due to better fuel efficiency of the newer cars. One recent study, however, considered the lifetime effect for CS manufacturing emissions admitting significantly lower emissions reduction in Beijing if long-term perspective is taken (Ding et al., 2019). That study, however, assumed a vehicle lifetime and an LTM of 30 years and 600 000 km, respectively. In contrast, Mont (2004) reported that car-sharing vehicles are usually sold to private owners in 2-3 years after being in shared use. Mitropoulos & Prevedouros (2014) suggested that this is closer to 1-2 years and reported 29000 km yearly mileage for the shared vehicles versus 18200 km for the average private vehicle in the US assuming the same 10.6-year average lifetime. Other than that, Oguchi and Fuse (2015) in their study showed that a vehicle's LT varies significantly from country to country and, hence, should be considered for the LCA of such for different regions.

It is not possible to compare the influence of the last two effects (non-operational emissions and lifetime shift) on the total emissions reduction estimations in case of their absence within the scope of this study as they are the inherent elements of the LCA-based model itself. Nevertheless, even though the total reduction is not significantly sensitive to the proposed LTM scenarios (see Table 2.5), introducing this parameter into the assessment by itself restricts the positive manufacturing impacts claimed by the previous studies (Chen & Kockelman, 2016; Nijland & van Meerkerk, 2017). Here, we assume that the per-km use of the automobile (both private and shared) induces corresponding portion of such emissions rather than the mere ownership of the vehicle. Considering the lifetime rebound effect, in case if the total annual driving demand stays similar, merely switching from private ownership to a CS scheme does not introduce any non-operational (manufacturing, infrastructure) GHG reductions, as the shared vehicles' lifetimes will be shrinking accordingly, preserving production rates in the long-term.

Comparison of the reduction of the driving-related non-operational emissions in our study (26 to 52 kg of CO_2-eq for the Dutch case study) with the value (125-281 kg of CO_2-eq) claimed by the original study (Nijland & van Meerkerk, 2017) exemplifies the impact of the lifetime shift effect on such estimations. This does not consider several other manufacturing-related misalignments in their study (Appendix F of the supplementary).

2.5.4 Sensitivity Analysis

This study evaluated the effects of individual factors such as public transport occupancy levels and local energy production profiles on the GHG emission reductions.

The total annual emissions of an average Car2Go member (section Case studies 2.3.3) are highly sensitive to the occupancy levels of public transport they use to substitute a decrease in driving. For instance the average diesel bus from the US with a 10.5 passenger occupancy was considered while its occupancy ranges from on average 5 to 40 passengers during the day (Chester & Horvath, 2009). Corresponding per-PKT emissions range between 394 and 49 g of CO_2-eq. The resulting total mobility-related emissions change would vary from a decrease of 27 kg of CO_2-eq for a low-occupancy bus to a 121 kg of CO_2-eq emissions decrease for a high-occupancy bus (if the service and members' mobility habits would stay constant otherwise), see Figure 2.4.

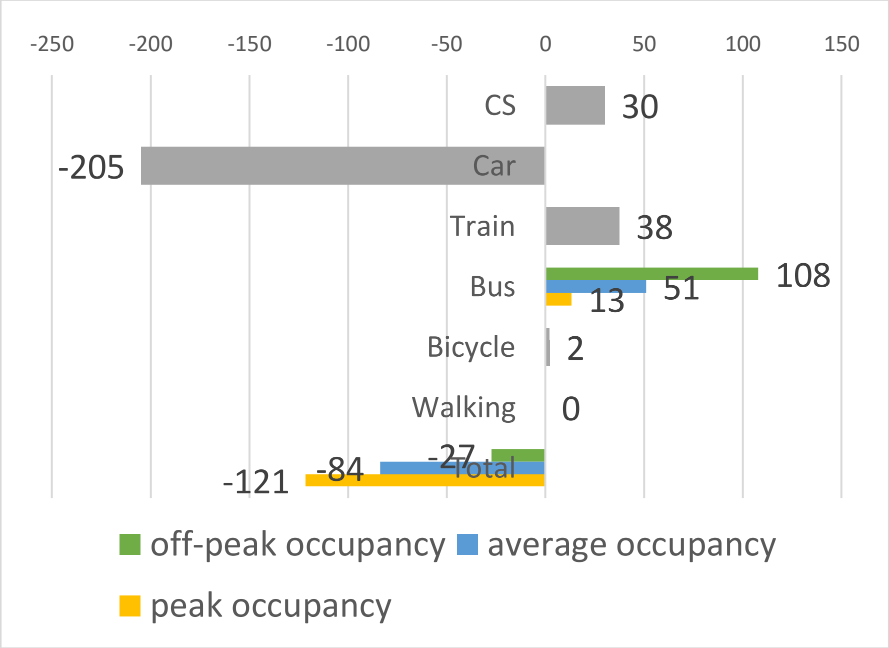

Figure 2.4 Sensitivity to bus occupancy. Total GHG emissions reduction (kg CO2-eq) of the Car2Go car sharing users in Calgary.

In some cases, CS activities could result in even higher total annual mobility-related emissions. For instance, while life-cycle electricity-related emissions factor for California was used, the total annual emissions of an average CarShare member are highly sensitive to the local electricity grid, which powers the trains and the required infrastructure (section Case studies 2.3.2). The resulting total emissions change would vary from a decrease of 663 kg of CO2-eq for a hydroelectric powered Vermont to a 250 kg of CO2-eq emissions increase in an oil and gas sourced electricity grid in Washington D.C, assuming the service and members' mobility habits would stay constant otherwise (see Appendix B of the supplementary materials). Figure 2.5 depicts such sensitivity analysis.

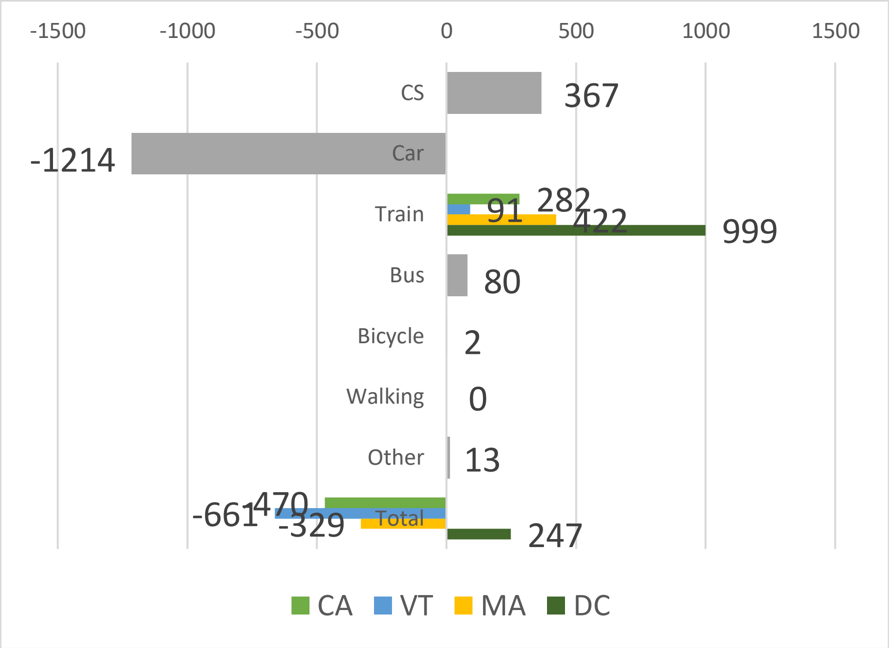

Figure 2.5 Sensitivity to electricity grid. Total mobility related GHG emissions change (kg CO2-eq) of the City CarShare users in San Francisco. Sensitivity to electricity grid in four different states in the USA (California, Vermont, Massachusetts, D.C.)

2.6 Limitations

Even though the socio-transportation system under consideration is highly dynamic, the LCA-based approach used in the study is inherently *attributional* (Jones et al., 2017). This implies that it is a static snapshot of the system at a particular moment in time and that it operates with the average values for the phenomena under consideration; that is, the total values are divided by the total number of functional units. For instance, the total manufacturing emissions attributed to an average single vehicle or the average emissions related to one additional km travelled by a mode of transport. A different, *consequential* LCA approach would rather consider marginal costs (diminishing returns) caused by an additional km travelled by a particular mode. However, it has been argued that such an approach is not usually feasible for complex transportation systems (Chester, 2008). Still, as this study aims to compare the environmental implications of different mobility habits within an otherwise constant transportation system (rather than system-wide marginal implications caused by changing behaviour), a simplified attributional approach is reasonable. Hence, the impacts of the total amount of the vehicles and the intensity of their usage on the existing infrastructure, fleet production, and maintenance were not considered. Differences between private and shared automobile fuel efficiency levels were not taken into account as well.

Still, it is important to notice that the model under consideration automatically accounts for the *direct rebound effects* (consequences) associated with CS participation. This is the case since it tracks changes in distances travelled by all the modes, and any unintended increase or decrease in the intensity of mobility incurred by an introduction to the eco-efficient innovation is explicitly included in the calculation (Frenken et al., 2017). Hence, our assessment holds characteristics intrinsic to consequential LCA as it evaluates impacts of a changing behaviour (compares mobility profiles) as well. Nevertheless, *the indirect rebound effects* associated with possibly increased or decreased consumption in other consumption categories caused by changing total costs of mobility were not considered in this study (Hertwich, 2005). For example, a study by Ottelin et al. (2017) revealed that reduced car-ownership can lead to significant rebound effects, particularly because of increased air travel. It could be speculated that if the annual costs of car sharing and the substituting modes of transport are lower than the average costs of car ownership and use, the indirect rebound effect would be positive (undesirable), meaning that there are actually additional emissions due to increased consumption in other consumption categories.

Distances travelled annually by an ‘average’ CS member are considered in this study. Nevertheless, individual annual mobility habits of the CS members could vary significantly. Thus, the mobility-related GHG emissions’ 3-18% decrease reported in this study represents the cumulative impacts of such services rather than individual impacts of their members. Interestingly, it has been previously reported that CS participation provokes a slight increase in total driving distances for the majority of users, where a minor group of individuals sharply decreases total driving, allowing for a positive overall impact on the ‘average’ member (Martin et al., 2010; Martin & Shaheen, 2016). Hence, for more accurate estimation of such rather personal impacts, annual distances travelled by various modes by the interested individual have to be used in the Mobility Emissions Calculator (https://doi.org/10.5281/zenodo.3385074).

Additionally, citizen-wide surveys and proxies have been used in this study to estimate the distances travelled by all the modes for the before-and-after analysis, whereas, ideally, a survey on the distances travelled by the B2C car-sharing members specifically could provide a better assessment. Nevertheless, the central assumption in the proposed model (that was not followed in the previous studies) was that CS members do not significantly change their grand total annual transportation distance because of CS participation, and this consideration by itself brings in the greatest correction to the previously reported results. Thus, the total emissions reduction is not envisioned to alter significantly if the surveyed modal mix itself differs.

Another point to acknowledge is that, except country-specific electricity emissions factors, USA-based LCA transportation emissions factors are applied for the Canadian and Dutch case studies as well, even though the local transportation systems are different. This could be justified with several reasons. Firstly, the source study for those factors (Chester & Horvath, 2009) is still one of the most comprehensive assessments in the field of LCA for transportation as it includes not only the vehicle and fuel cycles but the infrastructure-related emissions for various transport modes as well. Secondly, applying emissions factors from several national studies with different methodologies could introduce difficult-to-measure distortion to the uniformity of the results. Finally, it seems logical to assume that the major underlining transportation manufacturing and infrastructure-related technologies in those countries are still very similar and that the real differences would not strongly affect the results.

Finally, it has been assumed in this study that occupancy of the shared and private automobiles are the same as it has been reported for the free-floating CS services (Ding et al., 2019). However, possible differences between various types of CS platforms and the corresponding average occupancy could affect the total per-PKT emissions factors significantly and may require further investigation.

2.7. Conclusions

A comprehensive LCA-based model Eq. (1 – 2) has been proposed to estimate the change in the total annual mobility-related GHG emissions caused by average B2C car-sharing participation in three regions (Netherlands, San Francisco, Calgary). For that, life-cycle emission factors for various modes of transport, including region-specific electricity emissions factors, have been used for private automobiles, bus, urban rail (tram, light rail), shared vehicles, and bicycles. To account for a lifetime shift effect induced by sharing, three different emission factors have been considered for a shared automobile given three possible lifetime mileage estimations of such. Moreover, before-and-after participation distances for all the modes under consideration were projected based on the existing data to properly account for the modal shift effect and to calculate total GHG emissions related to transportation habits of an average CS member.

Three case studies considered in this study resulted with a 3-18% reduction of mobility-related life-cycle GHG emissions caused by B2C car-sharing participation by the average member. For all the case studies, the behavioural change in driving had the most significant magnitude of change on the total emissions. The introduction of the distance-based modal shift and lifetime shift travel-related rebound effects limits such benefits of decreased driving on GHG emissions. Moreover, the environmental impacts were shown to be highly sensitive to the other characteristics of the transportation system surrounding a particular car-sharing service area: average occupancy of the modes and the electricity grid in the area of application. Interestingly, in rare cases, the total annual mobility-related emissions could even increase if the driving substitution modes are even more carbon-intensive than driving (section 2.5.4). This implies that merely using CS vehicles over the private ones does not introduce significantly lower total emissions if the total PKT demand for driving remains constant. On the other hand, it could be argued that given constant PKT distances demand, a ride-sharing or carpooling (versus CS) behaviour (higher automobile occupancy levels) would introduce much more significant reduction in per-PKT emissions factors and the total mobility-related emissions.

Hence, main policy implications should be directed towards reduced automobile use rather than ownership redistribution (sharing) of the vehicles per se. This could be achieved by stimulating use of public modes of transport (including ride-sharing) via corresponding legislative (taxation) and infrastructural measures. Moreover, future research on the environmental impacts related to CS should improve upon the limitations present in this study conducting complete multi-modal distance-based surveys, applying actual local life-cycle environmental impacts factors, as well as incorporating possible technics to account for indirect rebound effects (combined Life Cycle Cost and LCA assessments). Previous studies have also shown that new modes of travel such as bike sharing and shared e-scooters are gaining popularity and have assessed the life cycle emission factors of such (Hollingsworth et al., 2019; Luo et al., 2019). This may affect the modal substitution and change the usage of CS, which provides an interesting area for future research as well.