Environmental impacts of car-sharing: life-cycle assessment

Master’s Research Paper

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## Acronyms and Abbreviation

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<td>Life-Cycle Assessment</td>
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<td>Life-Cycle Assessment Inventory</td>
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<td>TS</td>
<td>Transportation System</td>
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<td>ETS</td>
<td>Extended Transportation System</td>
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<td>IP</td>
<td>Individual Profile</td>
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<td>CP</td>
<td>Collective Profile</td>
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<td>VKT/VMT</td>
<td>Vehicle Kilometer/Mile Travelled</td>
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<td>TVKT</td>
<td>Total Vehicle Kilometers Travelled</td>
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<td>PKT</td>
<td>Passenger Kilometre Travelled</td>
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<tr>
<td>LT</td>
<td>Lifetime</td>
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<td>LTM</td>
<td>Lifetime mileage</td>
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<td>ELV</td>
<td>End-of-Life Vehicle</td>
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<td>GHG</td>
<td>Greenhouse Gas</td>
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Introduction

Our planet faces increasing environmental risks imposed by alarming rates of greenhouse gas (GHG) emissions (WWF, 2018). Meanwhile, the transportation sector plays a very significant role in this increase. Approximately 23% of the global direct CO₂ emissions in 2010 originated in the transportation sector as it is still predominantly driven by fossil fuels (IPCC, 2014). This excludes additional indirect GHG emissions if accounting for fleet manufacturing, infrastructure building and fuels provisioning for the sector.

Lowering such emissions is a priority in the most economically developed countries as their national transportation emissions account for a big portion of their per capita emissions. These emissions comprise around 30% of the national total for the most economically developed countries whereas it’s only 3% for the least developed countries (IPCC, 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 changes such as promoting vehicle and ride sharing with others (Temenos et al., 2017). At the same time, it could be argued that focusing on the technological or infrastructural “fixes” which optimize transportation use won’t be ever nearly as effective as moving towards a more collaborative and “a resource-light” behavior (Leismann, Schmitt, Rohn, & Baedeker, 2013). Focusing on the realities of developed countries, this study explores previous environmental promises and assesses GHG effects of the car-sharing activities as an alternative to the conventional modes of ownership and transportation which facilitates various behavioural changes.

Car-sharing (CS) is a vehicle access scheme, usually delivered by a digital platform, which allows and facilitates public (shared) rather than private access to a pool of vehicles distributed in the city by the provider such as Car2Go or Turo. This should not be confused with on-demand ride-haling services such as Uber or Lyft (Frenken, Meelen, Arets, & van de Glind, 2015).
As various on-line sharing platforms such as Airbnb attract more and more users, car-sharing gained an impressive traction in the urban areas of the developed world within the last years. It has been reported that North America has had a 25% average compound annual member growth rate from 2010 to 2016 (S. Shaheen, Cohen, & Jaffee, 2018). The majority of car-sharing members report financial gains as the prime reason for their participation (S. A. Shaheen, Martin, & Bansal, 2018). At the same time, such ‘sharing’ practices are frequently advertised and perceived as being inherently more sustainable over private car ownership even though such claims could be misleading and require further evidence (Frenken, 2017).

Hence, this study aims to contribute to a more complete and systematic understanding of the environmental benefits of car-sharing versus other modes of transportation by applying the Life Cycle Analysis (LCA) approach. To my knowledge, there has been only one car-sharing LCA study

*Figure 1: Research steps*

- **Car-sharing**
  - Understanding its taxonomy
  - Behavioural effects

- **LCA: Overview**
  - General description of the LCA proposed and its phases

- **Transportation System**
  - Describing the system
  - Incorporating LCA related elements
  - Incorporating key car-sharing related concepts
  - Incorporating key GHG related elements

- **Analyzing previous studies**
  - Weaknesses

- **LCA: Description**
  - Inventorization and formalization for each transportation mode

- **LCA: Application**
  - Application
  - Sensitivity analysis
conducted which is a meta-analysis of the previous studies on car-sharing environmental impacts (Chen & Kockelman, 2016). After detailed analysis of the studies involved in that LCA, several areas of serious weaknesses were identified. That understanding allowed to question the results of the whole LCA conducted and to propose some important improvements. To do so, several steps will be conducted in this study (Figure 1).

First, the taxonomy of car-sharing platforms will be introduced to understand the specifics of the various platforms discussed in the rest of the study. Key behavioral changes induced by such sharing practices will be explored, as they will account for major environmental effects estimated later in the paper. Next, the general description of the LCA elements required for a complete analysis of car-sharing practices will be described. Following that, a comprehensive transportation system will be designed to account for various aspects of sharing, LCA life stages, and parameters affecting environmental effects of such. Following that, the weaknesses and misalignments from the previous studies on the environmental effects of car-sharing will be categorized and addressed by the transportation system proposed. Finally, a complete formalization of the LCA will be conducted followed by its application to various car-sharing cases. To conclude the study, alternative approaches will be discussed, and the results and limitations will be summarized.

Car-sharing participation forms and effects

Forms

Car-sharing could be generally defined as the shared use of a vehicle pool by members on a per trip basis (Martin & Shaheen, 2016). More specifically, four types of car-sharing are usually distinguished in the literature: station-based, free-float, peer-to-peer, and fractional car-sharing. At the same time, these types could be grouped under three major ownership profiles.

Business-to-Consumer (B2C)

In this case a company such as Car2Go or Zipcar owns a fleet of vehicles which is distributed in the city for users to access. Zipcar is an example of a station-based or a roundtrip platform as its vehicles are supposed to be rented from and returned to the same designated location in the
city, whereas Car2Go is an example of a free-float or a one-way car-sharing scheme as its members are free to pick and drop the company’s vehicles at any eligible parking location within a service area.

*Peer-to-Peer (P2P)*

This model of car-sharing leverages the fact that the majority of privately-owned vehicles sit idle for around 90% of the time (Hampshire & Sinha, 2011). In this case P2P car-sharing platform such as Turo allows private vehicle owners (hosts) to rent out (share) their cars with others in the community as it connects users with hosts for such transactions. This is the fastest growing form of car-sharing.

*Fractional (platform co-op)*

This rare approach to ownership implies that a group of members or a co-op owns and democratically governs the sharing platform themselves. In this case every member of a fractional car-sharing organization such as Modo is a fleet owner and a caretaker on an equal basis.

*Effects*

It could be seen that car-sharing platforms vary significantly in terms of the trip patterns performed by their users, ownership models, and stakeholders being involved. Nevertheless, members of all types of car-sharing expose two important behavioral effects: 1) change in distances travelled by various modes of transportation including their personal vehicles 2) change in the vehicle ownership or access patterns (Nijland & van Meerkerk, 2017; S. A. Shaheen et al., 2018).

Such effects could have a strong impact on the GHG emissions related to transportation habits. Yet, to estimate those accurately, a comprehensive understanding of the transportation system involved is required in addition to an appropriate application of the LCA to the its vehicles and processes involved.

In other words, LCA for multiple modes of transportation (rather than just car-sharing) will be required for a complete analysis as car-sharing environmental impacts are followed by changes
in other modes’ usage. To prepare grounds for that, first, I will briefly describe the Life Cycle Analysis in application to various modes of transportation.

**Transportation Life Cycle Analysis: Goal and Scope**

LCA is a methodological tool usually applied to evaluate environmental impacts (energy, GHG, materials, etc) of a particular product or service considering all the phases of its life span (EPA, 2006). Conventionally, these are the stages of materials extraction, product’s manufacturing, distribution, use, maintenance and disposal. For each phase all the resources consumed and emitted (depending on the focus of the investigation) are estimated towards the final total result.

Dealing with a systematic tool like that, it is crucial to define boundaries around what will be included in the analysis, specifically which processes and life stages will be considered. One of the goals of this study is to estimate full life-cycle GHG impacts of car-sharing versus other modes of transportation; however, it is rarely possible to account for absolutely all the phases of the vehicle’s life-cycle. Hence, we could, for instance, include vehicle manufacturing effects into consideration excluding the energy use involved in the digital platform maintenance or even all the impacts of disposal at the same time. Within the scope of this study, following four stages of a vehicle life (for each mode independently) will be considered for the LCA (Figure 2).

![Figure 2: Transportation LCA phases](image)
These particular boundaries for my assessment were suggested by the strongest GHG emitting life phases and processes described in results of the previous LCA on various modes of transportation in the US. In particular, based on the inter-modal analysis conducted by Chester et al. (M-LCA), it became evident that if normalized by the lifetime distances travelled, on average, vehicle operation, vehicle manufacturing, infrastructure construction and operation, as well as the fuel production were the most energy consuming and GHG emitting components of a vehicle life at least for one of the modes (at least 5% of the total per km amount). These four stages (LCA inventory for our study) together contribute at least 90% of the total emissions for every mode (Chester, 2008). End-of-life emissions were not considered due to lack of data on such.

Next, it is important to pick the functional unit of the LCA assessment, which is the unit of service for which the environmental impacts will be estimated. In the case of this study, total GHG emissions are investigated for transportation; thus, it’s natural to pick a distance measure (one kilometer) as a functional unit since it is a universally deliverable across various modes. Based on the amount of the total lifetime GHG emissions normalized per one kilometre travelled by one passenger (PKT) of a given transportation mode \(e_{PKT_{mode}}\) compared to other modes, inferences about that mode’s relative sustainability could be made.

In this case, total lifetime (LT) GHG emissions of a particular vehicle \(E_{LT_{mode}}\) will be divided by the total vehicle kilometres travelled or its lifetime mileage (LTM), and this procedure will be repeated for each mode separately:

\[
e_{VKT_{mode}} = \frac{E_{LT_{mode}}}{LTM_{mode}} = e_{mode}
\]

\[
e_{PKT_{mode}} = \frac{e_{mode}}{occu_{mode}}
\]

Here, per-PKT emissions are obtained from the per-VKT emissions dividing them by the number of passengers (occupancy) in the vehicle, and the total vehicle lifetime emissions are estimated using the four aforementioned phases of a vehicle’s life:

\[
E_{LT_{mode}} = E_{INFR} + E_{MANUF} + E_{FUELS} + E_{OP}
\]
Transportation System

Extended Transportation system overview

Even though this study discusses the environmental effects of car-sharing, it will be limited to GHG emissions only, which will be in turn expressed in CO₂e (carbon dioxide equivalent) mass.

For a systematic perspective on the issue, I first define the transportation system (TS) as a set of elements (stocks), the processes in between of them, the system’s purpose in general, and its boundaries (H.Meadows, 2008).

Boundary of the system is defined by a given geographical or urban area as well as a particular set of the local modes of transportation: 1) private car 2) car-sharing 3) bus 4) light rail (tram or metro).

The stocks of the TS are: 1) the stock of all the vehicles 2) the stock of all the infrastructure 3) the fuel required for the modes involved to operate.

The processes occurring between and influencing these stocks are the four life phases suggested by the LCA scheme: 1) the modes actual operation or usage (vehicle kilometres travelled) 2) vehicles manufacturing 3) infrastructure construction and operation 4) fuel production. These are not the only processes involved in the real transportation systems. However, as we focus on the GHG emissions only, it was already mentioned that such set of the processes account for majority of the emissions within the system.

Finally, the purpose of the whole transportation system is its continuous correspondence to and satisfaction of the public’s usage demands – the external factor. Generally speaking, it could be claimed that the transportation system and, consequently, the GHG emissions behind it are strongly determined by our personal choices of the particular modes and the patterns of their use. Collectively, our personal choices strongly influence the whole TS and its processes in the long term. This is not to say that the existing TS that we are placed into does not strongly influence our personal choices itself. On the contrary, our collective mobility behaviour, referred to as a collective transportation profile (CP), and the TS coexist in a continuous self-
organizing cycle with feedback loops and delays (H. Meadows, 2008). I will call this extended system an extended transportation system (ETS) - pictured on the Figure 3.

**Extended Transportation System**

![Extended Transportation System Diagram](image)

Figure 3: Extended Transportation System. It includes the TS itself, the individual profile (IP) and the collective profile, and the emissions stock. Stocks of the TS are shaped as rectangles. Blue lines describe the causal links between TS’s parameters, processes and stocks. The effects of the dotted causal links will not be considered in this study, even though their existence was acknowledged. The GHG emissions stock (level) is colored in pink. Lifetime and LTM orange block will be considered in detail later in the study.

We will have a closer look now. Our personal transportation habits could be defined as the distribution of the distances travelled using various modes of urban transportation during a given period of time (a year for our analysis), I will call it an individual transportation profile (IP). As an individual, for example, starts using buses more intensively instead of the private car, their IP changes and immediately modifies the collective profile. After some delay, the larger scale and higher level urban transportation system will adapt to this change as it could be suggested by the theory of adaptive circles (Holling, 2011). Such adaptation to an individual change could be left unnoticeable; however, if enough citizens would similarly switch to buses, the TS could adapt by providing with an additional bus, followed by extra GHG emissions.
associated with that extra bus’s manufacturing, maintenance and operation, as well as lower GHG emissions related to personal driving.

Ownership versus access (sharing)

Since this study aims to determine the position of the car-sharing and its impacts mechanism within the ETS, it is very important to define carefully the ‘ownership’ phenomena and its effects within the combined system first. It is natural to assume that our private vehicle ownership habits (for instance, the number of the vehicles we own) shape our individual transportation profiles, consequently influencing the TS itself (for instance, the parking infrastructure built to accommodate our ownership). For instance, it has been shown using a survey data that the Ithaca Carshare program in the US allowed its participants to own less vehicles, and as the result the parking need fell on average by 28% (Stasko, Buck, & Oliver Gao, 2013).

Nevertheless, I argue that for an accurate understanding of the car-sharing life-cycle GHG impacts in comparison to other modes of transportation or, alternatively, to be able to compare GHG emissions behind distinct individual profiles, it is crucial to equally consider the ‘ownership’ phenomenon for all the various modes. The idea of ‘sharing’ versus ‘ownership’ implies that there are less vehicles of a particular mode per capita in the TS, as the same vehicle will be accessed by more users at the same time. Indeed, it could be argued that such access-based consumption (Bardhi & Eckhardt, 2012) could potentially have lower environmental impacts per user as the resources are used less wastefully. Within the scope of this study I perceive the private ownership as the derived form of ‘sharing’ where access to a vehicle is

![Figure 4: Levels of access (sharing)](image)
constraint by the owner’s household. At the same time, all other public modes of transportation are shared and commonly accessed as well, but by all users of the TS (Figure 4).

In using private cars which we own, we clearly are responsible for some portion of GHG emissions behind, for instance, these vehicles’ manufacturing; however, as we use other (public) modes of transportation as well, we should be considered responsible for their production as we ‘own’ them collectively within the TS.

As the goal of this study is to estimate personal life-cycle GHG emissions of car-sharing use versus other modes of transportation, it is crucial to consider our individual GHG contributions in the same manner across all the modes. Moreover, the model under consideration should reflect that uniformity.

Inclusion of car ‘ownership’ under an individual profile as its parameter will require considering ‘ownership’ of the other vehicles of transportation (or their portions) by an individual which is not conceivable within the scope of such studies. Thus, it is proposed, for the sake of the system’s uniformity, to consider car and car-sharing as alternative modes of transportation whose vehicles are ‘owned’ or rather accessed by the whole TS and its users. There is another reason for that. As cars and other public modes of transportation usually utilize the same infrastructure within the TS, it would be almost impossible to distribute the GHG contributions of such shared infrastructure between the private and public vehicles. Finally, the third reason for considering all the vehicles as shared modes of transportation – the average vehicle will have several owners during its lifespan (IHS, 2015). Hence, rather than trying to estimate individual GHG contributions within such circular ownership practice, it would be more reasonable to consider an automobile as a shared source of transportation during its lifetime (as all other vehicles).

To conclude, because of the rationale to estimate and compare GHG emissions behind distinct individual transportation profiles of the TS users, all the modes of transportation including cars and car-sharing will be considered from the access-based rather than ownership-based
perspective. The number of users who access a particular vehicle of transportation will be considered as an inherent characteristic of the TS rather than of the individual profile.

Car-sharing versus private car modes

Compared to private vehicles, most car-sharing platforms require an additional unique infrastructure such as a digital platform itself. Nevertheless, such car-sharing exclusive elements of the TS won’t be considered within this study, as they are considered to be relatively low. Otherwise, car-sharing vehicles are going through the same four phases of the LCA as private vehicles with mostly the same outcomes. The only difference, which will eventually affect the resulting per-PKT emissions, is that car-sharing vehicles are used in a different manner and, thus, they arguably could have a different lifetime mileage (LTM). That important question will be investigated later in the study.

In other words, from the system’s perspective, car-sharing mode of transportation won’t differ from the private car mode except in the intensity of its usage and, as a result, total LTM of the car-sharing vehicles. Still, these two modes will be considered analogues in terms of the factors and mechanisms of their environmental impacts. This approach will allow for a more accurate comparison of such effects between modes and of the cumulative effects of the behavioral changes induced by car-sharing participation.

Mode’s usage (operation)

A particular mode’s usage is defined as the main mobility characteristic of each individual and of the resulting collective profiles. This personal usage is measured in the total kilometers travelled (TPKT) during the year by a particular individual by each mode. Similarly, CP reflects total distances travelled by different modes of transportation by all users of the TS within a year. In practice, the operational stage of the LCA (Figure 2) is the greatest and the major contributor of GHG emissions during the average vehicle’s life (except for railroad transportation). This was shown by several previous studies (Chester, 2008; Samaras & Meisterling, 2008). Such emissions originate directly from the distances travelled by the vehicle
versus production related emissions originating in manufacturing and infrastructure related processes.

**Occupancy versus access per vehicle**

There are two additional emergent properties of the extended system and, specifically, of the public profile: the *occupancy* and *access* per vehicle. From the systems theory, emergent properties are those emerging from and pertaining to the system as a whole rather than to its separate parts (elements).

Occupancy is the average number of passengers occupying a vehicle of a particular mode during its trip. The higher this number, the more people are held accountable for the same amount of vehicle kilometers travelled (VKT) and related emissions. For instance, ride sharing (pooling) platforms such as Lyft Pool or BlaBlaCar are targeting this specific characteristic of transportation, hence, allowing lower per-PKT emissions compared to private vehicle operation as the total VKT could decrease significantly with higher occupancy rates.

On the contrary, the ‘access per vehicle’ property characterizes the number of users who have access to the vehicle and share it between them. For a private car this will likely be restricted by the size of the owning household. For a car-sharing vehicle this is the number of platform users per shared vehicle. If nothing else is changed in the system, a higher access (sharing) will result in less vehicles being required to be stocked in the system and, as a result, vehicles being occupied (occupancy) or used (VKT per vehicle) more intensively. This could, possibly, affect production related emissions as it could be argued that more intensively driven vehicles will have a different life expectancy which will in turn affect the rates of production (Figure 3).

**Stocks**

One of the most comprehensive LCA of the various modes of transportation in the US conducted in Berkley in 2008 grouped components of the LCA analysis in vehicles, infrastructure and stocks (Chester, 2008). Thus, the system I propose consists of these three stocks. The ‘vehicles’ stock is the pool of all the vehicles in the system. Their number is primarily controlled by the manufacturing rate which in turn is regulated by the demand (required fleet)
and vehicles’ lifetime. The number of vehicles in the system as well as the intensity of their use (total VKT) undoubtfully affects the need in construction and maintenance of the infrastructure stock. However, these two causal links (dotted lines in Figure 3) won’t be taken into account for the purpose of simplicity. Finally, fuel stock is defined by its own production level which in turn is following the use of fuel by vehicles in the TS.

Processes
Hence, four GHG emitting processes (red lines on the scheme) which define the levels of stocks required for the TS to satisfy the CP are the vehicles’ manufacturing, infrastructure maintenance and construction, fuel production, and operational fuel or energy consumption.

Vehicles’ Lifetime
Since the functional unit chosen for the proposed LCA is a kilometer travelled by a particular mode, it is crucial to understand the implications of car-sharing practices on the vehicle’s end of life total mileage. To my knowledge, there is no data available on the lifetime mileage of the vehicles which take part in car-sharing services. Moreover, there were no studies found which show how the change in VKT driven by a car affects its expected lifetime. As for this study, two direct parameters, wear & tear and outdatedness, and two indirect parameters affecting the former, age and mileage, were chosen to describe the system, and a justification of this choice will be discussed later in the paper.

Modes
Even though the described TS with its stocks and processes is generalized and applicable to all four modes of transportation (private car, car-sharing, bus, rail), it is important to understand that various modes will actually have different vehicles, infrastructure, fuels and energy involved in the processes. Thus, a complete picture of the GHG emissions by TS use will be achieved after reapplying the LCA and summarizing the resulting emissions from all the modes present under the collective profile under investigation.
GHG emissions

Formally, GHG emissions stock is not part of the TS, however, it is connected to the extended TS so that GHG emitting processes are linked to their output explicitly. The total yearly GHG emissions under a given collective profile (CP) will be later calculated as:

\[
E_{CP} = e_{car} \times TVK_{car} + e_{cs} \times TVK_{cs} + e_{bus} \times TVK_{bus} + e_{rail} \times TVK_{rail}
\]

Here, \(e_{mode}\) are the per kilometre emissions of a particular mode resulting from its LCA, and \(TVK_{mode}\) are the total vehicle kilometers travelled by the same mode within the system in a year.

Average versus marginal emissions

It is crucial to understand that the extended transportation system under consideration is a dynamic system whose stocks, processes, and parameters are constantly changing. In general, there are two types of LCA: attributional or ALCA and consequential or CLCA (Brander & Tipper, 2008).

The former is a static snapshot of the system at a particular moment, and ALCA assesses systems total emissions at that moment. This is exactly what the, fundamental for my analysis, Chester’s 2008 study does. For instance, single car’s manufacturing GHG emissions are calculated as a portion (using the Economic Input Output LCA approach) of the total sector’s emissions in the US at a particular time. This result does not reflect the dynamics of the system as the number of the vehicles manufactured is actually changing all the time. Moreover, ALCA does not reflect individual characteristics behind manufacturing various cars as it focuses on the average manufacturing emissions instead. Finally, when calculating the emissions for the functional unit, total manufacturing emissions will be divided by the average mileage of a car in the US. Similarly, for other stages of the LCA inventory. As a result, this type of LCA allows for a complete picture of life emissions; however, it represents results in averages across the system at a static state of the system.
The latter type of the assessment, CLCA, compares outcomes of the systems at two different moments to account for changes happening in the system. As CLCA focuses on the difference in emissions between two different states of the system in time rather than the total emissions, only these elements of the system which changed could be taken into account. Moreover, as CLCA focuses on the changes it tends to use the marginal data instead of the averages. In other words, it allows to observe a marginal change in total emissions relative to the original state of the system after one additional unit of change was introduced, for instance, an additional kilometer of the total bus VKT driven by the public yearly. Per kilometer emissions (per-VKT) of such additional value is the marginal cost which is in most cases different from the average per-VKT emissions in the original and the resulting systems. It was argued that such an approach is not usually feasible for such complex transportation systems (Chester, 2008).

Nevertheless, as my study aims to understand the environmental implications of individual behavioural change such as an increased car-sharing use within the TS (rather than system-wide averages), a simplified approach to CLCA is proposed.

**Individual profile dynamics and personal transportation emissions**

Each individual profile is characterized by a set of distances travelled by the user by each mode of transportation within the system (PKT). As a result, a CP is formed which is characterized by the total PKT travelled for each mode as well as the vehicle access and occupancy parameters averaged across all the IP for each mode. LCA based on such averaged CP is inherently an attributional LCA and its results are the per-PKT emissions of the ‘average’ user of that static moment (2008 assessment in the US in our case). Nevertheless, the distribution of all the individual users already exposes us to a variety of behavioral profiles. Instead of focusing on the challenging task to assess the marginal changes of emissions in the system caused by one user A changing their profile from A to A′ (CLCA), that user’s initial profile A could be contrasted with any other user B from the same original static ALCA whose profile is equal to A′. Specifically, modes distances of each user will be multiplied by the per-PKT averages from the initial analysis to compare their contributions to the total GHG emissions.
In other words, instead of asking the question of *how individual profile dynamics (transportation behaviour) will affect total emissions of that user in time* I will ask the question *how does the estimate of the total individual emissions of a user differ from the emissions of other users from the same time?* Ultimately, this allows to access our personal mobility behaviour from the environmental perspective contrasting us to other individuals. It is important to acknowledge that such individual emissions estimations, based on the average per-PKT values, assumes a positive linear relationship between distances travelled by various modes and the resulting emissions. Hence, a formula to estimate personal per-PKT emissions under a given individual profile IP is:

\[ E_{IP} = e_{PKT_{car}} \times VKT_{car} + e_{PKT_{cs}} \times VKT_{cs} + e_{PKT_{bus}} \times VKT_{bus} + e_{PKT_{rail}} \times VKT_{rail} \] (0)

Comparing emissions behind two individual profiles \( E_A \) and \( E_B \), we will be able to make accurate inferences about environmental (GHG) implications of the behavioral change induced by car-sharing participation.

**Environmental impacts of car-sharing: previous studies**

Research on environmental consequences of car-sharing and of the sharing economy field in general is scarce. It was argued that, even though sharing platforms operators such as AirBnb or Zipcar as well as the media tend to depict such platforms as being inherently more sustainable, the real implications of such sharing are far more complicated and not well investigated (Schor, 2014).

For instance, it was shown that peer-to-peer second-hand platforms could facilitate both positive as well as negative environmental impacts as some users will actually increase their goods consumption as such platforms provide with more affordable and easy to resale goods (Parguel, Lunardo, & Benoit-Moreau, 2017). Similarly, it could be argued that for car-sharing platforms various types of behaviour could be possible. For instance, peer-to-peer car-sharing hosts could be incentivised to own their cars even more as renting them out offsets some costs. Other users will find driving more affordable, as a result offsetting their public transportation
use (Parguel et al., 2017). Previous European and American studies show that only a small fraction of car-sharing users actually decrease their emissions; nevertheless, the average effect is still positive because of the magnitude of these positive changes versus the negative changes (Martin & Shaheen, 2011; Nijland & van Meerkerk, 2017). However, such results express the average user-wide effects of car-sharing whereas individual behavioral implications are left unstudied. Moreover, analysing such previous research allowed me to identify three common significant weaknesses which arguably didn’t allow previous studies to assess environmental impacts correctly.

Modal shift and distances travelled

It is important to quantify distances travelled by a user in various modes of transportation before and after the start of car-sharing use to assess environmental impacts completely. Many studies have shown that for some participants car-sharing leads to behavioral changes in distances travelled by various modes of transportation, and the latter effect is of our particular interest. Most of the studies which quantify the effects of car-sharing on the modes and distances travelled have conducted surveys which compare individual’s habits before or at the very beginning of participation in a car-sharing program and some period later in the program.

Cervero et al. surveyed station-based car-sharing service members in San-Francisco and showed that between 2003 and 2005 their daily car-VKT decreased by 38% (Cervero, Golub, & Nee, 2006). Nevertheless, this result explicitly neglected VKT changes in other motorized modes of transportation as they (other modes’ vehicles) were taken as pre-existing. It has been discussed in my paper that the transportation system is dynamic and accommodates, including its public transport fleet, to the public demand in time. Thus, it is important to account for the impacts induced by all the modes travelled in the system.

Similarly, a 2010 report concluded an impressive decrease in carbon emissions based on the average 31% decrease in driving and an impressive replacement of each 15 personal cars by only one car-sharing vehicle (Frost & Sullivan, 2010). However, our systems approach to GHG emissions assessment suggests that it is not appropriate to ignore emissions from the
substitute modes of transportation as well as to account for the manufacturing emissions of cars without doing this for other modes.

Finally, one of the most prominent research groups in the field in North America, Transportation Sustainability Research Center from University of California, Berkeley, studied free-float car-sharing platform Car2Go and its impacts on participants behaviour (Martin & Shaheen, 2016). The report estimated a significant average decrease in VMT driven by the participants induced by the reported number of sold and suppressed vehicles, those which would be bought if car-sharing wouldn’t exist. These estimations were approximated by the average annual mileage of the sold vehicles. However, it was never surveyed if these previously driven miles had been substituted by other cars in possession or other modes of transportation at all. Instead, these previous miles were rather considered as being removed from the average member’s annual mobility pattern after a year of car-sharing participation.

It is important to acknowledge that this study as well as several others attempted to include modal shift effect in their assessment; however, it could be argued that such trials were not conducted properly. Aforementioned iconic Martin and Shaheen’s study (together with their earlier 2011 study) surveyed Car2Go users participants by questioning them if they changed their use of other modes of transportation after they started using the car-sharing platform (Martin & Shaheen, 2011, 2016). Nevertheless, the answers proposed were a set of ordinal values (no change, increased, decreased), whereas behavioral changes in VKT driven after car-sharing participation were measured in cardinal values (exact distances). The authors have found that there was no significant reported change in public transportation use on average and accounted for no significant effects of such. Nevertheless, even though users on average reported increase in car use (in ordinal sense), authors have surveyed and estimated cardinal surveyed distances driven by users before and after car-sharing participation and found out that a small proportion of users offset that increase by a substantial and overweighing reduction in their car-VKT. Such discrepancy between car and other modes assessment approaches in their “before-and-after” analysis leads to a fundamental gap. For instance, two users who reported opposite answers (increased, decreased) in rail use would cancel each
other’s effects out even if one of them would have increased their distances travelled by rail much more significantly. At the same time, changes in distances driven by cars are estimated precisely.

One of the rare but significant European studies on car-sharing environmental impacts conducted by the Netherlands Environmental Assessment Agency does not commit this mistake and calculates (based on a survey) real distances travelled by other modes of transportation before they had been replaced by car-sharing kilometers (Nijland & van Meerkerk, 2017). However, they do not check if the average decrease in reported 1,750 annual kilometers driven were replaced by increased distances driven by other modes – another fundamental gap.

To summarise, to my knowledge, none of the previous American and European studies which estimated environmental impacts of car-sharing participation properly assessed modal shifts effects of such. Studies either have quantified changes in distances travelled by cars but not the other modes or did not do that completely, assuming that users merely reduced their total distances travelled, which could be seen as unlikely. However, strong positive environmental impacts of car-sharing in these studies was mainly attributed to a significant decrease in driving, again, neglecting changes in the use of other modes. To account for such changes, proper surveys which question changes in distances travelled by all the modes (motorized and non-motorized) should be conducted. In the scope of this study, to favour a complete analysis only several possible scenarios will be proposed and discussed. The individual profiles described earlier and the total emissions associated with them implicitly resolve this issue as they account for the VKT for all the different modes involved in the individual’s mobility patterns.

**Vehicle ownership**

It was shown that non-operational stages (manufacturing, infrastructure) of a vehicle life are significant for an accurate and complete environmental assessment (Chester & Horvath, 2009). Earlier in the paper, I argued that to keep environmental assessments of the car-sharing participation complete and balanced, we would need to account for the individual contributions or the portions in ownership for all the modes, including public, which are
accessed by the user, not only personal cars. However, such “ownership focused” approach appears to be impractical for environmental assessment, and a more adequate “access based” lens was proposed for our analysis. There is no doubt that a purchase of a new personal car acts as a clear and immediate contribution to private ownership and, logically, suggests responsibility for additional manufacturing emissions, whereas increased use of a particular mode of public transportation does not suggest such. Nevertheless, it could be argued that the car, the same as a bus, was already manufactured and existing in the TS and would be bought or used by a different user anyway, and what really defines our environmental responsibility is the choice to access and to use a particular mode. I argued that a constantly adapting TS, with a delay, will adjust the number of vehicles manufactured given the current demand, equally for private and public vehicles. Thus, it seems to be accurate not to focus on the car ownership and its non-operational environmental impacts (manufacturing, etc.) exclusively but to all the modes of transportation under consideration together.

Nevertheless, there were no studies found which take into account non-operational emissions for all the modes of transportation accessed by the respondents. The aforementioned Dutch study is the only one which does account for reduced manufacturing and demolition emissions associated with a lower ownership and higher vehicle sharing rates by the car-sharing users, yet, not for the other modes under their consideration (Nijland & van Meerkerk, 2017). Moreover, this study attributed all the shed vehicles (sold before the car-sharing membership) to the decrease in manufacturing emissions, even though it was shown before that majority of shed vehicles by car-sharing new members were, actually, close to their end of life already (Martin, Shaheen, & Lidicker, 2010).

To summarize, to my knowledge, none of the existing car-sharing studies fully considered non-operational emissions related to a changing user’s behaviour in accessing various modes. As the proposed LCA suggests, non-operational components of the total emissions for each mode will be reflected in its per-VKT emissions. Thus, the proposed comparison of the total personal emissions under different individual profiles will implicitly account for the changes in non-operational emissions expressed in changing distances travelled by various modes.
Vehicle Lifetime

Increased access to the same vehicle that car-sharing facilitates could sharply affect the mileage of such a vehicle, which is not usually the case for public transport. Arguably, this could either affect the lifetime (LT) of the shared vehicles and, consequently, the rates of their manufacturing or the lifetime mileage (LTM) of the shared vehicles changing their per-VKT emissions as a result, or even both. In any case, it is important to understand the implications of car-sharing on the LTM to be able to compute per-VKT emissions accurately for car-sharing use. Nevertheless, to my knowledge, this important question was never brought up within the studies that have quantified environmental impacts of car-sharing behaviour.

The only existing LCA meta-analysis of car-sharing acknowledged a possibility of a faster wear and tear, however, the authors used that idea to explain a better fuel efficiency of the shared vehicles only (Chen & Kockelman, 2016). Similar positive environmental impacts induced by a more frequent shared vehicle replacement were suggested by other studies (Meijkamp, 1998). Mont, in her 2004 study, reported that car-sharing vehicles are usually sold to private owners in 2-3 years after in shared use (Mont, 2004). Mitropoulos et al. in 2014 suggested that this is closer to 1-2 years and reported 18,000 mi yearly mileage for the shared vehicles versus 11,300 mi for the average private vehicle in the US assuming the same 10.6 years average lifetime (Mitropoulos & Prevedouros, 2014). Other than that, Oguchi et al. in their study showed that vehicle’s LT varies significantly from country to country and, hence, should be considered for the LCA of such for different geographical regions (Oguchi & Fuse, 2015). Interestingly, the Dutch study assumed a constant LT and LTM for shared and private vehicles to be 15 years and 250,000 km correspondingly (Nijland & van Meerkerk, 2017), however, it quantifies vehicle’s manufacturing emissions indirectly through their proposed LTM based on a study with a very different LTM assumed (Nijland & van Meerkerk, 2017). This could be seen as an accidental but a significant misrepresentation of the non-operational emissions in their analysis. Moreover, the authors mistakenly multiply the average amount of the reduced vehicles per member (0.4) by the shared car ‘ownership’ (1/15) instead of adding these numbers. Accounting for only these two last misconceptions, the reductions in manufacturing emissions drop from the
proposed 125-281 to 142-186 kg CO2e per year which is an enormous difference relative to their final results of 236–392 kg CO2e per year reduction for the average car-sharing member. This clearly exemplifies, how sensitive results are to an inaccurate operation with the lifetime and its mileage of the vehicles under consideration.

Unfortunately, there is no data on the car-sharing vehicles LTM, especially given that shared vehicles are usually sold into the second-hand market and continue their lives as regular personal cars. Nevertheless, for the completeness of the following LCA, based on the studies mentioned in this chapter, various scenarios for car-sharing vehicles’ LT and LTM will be proposed and analysed.

Summary of the issues

To summarize, the following set of issues was identified in the previous studies on environmental impacts of car-sharing:

- Manufacturing (non-operational) emissions of the substitute modes ignored
- The actual VKT change versus ordinal change for the substitute modes misalignment
- Possibility that the decreased VKT previously driven by one vehicle were replace by a different private vehicle ignored
- Changes in LTM for shared vehicles ignored
- Numerical mistakes

Existing LCA of car-sharing

The only existing LCA for car-sharing is an important and an accurate study; however, it as a meta-analysis which is based on many partially inaccurate studies or assumptions listed above (Chen & Kockelman, 2016). Accordingly, it could be suggested that the results of that study are not accurate themselves and exhibit all of the issues discussed in the previous section.

That study involved similar LCA phases to those proposed in this paper: vehicle operation and manufacturing, fuel production, parking infrastructure, and the increased use of other modes. The concrete issues of an inadequate assessment of the usage (VKT) changes for the public
transportation modes were already discussed. In addition to that, authors mistakenly refer to the infrastructure manufacturing (mainly roadway construction) emissions from Chester’s study as ‘parking infrastructure’ (Chester, 2008). Interestingly, parking infrastructure related emissions were, actually, shown to be very minor relative to other infrastructure related emissions in the M-LCA and, thus, were not considered in my analysis.

LCA: Inventory Analysis

Taking into account weaknesses of the previous studies, a Life Cycle Assessment of car-sharing participation (CS-LCA) will be proposed. The following Life Cycle Assessment of car-sharing is based on a modification of the discussed M-LCA (Chester, 2008). Importantly, a car-sharing mode will be added to the set of modes as a derivative of an automobile from the same study, however, with a higher level of sharing. Following that, a complete CS-LCA will be conducted based on the simulations of the car-sharing behavior defined by two different individual transportation profiles given before and after the participation.

To proceed with this task, I describe the LCAs for all the modes involved in the assessment separately. To repeat, the per-PKT emissions for each mode are defined as:

\[
e_{VKT_{mode}} = \frac{E_{LT_{mode}}}{LTM_{mode}} = e_{mode}
\]

\[
e_{PKT_{mode}} = e_{mode} / oc\cup_{mode}
\]

\[
E_{LT_{mode}} = E_{INFR} + E_{MANUF} + E_{FUELS} + E_{OP}
\]

The LCA inventory (LCAI) for each mode will be described separately.
Automobile (private and shared)

A regular sedan car is considered for an automobile example in this study. The average occupancy is taken as 1.58 passengers per vehicle based on the most recent Canadian Vehicle Survey (Statistics Canada, 2009). Emissions parameters were found in the M-LCA for the Toyota Camry 2005.

<table>
<thead>
<tr>
<th>LCAI</th>
<th>kg CO₂e per vehicle life private</th>
<th>kg CO₂e per vehicle life shared</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infrastructure construction</td>
<td>14000</td>
<td>14000</td>
</tr>
<tr>
<td>Vehicle manufacturing</td>
<td>8500</td>
<td>8500</td>
</tr>
<tr>
<td>Fuel production</td>
<td>0.061 * ( LTM_{\text{car}} )</td>
<td>0.061 * ( LTM_{\text{cs}} )</td>
</tr>
<tr>
<td>Vehicle operation</td>
<td>0.370 * ( LTM_{\text{car}} )</td>
<td>0.370 * ( LTM_{\text{cs}} )</td>
</tr>
</tbody>
</table>

*Table 1: LCA inventory (automobile). Source: M-LCA*

Lifetime mileage (LTM) does not affect the usage related per-VKT emissions (\( e_{\text{car}} \)) as the \( LTM_{\text{mode}} \) cancels out; however, it does affect the production related emissions (infrastructure and vehicle manufacturing). Within our LCA analysis, the automobile (car) and the car-sharing modes will be distinct in their corresponding LTM only. Thus, for an accurate comparison, it is crucial to understand how car-sharing services affect the LTM of their fleet.

Lifetime mileage (LTM) for private and shared automobiles

Drawing on the previous studies on vehicle lifetime determination, the following causal diagram could be suggested (Figure 5).

*Figure 5: Automobile’s lifetime mileage causal diagram*
First, a vehicle’s LTM is defined by the total lifetime (ages) multiplied by the annual mileage. In turn, an automobile’s total lifetime itself will be directly linked to its outdatedness (aesthetical obsolescence) and technical or physical condition (wear and tear, corrosion) as was suggested by previous studies (Meijkamp, 1998). Outdatedness is directly defined by the vehicle’s age, whereas its technical condition is defined by its age (corrosion) and the intensity of use (wear and tear). In addition to that, other parameters such as driver’s care or road accidents definitely affect vehicle physical condition. However, since car-sharing primarily affects the use intensity, I will focus on the usage parameter (annual mileage) first.

**Lifetime mileage: End-of-life predictors**

To check the hypothesis that the automobile’s total distance travelled rather than its age is a better predictor for vehicle’s end-of-life, I analysed the UK’s periodic technical inspection (MOT) vehicle database. This database allowed to track the same vehicle using their unique vehicle IDs from 2013 to 2015. As soon as a vehicle appeared at the test for 2013, failed it for that year, and never appeared back for the test within next two years, it was considered to be discarded (end of live vehicle - ELV). It was shown in a similar study that such an approach mitigates distortions because of the crashed or exported vehicles (Dun, Horton, & Kollamthodi, 2015).

In total, 156,838 ELVs were extracted from the 2013 dataset with an average age of 14.7 years and average mileage of 173,000 km. These data were balanced with non-ELVs from the same year to prepare for a logistic regression analysis.

In particular, two models with one independent parameter each were assessed - the age and the mileage of the vehicle, to predict the vehicle’s end-of-life status.

The results O could obtain witnessed that, even though both parameters had a statistically significant positive relationship with the ELV status (positive regressions coefficients and P-values lower than 0.05), none of them explained the variance of the dependent variable well enough (very low pseudo R-squared values).

The results are described in Table 2.
Unfortunately, such results do not allow to prove any hypothesis about explanatory power of the age and mileage for the end-of-life of the automobile. It could be argued that much more complex models involving various technical characteristics of a vehicle should be developed for an accurate explanation, as it was attempted in some recent studies (Kalmakov, Andreev, & Martyanov, 2017).

**Lifetime mileage: Possible scenarios**

Based on the proposed causal diagram and several previous studies, several possible scenarios for the $LTM_{car}$ and $LTM_{cs}$ will be proposed and discussed, as there is no data available on how car-sharing effects the total lifetime mileage of its fleet compared to private vehicles.

For an accurate comparison between the scenarios, a base private vehicle lifetime and annual mileage will be set to 15 years and 10,000 miles accordingly for all the scenarios. To obtain these specific values for private vehicles, results from several sources have been averaged (Table 3).

<table>
<thead>
<tr>
<th>Source</th>
<th>Age (years)</th>
<th>Annual mileage (mi)</th>
<th>$LTM_{car}$ (mi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Mitropoulos &amp; Prevedouros, 2014)</td>
<td>10.6</td>
<td>11,300</td>
<td>120,000</td>
</tr>
<tr>
<td>(Martin et al., 2010)</td>
<td>17.3</td>
<td>7,700</td>
<td>133,000</td>
</tr>
<tr>
<td>(Chester, 2008)</td>
<td>16.9</td>
<td>11,000</td>
<td>186,000</td>
</tr>
<tr>
<td>Average</td>
<td>15.0</td>
<td>10,000</td>
<td>150,000</td>
</tr>
</tbody>
</table>

**Table 3: Lifetime and lifetime mileage for an average private automobile in the US**

$LTM-S1$: ($LTM_{cs} \approx LTM_{car}$)

One possible scenario is to assume that vehicles which participated in car-sharing at some point in their life do not have a significantly different $LTM_{cs}$ compared to an average private ELV.
This could be the case if these vehicles are not used that 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 & tear) while the mileage increases faster (because of the higher use intensity) still being a strong determinant of the vehicle’s end-of-life. No evidence for neither situations was found as for now.

$LTM-S2: (LTM_{cs} \gg LTM_{car})$

The most natural to assume scenario is the increase of an average lifetime mileage for the car-sharing vehicles due to their more intensified use.

This will be the case if the annual mileage increase effect overweighs vehicle’s shrinking lifetime. A couple of studies supported this scenario. Meijkamp suggested that the car-sharing intensified use does not allow such age related causes as corrosion to effect a vehicle’s lifetime as fast as its wear & tear, and, as a result, the vehicle reaches its lifetime mileage potential more freely (Meijkamp, 1998). In addition to that, significantly higher annual mileages (18,000 mi vs 11,300 mi for a private vehicle) was reported for car-sharing vehicles; however, this data was not verified by other studies yet (Mitropoulos & Prevedouros, 2014).

Assuming 3 years shorter LT for this scenario, a car-sharing vehicle will accumulate $12 * 18,000 = 216,000$ mi before its end-of-life.

$LTM-S3: (LTM_{cs} \ll LTM_{car})$

Finally, it could be assumed that car-sharing 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 car-sharing platform logistics or more driving-conscious car-sharing members’ due to the participation’s explicit costs. Moreover, it could be speculated that the car-sharing vehicles have a significantly lower lifetime as they are sold to the second-hand market much faster, in
around 2 years (Mitropoulos & Prevedouros, 2014), and that this could possibly lower their LTM as well.

To check the first hypothesis, usage data of the free-floating car-sharing provider Car2Go in several North American cities was aggregated. The annual company’s report (Car2Go, 2017) was used for the fleet sizes, and Martin’s study was used for the total annual mileage for each city (Martin & Shaheen, 2016). The results are listed under the following Table 4.

<table>
<thead>
<tr>
<th></th>
<th>Calgary</th>
<th>Seattle</th>
<th>Vancouver</th>
<th>Washington D.C</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total VMT (annual)</td>
<td>5,221,000</td>
<td>6,126,000</td>
<td>9,108,000</td>
<td>3,624,000</td>
<td></td>
</tr>
<tr>
<td>Fleet size</td>
<td>630</td>
<td>750</td>
<td>1275</td>
<td>600</td>
<td></td>
</tr>
<tr>
<td>Mileage (annual, mi)</td>
<td>8287</td>
<td>8168</td>
<td>7143</td>
<td>6040</td>
<td>7410</td>
</tr>
</tbody>
</table>

*Table 4: Projecting car-sharing vehicle lifetime mileage from Car2Go data*

In addition to that, a very recent Car2Go press release reported 90 million kilometers driven by 14,000 Car2Go vehicles in 6 months (Car2Go, 2018). This translates to the 8,000 mi in annual mileage for car-sharing vehicles.

Thus, it could be assumed for this scenario that relatively lower annual distances (7600 miles) are driven by the shared automobiles during the same lifetime (15 years). This will total to 114,000 miles.

**Lifetime mileage: Scenarios overview**

To summarize the results, three scenarios for the total lifetime mileage of the shared sedan automobiles are proposed in Table 5.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Age (years)</th>
<th>Annual Mileage (mi)</th>
<th>LTMCS (mi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>𝐿𝑇𝑀𝑐𝑠 ≈ 𝐿𝑇𝑀𝑐𝑎𝑟</td>
<td>15</td>
<td>10,000</td>
<td>150,000</td>
</tr>
<tr>
<td>𝐿𝑇𝑀𝑐𝑠 ≫ 𝐿𝑇𝑀𝑐𝑎𝑟</td>
<td>12</td>
<td>18,000</td>
<td>216,000</td>
</tr>
<tr>
<td>𝐿𝑇𝑀𝑐𝑠 ≪ 𝐿𝑇𝑀𝑐𝑎𝑟</td>
<td>15</td>
<td>7,600</td>
<td>114,000</td>
</tr>
</tbody>
</table>

*Table 5: Overview of the three proposed scenarios for car-sharing vehicle lifetime mileage*
Buses

A common 40-foot bus is considered in this study. The average occupancy is taken as 10.5 passengers even though it varies significantly from 5 during off-peak and 40 during peak times. A bus’s $LTM_{\text{bus}}$ is taken as 500,000 miles. All these data as well as the emissions parameters are taken from the M-LCA (Table 6).

<table>
<thead>
<tr>
<th></th>
<th>LCAI</th>
<th>Emissions per vehicle life kg CO$_2$eq</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infrastructure construction &amp; operation</td>
<td></td>
<td>34,000</td>
</tr>
<tr>
<td>Vehicle manufacturing</td>
<td></td>
<td>160,000</td>
</tr>
<tr>
<td>Fuel production</td>
<td></td>
<td>$0.38 \times LTM_{\text{bus}}$</td>
</tr>
<tr>
<td>Vehicle operation</td>
<td></td>
<td>$2.4 \times LTM_{\text{bus}}$</td>
</tr>
</tbody>
</table>

Table 6: LCAI for a gasoline 40-foot bus (US). Source: M-LCA

Rail

These data have been taken from the M-LCA for a Light Rail train from the Boston Green Line with the average occupancy of 54 passengers, system’s total annual VMT of 3.3 mln. miles, fleet size of 144, and train’s LT of 27 years. Hence, one train’s LTM has been calculated as: $LTM_{\text{rail}} = \frac{(3.3 \times 27)}{144} = 620,000$ (miles), even though, in contrast to other modes, it will not affect our calculations as all the life-cycle components’ emissions are taken as per-VMT. Importantly, the fuel (energy) production component was omitted for this mode’s LCAI since I will use the more recent full-fuel-cycle emission factors for energy to emissions conversion. Specifically, such infrastructure and vehicle operation emissions will already include extraction, processing, transmission, and distribution emissions related to energy production and use.

<table>
<thead>
<tr>
<th></th>
<th>LCAI</th>
<th>Emissions per-VMT kg CO$_2$eq</th>
<th>Energy per-VMT MJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infrastructure construction</td>
<td></td>
<td>1.51</td>
<td>-</td>
</tr>
<tr>
<td>Infrastructure operation</td>
<td></td>
<td>-</td>
<td>14.3</td>
</tr>
<tr>
<td>Vehicle manufacturing</td>
<td></td>
<td>0.061</td>
<td>-</td>
</tr>
<tr>
<td>Vehicle operation</td>
<td></td>
<td>-</td>
<td>48.3</td>
</tr>
</tbody>
</table>

Table 7: LCAI for the Boston Green Line light rail (metro tram). Source: M-LCA
Energy related emissions (full-fuel-cycle)

The emissions behind infrastructure and vehicle operations are dependent on a particular energy source profile in the region of operation. For the Canadian provinces of Ontario (ON) and Alberta (AL) these are reported by the NEB of Canada (National Energy Board of Canada, 2016) (NL) by the Dutch state (Energie Beheer Nederland, 2018) See Table 8.

<table>
<thead>
<tr>
<th>Province</th>
<th>Uranium</th>
<th>Coal</th>
<th>Hydro</th>
<th>Natural Gas</th>
<th>Wind</th>
<th>Solar</th>
<th>Biomass</th>
<th>Petroleum</th>
</tr>
</thead>
<tbody>
<tr>
<td>ON</td>
<td>58%</td>
<td>-</td>
<td>23%</td>
<td>8%</td>
<td>8%</td>
<td>2%</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td>AL</td>
<td>-</td>
<td>47%</td>
<td>3%</td>
<td>40%</td>
<td>7%</td>
<td>-</td>
<td>3%</td>
<td>-</td>
</tr>
<tr>
<td>NL</td>
<td>1%</td>
<td>14%</td>
<td>-</td>
<td>40%</td>
<td>1%</td>
<td>1%</td>
<td>4%</td>
<td>39%</td>
</tr>
</tbody>
</table>

Table 8: Energy sources profiles. Sources: NEB Canada, EBN Nederland

Given the energy sources profile for a particular region, the following full life-cycle emissions factors for energy production and distribution by different energy sources are used to calculate the average emissions factor for each region (Schlomer et al., 2014). Petroleum’s emissions were not found and were taken as for the biomass (Table 9).

<table>
<thead>
<tr>
<th>gCO2eq/kWh</th>
<th>Nuclear</th>
<th>Coal</th>
<th>Hydro</th>
<th>Natural Gas</th>
<th>Wind</th>
<th>Solar</th>
<th>Biomass</th>
<th>Petroleum</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>820</td>
<td>24</td>
<td>490</td>
<td>11</td>
<td>44</td>
<td>230</td>
<td>230</td>
<td></td>
</tr>
</tbody>
</table>

Table 9: Full-fuel-cycle electricity emissions factors. Source: Schlomer et al., 2014

As a result of multiplying these two data sets, the average emissions factor for Ontario weighted by its energy profile is 58 gCO2 eq per a kWh of energy used, and 590 gCO2 eq for Alberta. For the Netherlands this comes to 410 gCO2 eq per kWh of energy (will be needed for the following analysis).

For the province of Quebec the life-cycle emission factor was found to be 21 gCO2 eq (Hydro-Québec, 2014). For the US states, energy life-cycle emissions are taken from the previous report (Leslie, 2014): 538 gCO2 eq for a kWh of energy produced in Massachusetts, 327 gCO2 eq in California, 39 gCO2 eq in Vermont, 1397 gCO2 eq in Washington D.C., and 50 gCO2 eq in Washington state.
Non-motorized transport

According to the European Cyclists' Federation’s report, cycling is responsible for CO2 emissions of 21g per-VKT, including the bicycle production, maintenance and fuel (Blondel, Mispelon, & Ferguson, 2011). Emissions from walking were considered to be zero in this study.

Summary of the per-PKT emissions

Taking into account all the data collected and the formulas (1)-(3) in the page 27, the following per-PKT results emerged for all the modes under consideration, including three LTM scenarios for car-sharing vehicles (Figure 6).

Figure 6: per-PKT emissions for various modes of transportation resulting from my CS-LCA. Includes three car-sharing vehicle LTM scenarios. Average occupancy is considered.
LCA: Application results (case studies)

To understand the complete picture of car-sharing participation environmental effects, two individual profiles - before and after/during participation, with all the distances travelled by all the modes should be available for comparison. However, as to my knowledge, there were never surveys conducted on how car-sharing participation affects the distances travelled by various motorized and non-motorized modes in their cardinal values. As discussed in the previous chapters, existing studies surveyed a modal shift caused by the CS in the ordinal sense values (less, more, etc) rather than distances. Nevertheless, to be able to make some inferences about potential effects, three possible scenarios (case studies) will be explored.

The Netherlands case study

Nijland and colleagues showed that the average Dutch car-sharing participant (B2C and P2P platforms averaged) drives 1750 km/year less, and the authors surveyed participants on how their CS related VKT would be travelled otherwise, in the absence of the service (Nijland & van Meerkerk, 2017). The reported car-sharing substitution profile is shown below (Table 10).

<table>
<thead>
<tr>
<th>Mode of transport</th>
<th>Kilometres (in%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car</td>
<td>34</td>
</tr>
<tr>
<td>Train</td>
<td>41</td>
</tr>
<tr>
<td>Bus, tram, rapid transit</td>
<td>4</td>
</tr>
<tr>
<td>Bicycle</td>
<td>3</td>
</tr>
<tr>
<td>Car passenger</td>
<td>1</td>
</tr>
<tr>
<td>Other</td>
<td>2</td>
</tr>
<tr>
<td>Not travelled</td>
<td>15</td>
</tr>
</tbody>
</table>

*Table 10: Car-sharing substitution in the absence of the service. Source: (Nijland & van Meerkerk, 2017)*

This, unfortunately, does not present a whole picture of the modal shift as this information does not reveal how the distances travelled by other modes previously changed because of the CS participation, as if the users started travelling less in general. This assumption could be seen as unlikely, and for this scenario (the same as for the other two) the decreased driving distances will be projected on other modes of transportation using exactly the same results for the
hypothesis car-sharing substitution answers. The results of such extrapolation are shown on
the following Figure 7.

![Figure 7: Extrapolating 'before' and 'after' participation modal annual distances travelled by car-sharing members based on the reported substitution profile from Table 10 for Dutch car-sharing survey. Distances travelled by all the modes (except car and CS) are relative rather than absolute.](image)

Specifically, the ‘before’ bar in addition to the car was complemented by a set of alternative
modes which would be taken in the absence of CS kilometers (from the survey). Similarly, the
‘after’ bar was complemented with the modes travelled as a substitute for the avoided car
driving extrapolated based on the same respondents’ substitution profile. Two bars are of a
different length as users reported that 15% of the trips would not happen in the absence of the
CS service (hence, extrapolated similarly for the ‘before’ private driving substitution).

To conclude, differences in the total distances travelled by each mode were calculated and
multiplied by the per-PKT emission factors from our CS-LCA (Table 11).

<table>
<thead>
<tr>
<th></th>
<th>Car</th>
<th>CS</th>
<th>Train</th>
<th>Bus</th>
<th>Bicycle</th>
<th>Carpooling</th>
<th>Other</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>VKT change (km)</strong></td>
<td>-3610</td>
<td>1850</td>
<td>1093</td>
<td>107</td>
<td>80</td>
<td>27</td>
<td>53</td>
<td></td>
</tr>
<tr>
<td><strong>Emissions per-PKT (gCO2 eq)</strong></td>
<td>228</td>
<td>210-247</td>
<td>101</td>
<td>187</td>
<td>20</td>
<td>144</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td><strong>Total emissions change (kg)</strong></td>
<td>-823</td>
<td>422</td>
<td>110</td>
<td>20</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td><strong>-261</strong></td>
</tr>
</tbody>
</table>
Table 11: Total change in annual emissions for each mode based on the projected Dutch car-sharing behavioral scenario

Here, train per-PKT emissions were calculated using the CS-LCA using the previously mentioned electricity emissions factor for the Netherlands. Carpooling per-PKT emissions were taken as regular car emissions adjusted for 2.5 occupancy rather than 1.58 occupancy. Per-PKT emissions for ‘other’ modes was averaged across other modes and halved to account for walking (zero emissions). Car-sharing per-PKT emissions were set as a range based on the three CS lifetime mileage scenarios for sensitivity analysis (discussed in the previous section).

As a result, an annual decrease in 226-295 kg of CO2 eq. is estimated (depending on the car-sharing LTM scenario), 261 kg of CO2 eq. for the first LTM scenario. This decrease could not be presented as the percentage from the pre-CS emissions as distances for all modes (except the car and CS) are not absolute but rather relative to the post-CS state. Interestingly, the lower (conservative) bound of my result is very close to the results obtained in Nijland’s study (236-392 kg of CO2 eq. per year) whereas the upper bounds differ significantly. This could be explained by the fact that the average CS user’s mobility behaviour relies heavily on driving anyway which use-phase emission dominate the cycle and are accounted for in both cases. However, more careful estimations of the non-operational emissions for various modes as well as the modal shift factors allowed us to show a more modest emissions reduction range.

Several important limitations of the proposed scenario should be mentioned. Firstly, the US-based per-PKT emissions estimates were applied to a, possibly, different Dutch transportation system (vehicles, infrastructure, occupancy, etc). However, this will allow us to compare our CS-LCA model on various scenarios. Secondly, two individual profiles under consideration (before and after) are the representation of the average Dutch CS member and of the cumulative impact of car-sharing. Any individual emissions estimations will vary significantly across the user base. Finally, the car-sharing substitution profile considered here reports otherwise preferred modes of transportation on a per-trip basis rather than the exact distances for the alternative modes. Because of this uncertainty, it was assumed that the change in annual car distances is uniformly distributed between alternative modes weighted using the substitution profile.
A different possible approach is to reconstruct the absolute values for annual distances travelled (for all the modes) by the CS members. It was reported that Dutch citizens travel 11,000 km per year on average (Statistics Netherlands, 2016). Out of this number, 51% (5610km) by car, 22% (2420km) as a passenger (carpooling), 9% (990 km) by train, 9% (990 km) by bicycle, 3% (330 km) by bus, 3% (330 km) walking, and 3% (330 km) by other modes (Figure 8).

Here, carpooling will be considered as an extension of car driving as its form was not specified. Given the amount of driving and car-sharing before and after participation in the survey, the rest of the distances for other modes were extrapolated to satisfy the national modal distances’ distribution as much as possible. The ‘before’ distances distribution was extrapolated based on a surveyed distance for a car (73% of the total). The resulting annual mileage (12,630 km) appeared to be slightly greater than the reported national average. Then, all the modes except the automobile modes for the ‘after’ condition were extrapolated proportionally to achieve the same annual total mileage (except some CS trips which reportedly would not happen). Hence, this time the ‘after’ participation appeared to become longer than the initial one (Figure 9).
As a result, total reduction in annual emissions because of the such reconstructed mobility behaviour change were estimated to be 212 – 282 kg of CO2 eq. (247 for the middle LTM scenario) which translates into 9 – 12 % reduction relative to the ‘before’-participation mobility profile (Table 12).

<table>
<thead>
<tr>
<th>Mode</th>
<th>Total emissions change (kg)</th>
<th>VKT change</th>
<th>Emissions per-PKT (gCO2 eq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car</td>
<td>282</td>
<td>-3610</td>
<td>228</td>
</tr>
<tr>
<td>CS</td>
<td>422</td>
<td>1850</td>
<td>210 – 247</td>
</tr>
<tr>
<td>Train</td>
<td>69</td>
<td>679</td>
<td>101</td>
</tr>
<tr>
<td>Bus</td>
<td>42</td>
<td>226</td>
<td>187</td>
</tr>
<tr>
<td>Bicycle</td>
<td>14</td>
<td>679</td>
<td>20</td>
</tr>
<tr>
<td>Walking</td>
<td>0</td>
<td>226</td>
<td>0</td>
</tr>
<tr>
<td>Other</td>
<td>29</td>
<td></td>
<td>127</td>
</tr>
</tbody>
</table>

Table 12: Total change in annual emissions for each mode based on the projected Dutch car-sharing behavioral scenario (absolute annual distances reconstructed)

In any case, behavioral change in driving has the most significant magnitudes of change of the total emissions (Figure 10).

Figure 10: Sensitivity analysis for the three lifetime mileage scenarios on the basis of the Dutch car-sharing related mobility behavioral change (before-and-after annual emissions comparison).
San-Francisco case study (City CarShare)

Another rare study which gives at least some hints on how CS-user distances travelled by other modes is the Cervero and colleagues’ survey on how station-based car-sharing service CarShare in San-Francisco impacts automobile, public transport and non-motorized travel (Cervero & Tsai, 2003). Similarly to other studies, it did not survey the exact change in the distances travelled; however, the authors reported around 1609 km of annual car-sharing mileage which constituted 10.1% of the total annual travel distance. In addition to that, the authors’ later 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 (Figure 11).

![Figure 11: Car-sharing substitution preference profile reported by the San Francisco CarShare platform members. Source: (Cervero & Tsai, 2003)](image)

All this data allowed me to reconstruct the following scenario for the before-and-after individual profiles (Table 13).

<table>
<thead>
<tr>
<th></th>
<th>Before CS (km)</th>
<th>During CS (km)</th>
<th>Change (km)</th>
<th>per-PKT (g)</th>
<th>Emissions (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS</td>
<td>0</td>
<td>1609</td>
<td>1609</td>
<td>210-247</td>
<td>367</td>
</tr>
<tr>
<td>Car</td>
<td>9774</td>
<td>4451</td>
<td>-5323</td>
<td>228</td>
<td>-1214</td>
</tr>
<tr>
<td>Train</td>
<td>1905</td>
<td>5257</td>
<td>3352</td>
<td>84</td>
<td>282</td>
</tr>
<tr>
<td>Bus</td>
<td>1905</td>
<td>2331</td>
<td>427</td>
<td>187</td>
<td>80</td>
</tr>
<tr>
<td>Bicycle</td>
<td>519</td>
<td>636</td>
<td>116</td>
<td>20</td>
<td>2</td>
</tr>
<tr>
<td>Walking</td>
<td>919</td>
<td>1125</td>
<td>206</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Other</td>
<td>426</td>
<td>522</td>
<td>95</td>
<td>125</td>
<td>12</td>
</tr>
<tr>
<td>Total</td>
<td>15448</td>
<td>15931</td>
<td>-470</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 13: Before-and-after annual modal distances estimation and emissions comparisons for the City CarShare member. The absolute annual distances reconstructed. Grey cells – from (Cervero & Tsai, 2003)
The ‘after’ car-sharing distances for all the modes (except the given CS and rail) were extrapolated using the mentioned substitution profile to achieve the same given annual total distance. Transit modes were divided equally between bus and train. The ‘taxi’, ‘rent a car’, ‘get a ride’, and the ‘drive myself’ options from the profile were combined under the car mode for our analysis. Interestingly, private car distances travelled in this scenario happen to be significantly lower than other modes such as train which was reported by the same studies for the member of the CarShare service in San Francisco. Moreover, it was previously reported that the average distance for the public transportation in San Francisco is greater than the average car trip distance (SFMTA, 2015). The distance driven before CS participation by cars was then obtained based on the previous statement that CarShare service decreased the average VKT for automobiles by 38%. Distances travelled before car-sharing participation by the rest of the modes were extrapolated using the same substitution profile. Noticeably, the total distance travelled after participation increased as there was a significant number of CS trips which would not happen in the absence of the service (30.1%).

As a result, similar to the previous scenario, emissions reduced because of the decrees in driving outweighed the emissions increase because of the more intensified public transportation use (Figure 13).

![Figure 12: Total change in annual emissions for each mode based on the projected San Francisco car-sharing behavioral scenario (three car-sharing vehicle LTM scenarios applied).]
A total decrease of 440 – 500 kg of CO2 eq. per member accounted for a 16-18% decrease relative to the pre-CS emissions.

**Sensitivity analysis (electricity production)**

As users of the car-sharing platforms show higher use of public transportation, it is important to understand how sensitive overall emissions are to environmental impacts of a particular mode. Electrified railroad emissions are especially sensitive to the local energy production profile. It was discussed in the previous section how life-cycle emissions factors for electricity use were calculated for various states in the US. Here, the CarShare service per average member annual emissions are recalculated for four US states. I speculate that the service became available in other cities of the country, and that the modal shift scenario for San Francisco would remain the same in other states. Here, only the first scenario for car-sharing vehicle life-time mileage (same as for a regular vehicle) was considered (Figure 14).

![Emissions change by mode (kg CO2 eq.) before-and-after comparison](chart)

*Figure 13: Electricity grid sensitivity analysis across four US states on the basis of the City CarShare (San Francisco) car-sharing related mobility behavior change (Table 13)*
It could be seen that 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. The resulting emissions change varies 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. The percentage changes of per-member annual emission relative to the pre-car-sharing mobility behaviour on four states are listed below (Table 14). Noticeably, it shows that the total annual mobility related emissions could even increase because of the car-sharing participation in case if the driving substituting modes are even more ‘dirty’ than driving.

<table>
<thead>
<tr>
<th>California</th>
<th>Vermont</th>
<th>Massachusetts</th>
<th>Washington D.C.</th>
</tr>
</thead>
<tbody>
<tr>
<td>-17%</td>
<td>-25%</td>
<td>-11%</td>
<td>+8%</td>
</tr>
</tbody>
</table>

*Table 14: Percentage change of the annual mobility related GHG emissions since car-sharing participation and the related modal shift. Applied to the City CarShare case for various electricity production profiles.*

North America (Car2Go)

The final case study I would like to discuss is based on the only other (except the Nijland study) existing research on car-sharing’s environmental impacts by Martin and colleagues. The study states some environmental benefits of free-floating Car2Go car-sharing service in North American cities (Martin & Shaheen, 2016).

The study reported was conducted in five cities, and I will build my scenario upon the Calgary case. The authors reported 12,429 VKT driven annually on average by a Car2Go member before car-sharing participation, an average 122 km of annual car-sharing distances for current members. Moreover, an average decrease of 898 km in private vehicle driving was estimated. An average annual decrease of 120 kg of CO2 eq. (4% from the pre-sharing emissions) was finally reported for Calgary.

Unfortunately, Martin’s study did not survey the average changes in distances travelled by other modes, and their users’ transportation preferences were not surveyed (as in the previous two scenarios). However, these could be approximated as a part of this scenario that will allow for the CS-LCA analysis. In particular, kilometers driven previously (before Car2Go participation) by automobiles were redistributed between the other four modes according to the previous
figures on a complete modal breakdown in Calgary (Behan & Lea, 2012). This allowed to account for a relative change in modal distances since CS participation. In addition, life-cycle electricity related emissions factor for the province of Alberta in Canada was used. The results of such a scenario analysis are listed below (Table 15).

<table>
<thead>
<tr>
<th></th>
<th>Before CS (km)</th>
<th>During CS (km)</th>
<th>Change (km)</th>
<th>Modal split</th>
<th>per-PKT (g)</th>
<th>Emissions (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS Car</td>
<td>0</td>
<td>122</td>
<td>122</td>
<td>228</td>
<td>28</td>
<td>83</td>
</tr>
<tr>
<td>Train</td>
<td>12429</td>
<td>11531</td>
<td>-898</td>
<td>228</td>
<td>-205</td>
<td></td>
</tr>
<tr>
<td>Bus</td>
<td>0</td>
<td>282</td>
<td>282</td>
<td>137</td>
<td>53</td>
<td></td>
</tr>
<tr>
<td>Bicycle</td>
<td>0</td>
<td>118</td>
<td>118</td>
<td>187</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Walking</td>
<td>0</td>
<td>118</td>
<td>118</td>
<td>20</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>133</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>12429</strong></td>
<td><strong>12453</strong></td>
<td><strong>24</strong></td>
<td><strong>100%</strong></td>
<td><strong>83</strong></td>
<td></td>
</tr>
</tbody>
</table>

Table 15: Before-and-after annual modal distances and emissions estimation and comparisons for the average Car2Go member in Calgary. The relative annual distances were calculated. Grey cells – survey data obtained from (Martin & Shaheen, 2016)

This results in 83 kg of CO2 eq. annual reduction per-member versus 120 kg of CO2 eq. claimed previously. Pre-car-sharing use of public transportation is unknown, and all the comparisons are relative; however, according to Martin’s study, 83 kg of CO2 eq. translates into 3% reduction of the total transportation related emissions induced by Car2Go participation of an average member.

**Sensitivity analysis (vehicle occupancy)**

For this scenario I would like to demonstrate how, nevertheless, sensitive the annual per-member emissions changes are to the occupancy levels of the public transportation which substituted the reduction in driving. Buses’ occupancy levels vary significantly which is a good base for such analysis.

In the proposed CS-LCA model, an average diesel bus with a 10.5 passenger occupancy was considered. Nevertheless, it’s 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 CO2 eq. Thus, it is not an accurate argument to consider public buses as universally more sustainable than automobiles in terms of the full life-cycle assessment.
The following chart (Figure 14) exhibits how annual per-member emissions changes vary depending on the average occupancy of the buses taken by the Calgary Car2Go user instead of driving (given constant other parameters).

It could be seen that the total per member emissions reduction ranges widely from 25 to 122 kg of CO2 eq. per year, an important phenomenon which none of the previous studies mentioned.
Individual Emissions Calculator

All the scenarios discussed are based on the data for the average car-sharing member. Nevertheless, previous studies underlined that car-sharing members are highly divided in their behavioral changes. The majority of the users actually slightly increase their total driving distances while a small fraction of members cut down on driving, significantly outweighing the negative environmental impacts of the other group (Martin & Shaheen, 2016; Nijland & van Meerkerk, 2017).

Hence, to evaluate environmental impacts of individual car-sharing members, personal data of a concerned user could be entered as an input into the proposed CS-LCA model. Moreover, as it could be seen already, environmental impacts are highly dependent on the other characteristics of the transportation system surrounding a particular car-sharing service area: types of vehicles involved, average occupancy of the modes, car-sharing vehicles’ life-time mileage effects, and the electricity grid in the area of application. All these parameters were included in the on-line tool (emissions calculator) interface for individuals and car-sharing providers to be able to evaluate their emissions according to the personal behavioral change or the exact conditions surrounding the practice (Amatuni, 2019).

Indirect Rebound Effects

The proposed CS-LCA allowed for an accurate life-cycle assessment of the environmental impacts of car-sharing participation accounting among others for direct rebound effects - increased consumption of various modes incurred by an introduction to the eco-efficient innovation (Frenken, Waes, Smink, & Est, 2017). Nevertheless, the indirect rebound effect, which is a potential to reinvest funds saved by the sharing service into different areas of consumption, could not be accessed using the CS-LCA model.

Thus, an interesting extension to the analysis is proposed here to be able to understand indirect rebound effects at least superficially. In particular, the following question will be asked: what are the per-dollar spent emissions for each mode of transportation? To understand those, it is
required to understand the average per-dollar spent distances travelled first. Infrastructure and
fuel production and operation related costs as well as governmental subsidies in such will not
be considered here. Seattle will be taken as a city for the purposes of such inter-modal
comparisons.

For a private car life-time total costs are calculated as:

\[
\text{TotalExpenses}_{\text{car}} = \text{Expenses}_{\text{year}} \times LT = 9,756 \times 15 = 146,340\,\$.
\]

The yearly amount includes average vehicle’s operation and includes its price, operation, and ownership costs in the US (BLS, 2017). The distance driven per dollar is calculated as:

\[
\text{DollarDistance}_{\text{car}} = \frac{\text{LTM}}{\text{TotalExpenses}_{\text{car}}} = \frac{150,000}{146,340} \text{ miles-per-dollar which equals to 1.65 kilometers per dollar spent.}
\]

For a car-sharing service, Car2Go example was taken as a base for calculation. Wang and
colleagues’ study surveyed Car2Go trips in Seattle and showed that the average trip cost $7.27
and involved 11 minutes of driving (Wang, MacKenzie, & Cui, 2017). Taking 35 km/hour as an
average driving speed, this cost translates into 6.4 km travelled. In addition to that, 113 km of
an average annual Car2Go travel was reported in the previous studies (Martin & Shaheen,
2016). There are no membership fees imposed by Car2Go membership in Seattle.

Hence, \( \text{DollarDistance}_{\text{cs}} = \frac{6.4}{7.27} = 0.88 \text{ kilometers per dollar spend.} \)

A bus ride, the same as a metro ride in Seattle costs $2.75. The average bus trip length was
reported to be 6.1 kilometers in the US (American Public Transportation Association, 2017). The
average light rail ride is 8.21 kilometers.

Hence, \( \text{DollarDistance}_{\text{bus}} = \frac{6.1}{2.75} = 2.22 \text{ kilometers per dollar spent.} \)

Hence, \( \text{DollarDistance}_{\text{rail}} = \frac{8.21}{2.75} = 2.99 \text{ kilometers per dollar spent.} \)

To obtain GHG emissions per dollar spend for each mode, the following formula is applied:

\[
\text{DollarGHG}_{\text{mode}} = \text{DollarDistance}_{\text{mode}} \times e_{\text{PKT}_{\text{mode}}}
\]
As a result, the following picture emerges:

<table>
<thead>
<tr>
<th></th>
<th>KM per $</th>
<th>g CO2 eq. per PKT</th>
<th>gCO2 eq. per $</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS</td>
<td>0.88</td>
<td>228</td>
<td>201</td>
</tr>
<tr>
<td>Car</td>
<td>1.65</td>
<td>228</td>
<td>376</td>
</tr>
<tr>
<td>Bus</td>
<td>2.22</td>
<td>187</td>
<td>415</td>
</tr>
<tr>
<td>Train</td>
<td>2.99</td>
<td>50</td>
<td>150</td>
</tr>
</tbody>
</table>

Based on that, it could be argued that in Seattle, car-sharing participation is the least environmentally friendly mode of transportation in terms of emissions per-PKT; however, it is one of the ‘cleanest’ modes of transportation in terms of the emissions per-dollar spent. Such approach is useful in case if we consider the total per-capita emissions related to a complete picture of the consumption habits given limited amount of funds for such. This allows to account for the indirect rebound effects behind modal shift involved in car-sharing activities, and this could be an interesting direction for further research in the field.

It is important to mention, that such analysis is highly sensitive to the regional transportation system parameters (trip costs and transportation life-cycle emissions).

**Discussion and conclusions**

To conclude, I would like to underline the achievements, the limitations, and the most important results of this study comparing those to the previous claims on the environmental impacts of car-sharing.

First of all, the place of car-sharing phenomena within the existing transportation systems was described from the systems perspective (Figure 3). Various observations from that point of view allowed me to justify approaching car-sharing as being analogous to a private car driving in terms of its LCA implications. Hence, car-sharing could have been incorporated into the existing LCA of transportation modes for the per-PKT emissions comparison.

The key parameter distinguishing car-sharing from personal vehicles (in the scope of the proposed TS and the annual LCA) was found to be shared vehicle’s average lifetime mileage. It was crucial to understand the car-sharing LTM for an accurate per-PKT comparison with other
modes. For that purpose, the UK vehicles database was analysed, and a logistic regression analysis was applied, unfortunately, with no strong evidence to predict a car’s lifetime through its total mileage in the result. Because of such proven uncertainty, three LTM for car-sharing vehicles were proposed and justified where possible using the existing evidence. This allowed to implement a LCA for four modes of transportation including car-sharing and compare the per-PKT GHG emissions of such (Figure 6).

These results, as well an accurate exploration of the mistakes from the previous studies on car-sharing environmental impacts, allowed me to justify the proposed comprehensive framework for understanding a complete picture of the environmental impacts of car-sharing induced by the behavioral change of its participants on an individual basis – Formula (0). Nevertheless, because of the absence of the actual individual data on such behavioral changes, three case studies in the Netherlands, San Francisco, and Calgary were taken and analysed as a base for the estimation of such missing mobility data (before-and-after distances travelled). The missing information was extrapolated and estimated from the existing sources where possible. Such quantitative analysis allowed for interesting comparisons with the rare several studies in the field. In addition to that, I have witnessed a strong sensitivity of such results that was never discussed in the previous studies (Table 16).

<table>
<thead>
<tr>
<th>Case study</th>
<th>Main Data Source</th>
<th>Prev. results</th>
<th>My results (LCA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Netherlands</td>
<td>Nijland &amp; van Meerkerk, 2017</td>
<td>-236 to -392</td>
<td>-226 to -295</td>
</tr>
<tr>
<td></td>
<td>Cervero &amp; Tsai, 2003</td>
<td>N/A</td>
<td>-440 to -500</td>
</tr>
<tr>
<td>Calgary</td>
<td>Martin &amp; Shaheen, 2016</td>
<td>-120</td>
<td>-83</td>
</tr>
<tr>
<td>LCA</td>
<td>Chen &amp; Kockelman, 2016</td>
<td><strong>33 – 67 %</strong></td>
<td>-</td>
</tr>
</tbody>
</table>

Table 16: Comparison of my results with the previous three studies and one LCA based car-sharing environmental impacts analysis. 33–67% (Chen & Kockelman, 2016) versus 10% annual reduction on average for 3 geographical case studies.
Results

In general, it could be seen that two existing partial environmental assessments (Martin & Shaheen, 2016; Nijland & van Meerkerk, 2017) concluded with greater emissions reduction than what my CS-LCA outputs on the same scenarios. More importantly, the only existing full LCA study of car-sharing life-cycle environmental impacts (Chen & Kockelman, 2016) had concluded 33 — 67 % for the emissions reduction rate whereas my analysis showed around 11% reduction rate only.

In addition to that, this paper shows how sensitive these results are to such factors such as public transportation occupancy levels, local energy production profiles, and the lifetime mileage of the vehicles involved in sharing. In some cases car-sharing activities could result even in higher total annual mobility related emissions (Table 14).

Suggestions

In general, based on this analysis it could be suggested that car-sharing in its current forms depends significantly on the local conditions and the concrete individual behaviour of an individual using the service. One of the natural outcomes of this study happened to be a web-tool allowing for an individual mobility related emissions assessment. It allows to estimate user’s total life-cycle emissions based on the distances travelled by various modes. Moreover, car-sharing services could possibly use the platform to assess the environmental effects behind their members participation patterns based on a particular local specificity of future inquiries.

In addition, it could be argued that on average, car-sharing does not exhibit significant environmental improvements given the constant amount of the total VKT (by all the modes) since the LCA emission are mostly dominated by the use phases of the transportation modes (Figure 6). This suggests that car-sharing could itself be considered an optimization tool rather than an inherently more sustainable mode of transportation. It is quite obvious from this analysis to conclude that ride-sharing (higher vehicle occupancy, lower TVKT) should become the focus of a transition to a low-carbon mobility society instead.
There are several extremely successful examples of a transition to a low-carbon mobility society from the past which were initially enforced by rather critical circumstances on the global scale than a collective conscious will. For instance, even though cycling in the Netherlands constitute only 9% of the total kilometers travelled in the country, this is a rare result which not many of the countries in the world could boast about (Statistics Netherlands, 2016). Energy and oil crisis in the 70s pushed Dutch people switching to their bikes which eventually led to a significant infrastructural development initiated by the government to support such demands, and that eventually allowed the cycling culture to persist until nowadays, a long time after the crisis ended. On the other side of the planet, Cuba was experiencing an extreme shortage of oil after the collapse of the Soviet Union in the end of the last century. That pushed Cuban society to adjust its mobility habits significantly. Sharing rides with others in the community extensively as well as the continuous repair and reuse of vehicles let Cuba demonstrate another great example of institutional and behavioural change towards a more sustainable transport system based on sharing and extended life-cycle of the vehicles in use (Enoch, Warren, Rios, & Menoyo, 2004).

Limitations

It is important to acknowledge that several important limitations of this study were discussed in this paper. First, because of the absence of an individual behavioral data, the cases considered required a lot of approximation for the missing distances traveled by the CS users. In addition to that, the per-PKT emissions resulting from my CS-LCA were heavily based on the US transportation system’s data and could be very carefully reviewed before applying them to other jurisdictions. Moreover, it was noticed that the TS is a dynamic system which changes constantly; however, my ‘before-and-after’ analysis framework was actually based on the static snapshot of the American transportation system, assuming that the system does not change between the car-sharing members changing behaviors. More specifically, the impacts of the total amount of the vehicles and the intensity of their usage on the existing infrastructure production and maintenance were not considered. Moreover, differences between private and shared automobile fuel efficiency levels were not taken into account as well. Finally, it was
underlined that the per-KM functional unit of the LCA is not the only option, and it was even shown that per-dollar emissions for all the same modes present a very distinct picture on their ‘sustainability’.

Once again, this study provides with a very useful framework for future environmental assessments of car-sharing and allows for more accurate and less utopian claims on its environmental effects.
References


2013 Update.


https://www150.statcan.gc.ca/n1/pub/53-223-x/53-223-x2009000-eng.htm


