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Car Sharing as a Strategy to Address GHG Emissions in the Transport System: Evaluation of Effects of Car Sharing in Amsterdam

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Abstract: Shared mobility options, such as car sharing, are often claimed to be more sustainable, although evidence at an individual or city level may contradict these claims. This study aims to improve understanding of the effects of car sharing on transport-related emissions at an individual and city level. This is done by quantifying the greenhouse gas (GHG) emissions of the travel habits of individuals before and after engaging with car sharing. The analysis uses a well-to-wheel (WTW) approach, including both business-to-consumer (B2C) and peer-to-peer (P2P) car-sharing fleets. Changes in GHG emissions after engaging in car sharing vary among individuals. Transport-related GHG emissions caused by car-free individuals tend to increase after they engage in car sharing, while emissions caused by previous car owners tend to fall. At the city level, GHG emissions savings can be achieved by using more efficient cars in sharing systems and by implementing greener mobility policies. Changes in travel habits might help to reduce GHG emissions, providing individuals migrate to low-carbon transport modes. The findings can be used to support the development and implementation of transport policies that deter car ownership and support shared mobility solutions that are integrated in city transport systems.

Keywords: car sharing; GHG emissions; Amsterdam; travel behaviour; sustainability assessment

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1. Introduction

The transport sector is a significant contributor to climate change, due to its large emissions of greenhouse gases (GHG). In 2017, the sector generated 1.1 Gt of CO_2-eq, corresponding to about 25% of the total emissions in the EU. Seventy-two percent of emissions came from road transport, of which 44% was from passenger cars, 19% from heavy goods vehicles and buses, and 9% from light commercial vehicles [1]. This sector is also responsible for other negative effects, such as air pollution, noise, and traffic congestion [2,3]. Increasing urbanisation, affluence, and car ownership are exacerbating these effects [4,5].

The modalities of shared mobility are often seen as promising options for sustainable transport. Examples include bike, car, or ridesharing. Shared mobility gives access to a vehicle or space in a vehicle for a short period of time (hours or days). The user of the vehicle pays a fee for the time or distance travelled, meaning they are not burdened with the costs of ownership [6]. Car sharing has been reported to reduce car ownership and individuals' annual vehicle kilometres, and promote shifts to other forms of transport, such as walking, cycling, and public transport [7–10]. All these changes can potentially reduce transport emissions.

Studies with different scopes have quantified the environmental effects of shared mobility. For example, Amatuni et al. [11] used lifecycle assessment (LCA) to evaluate changes in GHG emissions attributed to individuals before and after becoming involved with car sharing, and Chen et al. [12] evaluated the effects of sharing a bike during its lifetime. Available studies measure the effects of shared mobility at an individual or organisational level, but they fail to provide a city-wide perspective [13]. There is therefore a need for sustainability assessments that capture the effects of shared mobility on the urban transport system, to enable development and implementation of effective transport policies.

The objective of this study was to assess potential changes in GHG emissions at an individual and city level, by considering changes in the travel habits of individuals who engage in car sharing. We also evaluate changes in emissions resulting from the implementation of environmental policies and adaptation of technology. The study is based on Amsterdam, and quantifies the total annual well-to-wheel (WTW) emissions of the city inhabitants, taking into account all available mobility options. WTW emissions correspond to the emissions caused during the use phase of any transport mode, including the emissions caused by fuel production and during the actual transport. We developed different scenarios to simulate changes in travel habits, implementation of environmental policies, and adaptation of technology.

This study contributes to the understanding of environmental consequences of car sharing at an individual and city level. We show that changes in individuals' transport emissions due to car sharing vary. When developing urban transport policies, comprehending and considering these differences is needed to ensure positive sustainability outcomes at the city level. We also contribute to the understanding of differences in emissions from different car-sharing schemes. The novelty in our study is the combined assessment of effects of car sharing, environmental policies, and technological adaptation.

2. Background

In recent years, many different modalities of shared mobility have emerged, including ride-hailing (e.g., Uber), car sharing (e.g., Zipcar), personal vehicle sharing (e.g., Getaround), sharing of bikes and e-scooters, car-pooling, and ride-splitting [8]. These have attracted attention on account of both potential sustainability gains [8,14] and losses [15]. This section contextualises different modalities of shared mobility, and reviews studies that explore changes in travel habits, vehicle ownership, and sustainability effects induced by car sharing in Europe.

2.1. Shared Mobility

Shared mobility includes a variety of modalities. Machado et al. [8] presented an overview of shared mobility in which they distinguished between car sharing, personal vehicle sharing, ridesharing, on-demand ride service, and bike sharing. Car sharing or business-to-consumer (B2C) car sharing is when several people have access to the same vehicle; these vehicles are owned by companies that rent per hour or per day [6]. In the case of personal vehicle sharing or peer-to-peer (P2P) car sharing, private individuals rent their vehicles to others and receive financial compensation in return. The transaction and matchmaking takes place via an IT platform [8]. Ridesharing refers to individuals sharing the same vehicle to travel because it is convenient due to their departure time and destination. These vehicles might be privately owned [16]. On-demand ride service is a similar service to taxis, where the driver owns the vehicle and picks up individuals, offering a flexible door-to-door service [17]. Bike sharing is when several people have access to the same bike, and e-scooter sharing is offered through a similar service to bike sharing.

B2C car-sharing fleets employ vehicles that are more efficient than the average national fleet. B2C car-sharing fleets are reported to be 10–20% more fuel efficient than the average national fleet [14]. However, to our knowledge, no study has described P2P car-sharing fleets, and few studies have compared fuel efficiencies and the environmental effects of P2P and B2C fleets in car-sharing schemes.2.2. Effects of Car Sharing at Individual Level

Car sharing usually induces changes in individuals' car ownership, total travel distances, and mobility modes [7,18,19]. These changes may imply a reduction in the GHG emissions, less road congestion, or reduced need for parking spaces [18,19].

Shaheen and Cohen [20] reported reductions in vehicle kilometres travelled (VKT) in Europe of between 20 and 45% due to car sharing. Wu et al. [21] found that new users of car sharing in London increased their VKM, while users who had been engaged for a longer period decreased their travel distances. According to Nijland and van Meerkerk [22], car-sharing users in the Netherlands reduced their annual distance travelled by 1750 km after engaging with car sharing. These avoided kilometres were previously travelled using private vehicles. They also estimated that 15% of the distance travelled in shared vehicles was travelled because users had access to shared vehicles. Changes in annual distance travelled after engaging in car-sharing vary among individuals. These varied effects in the annual distance travelled after engaging in car sharing are not generally acknowledged in the literature.

Car sharing also reduces car ownership. According to Gleave [23], new members of car-sharing schemes reduced their car ownership by between 34% and 47% in Scotland. In France, the reduction was estimated at 23% [24] and in Germany 7–15% [25]. Car sharing also postpones the purchases of new vehicles. For instance, in Scotland, 56% of the car-sharing users indicated they were less likely to buy a car [23].

2.2. Sustainability Consequences of Car Sharing

These changes in vehicle ownership and travel habits may have environmental implications. Some studies have quantified changes in transport-related emissions due to car sharing. In the Netherlands, individuals who joined car-sharing schemes avoided the emission of 236 to 392 kg CO_2-eq per year, due to reductions in kilometres driven and changes in their modal share [22]. A study by Amatuni et al. [11] estimated lower potential emissions savings in the same country, between 150 and 219 kg CO_2-eq. The difference in estimates is due to the scope of each study. Nijland and van Meerkerk [22] estimated the impacts only from the use phase, while Amatuni et al. [11] also included impacts of other life phases of vehicles. Both studies quantified changes for average individuals, so they did not capture the effects of car sharing concerning individuals with different travel habits, nor did they analyse the effects of car sharing at the city level.

Other studies have aimed to capture the environmental effects of car-sharing organisations. Migliore et al. [26] modelled the effects of car sharing in Palermo using the COPERT methodology, including vehicle characteristic and traffic variables, to compare private cars and car-sharing fleets. The latter showed potential saving in CO_2 emissions, 38%, if the shared fleet is used. In Lisbon, Vasconcelos et al. [27] modelled the impacts of car sharing involving different technologies: electric, diesel, and petrol. They also evaluated the emissions caused by relocation of the fleet. Relocation refers to when vehicles are moved around the city to locations where they are more likely to be hired. This means that, during the relocation process, the vehicle does not make any profit or transport passengers. Their findings showed that the fleet with the greatest environmental gains was the electric fleet, but only when it was not relocated. Another study performed in the same city found potential savings from car sharing of 35% to 65% in CO_2 emissions due to car sharing [28]. Findings from the studies in Lisbon differ due to methodological considerations when calculating impacts. These studies capture the potential savings generated by the operation of shared-mobility organisations over a given period of time. However, these findings do not represent the sustainability effects of shared mobility in the transport system at the city level, partly because they do not capture changes in user behaviour, such as modal share or annual distance travelled.

Overall, studies have assessed the sustainability outcomes of car sharing from an individual or organisational perspective. Consequently, they do not capture the potential impacts of car sharing at the city level. Most of these quantifications neglect the effects of car-sharing fleets with different characteristics, and they do not acknowledge that the consequences of car-sharing on the travel habits can vary among individuals.

Our study adds to the literature an assessment of the effects of car sharing at an individual and city level, capturing how the impact of car sharing varies according to individuals with different travel habits. We also explore the effects of two car-sharing fleets, B2C and P2P, and examine the implementation of environmental policies and adaption of technological development.

3. Data and Methods

We quantified possible changes in GHG emissions from passenger transport due to the availability of car sharing, and assessed the effects at the city level using Amsterdam as a case study. First, we estimated average travel habits, distinguishing between car-dependent and car-free individuals, based on the annual mobility survey by Statistics Netherlands. We then modelled changes in travel habits induced by the availability of car sharing, and estimated WTW of the available transport modes. Finally, we calculated the individual emissions of different travel habits in different mobility scenarios, and scaled up to city level (Figure 1).

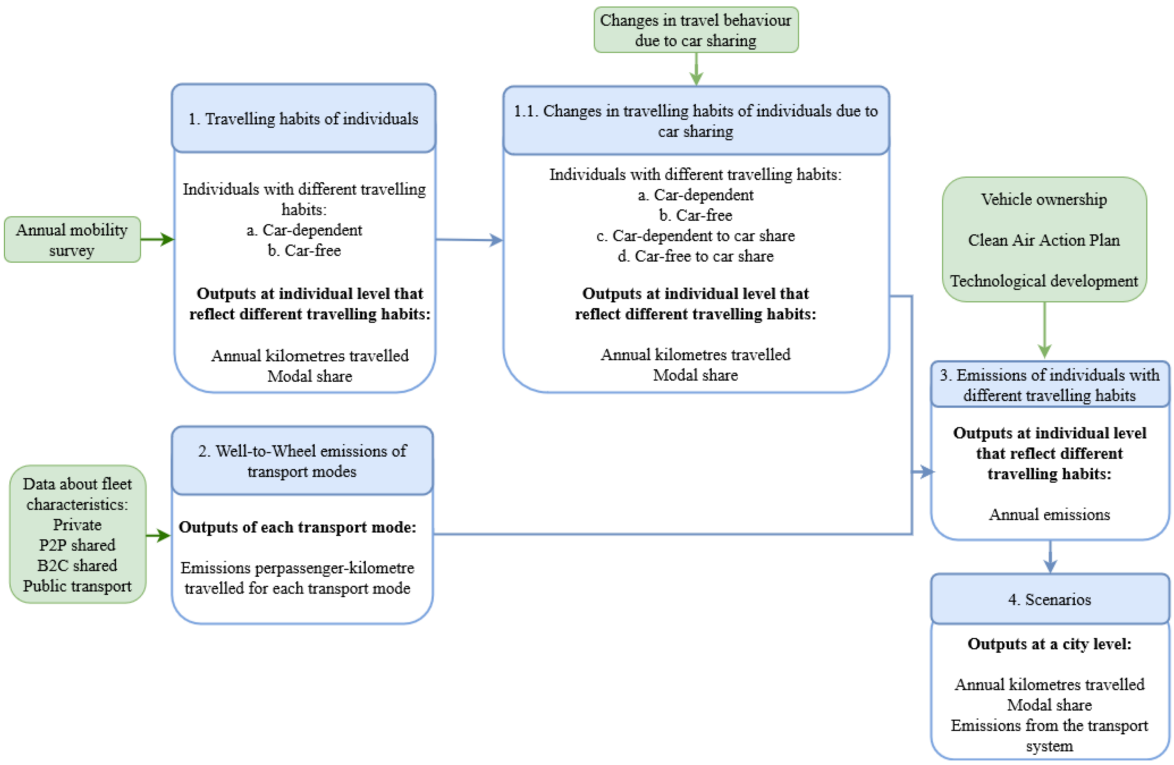

Figure 1. Method employed in the quantification of the greenhouse gases (GHG) emissions of car sharing at an individual and city level. Blue boxes are modelling steps and green boxes are data inputs.

3.1. Data

We estimated individuals' travel habits by using the mobility dataset ODiN2018, reflecting travel habits of the Dutch population in 2018, including transport modes and distances travelled [29]. We used the findings of Nijland and van Meerkerk [22] to estimate changes in individuals' travel habits after engaging with car sharing (explained in more detail in Section 3.2.2). Their study, based on a survey of users of car-sharing schemes in the Netherlands, aimed to capture travel habits after engaging in car sharing.

Estimates of WTW emission were based on public data of a B2C car-sharing organisation, GreenWheels [30], and proprietary data of a P2P car-sharing organisation. We modelled the baseline of the average national private vehicle fleet (vehicles that are not shared) using data on vehicle characteristics from public data sources in the Netherlands [31,32]. Other relevant data was obtained from Statistics Netherlands, such as vehicle ownership rates and demographics [33].

The scenarios were built in SimaPro using a Midpoint Hierarchical method, given that this method includes environmental effects that are science based. We used ecoinvent V3 to account for emission factors from well-to-tank (WTT). We accounted for emissions from tank-to-wheel (TTW) using available manuals of vehicle manufacturers; when this was not available, we used information reported by vehicle owners publicly available online (Supplementary Annex 2)) (WTT and TTW explained in Section 3.2.3.).

3.2. Methods

3.2.1. Travel Habits of Individuals

Individuals have different travel habits, implying different travel distances, modes, or frequencies. These depend on various life circumstances (e.g., car ownership status, commuting distances, income, having young children, or elderly people living at home) and external variables (e.g., weather, availability of parking, and public transport infrastructures) [34–36]. After consulting the literature, we decided to distinguish between individuals with car-dependent and car-free travel habits, identified using the ODiN2018 database, which distinguishes between households with or without their own car. Car ownership has been determined as a factor influencing modal splits of individuals [37]. By differentiating between car owners and non-owners, we estimated changes in modal shares after engaging with car sharing. In addition, we assumed that car-dependent individuals who start using car sharing dispense with their cars.

We used ODiN2018 to estimate the annual kilometres travelled and the modal shares of individuals with car-dependent and car-free travel habits. Amsterdam inhabitants reported the average distance travelled per trip and the number of trips in a particular transport mode. The sample size was 18,507(i). The daily distance travelled (DDT_i) per individual is expressed as:

$$DDT_i = \#\, trips\ per\ day_i \times DTT_i\,, \tag{1}$$

where DTT_i is the distance travelled per trip. The individuals were grouped according to their travel habits, represented by the subscript j. The average daily distance travelled ($\overline{DDT}_j$) was calculated for individuals with car-dependent and car-free travel habits:

$$\overline{DDT}_j = \frac{\sum_1^i DDT_j}{\#\, of\ individuals\ _j}\,. \tag{2}$$

The annual distance (YDT_j) was then calculated:

$$YDT_j = \overline{DDT}_j \times 365\frac{days}{yr}\,. \tag{3}$$

Next, we allocated this distance to different transport modes represented by h. We assumed that the $\%\, of\ daily\ trips$ can be used to represent the annual kilometres per modal share, described as:

$$\%\, of\ daily\ trips_{j,h} = \frac{\sum_1^{i=n} \#\, trips\ per\ day\ _{i,j,h}}{\sum_1^{i=n} total\ trips\ per\ day_{i,j}}, \tag{4}$$

$$DTpTM_{j,h} = YDT_j \times \%\, of\ daily\ trips_{j,h}\,, \tag{5}$$

where $DTpTM_{j,h}$ represents the distance travelled in different travel modes by individuals with specific travel habits. Distances travelled as driver or as passenger in private or shared vehicles are also accounted for (explained in Section 3.2.3).

3.2.2. Changes in Travel Habits Due to Car Sharing

We used the results from Nijland and van Meerkerk [22] to estimate changes in travel habits brought about by car sharing. Specifically, we based our assumptions on their results regarding changes of annual kilometres travelled because of car-sharing and the variation in modal split (detailed assumptions are presented in Supplementary Annex 1).

We accounted for changes in travel habits, people who migrate from car-dependent to car-sharing habits, and those who migrate from car-free to car-sharing travel habits. For each of these, YDT_j and $DTpTM_{j,h}$ were calculated (Tables 1 and 2).

Table 1. Annual distance travel (kilometres) (YDT_j) and modal split ($DTpTM_{j,h}$) of individuals with car-dependent travel habits before and after engaging with car-sharing. (Private car includes both travelling as driver and passenger).

	Before Car-Sharing	After Car-Sharing
Annual distance travelled (km)	12,897.4	10,435.4
Private car	53%	31%
Biking	18%	18%
Walking	15%	15%
Train	4%	2%
Others	10%	9%
Shared car	0%	25%

Table 2. Annual distance travel (kilometres) (YDT_j) and its distribution by transport mode ($DTpTM_{j,h}$) before and after engaging in car-sharing by individuals with car-free travel habits (Private car includes travelling as passenger).

	Before Car-Sharing	After Car-Sharing
Annual distance travelled (km)	8484.8	8824.3
Private car	21%	20%
Biking	32%	32%
Walking	17%	17%
Train	10%	7%
Others	20%	20%
Shared car	0%	4%

3.2.3. Well-to-Wheel Emissions of the Transport Modes

Factors of several transport modes were considered to account for WTW emissions (see Supplementary Annex 2). The WTW emissions include both WTT and TTW emissions. WTT emissions include emissions caused during the primary fuel production, including extraction and production, as well as the transport needed to make the fuel available for filling the vehicles. TTW emissions are caused during the burning of the fuel due to the motion of the vehicle. Emissions per passenger-kilometre for most transport modes were calculated as follows:

$$E_h = WTT_h + TTW_h, \quad (6)$$

where E stands for GHG emissions per passenger-kilometre travelled, WTT emissions, and TTW emissions (all per passenger-kilometre). Passenger emissions from private or shared fleets were calculated using Equation (7). A passenger represents an increase of the operating mass of a vehicle, so we added 6% to the fuel consumption [38]:

$$EP_h = WTT_h \times 0.06, \quad (7)$$

where EP_h is emissions per kilometres travelled as passenger and WTT_h is additional emissions due to additional fuel consumed. These emissions were only calculated for private and shared vehicles.

3.2.4. Emissions of Individuals with Different Travel Habits

Emissions at an individual level (ITE_j) can be expressed as:

$$ITE_j = \sum_{\forall h} E_h \times DTpTM_{j,h} + \sum_{h=1,2} EP_h \times DTpTM_{j,h}. \quad (8)$$

This equation captures the GHG emissions effects of individuals with different travel habits, distinguishing between emissions by the modal share.

3.2.5. Building the Scenarios

The baseline was built on the basis of the average values obtained from the previous estimations, so the results represent actual impacts of passenger transport in the city. Assumptions in the scenarios took into account the city's transport policies, technology adaptation, and changes in travel behaviour. The first set of assumptions is based on the Clean Air Action Plan of Amsterdam, which aims to work towards attaining the city's sustainability goals by creating zero-emission areas and building charging infrastructures for electric vehicles. Our interpretation of how this action plan may change the characteristics of the fleet is modelled in Scenario 1—Clean Air Policy.

In the scenarios, the city inhabitants were divided into individuals with different travel habits (Figure 1—Step 1.1). The travelling population (TP) can be represented as:

$$TP = \sum_{j} ITH_j,$$

where ITH_j stands for number of individuals with specific travel habits.

We determined the numbers of individuals with car-dependent and car-free travel habits by estimating the number of vehicle owners in the city on the basis of the total population of Amsterdam and vehicle ownership rate per relevant age on a national level (details in Supplementary Annex 3). This was done for the baseline and all scenarios. For scenarios 2 and 3, we simulated that a proportion of the travelling population migrate from car-dependent and car-free to car-sharing travel habits (Table 3).

Table 3. General description of the three scenarios.

Scenario	General Description
Sc 1— Clean Air Action Plan	The Clean Air Action Plan aims to create zero-emission zones. The main assumptions in the model were: Public transport buses are electric; Proportion of electric vehicles increases in private fleets; In all fleets, there is a gradual increase in lightweight vehicles.
Sc 2— Car sharing B2C	Some citizens migrate from car-dependent and car-free travel habits to car sharing. Distances by shared fleets are assumed to be travelled exclusively in a B2C fleet. The proportion of electric vehicles was increased in the shared fleet. Assumptions made in scenario 1 remain valid for this scenario.
Sc 3— Car sharing P2P	Some inhabitants migrate from car-dependent and car-free travel habits to car sharing. Distances by shared fleets are assumed to be travelled exclusively in a P2P fleet. The proportion of electric vehicles was increased in the shared fleet. Assumptions made in scenario 1 remain valid for this scenario.

The WTW emissions of the transport modes and the individual travel habits were used as inputs to calculate emissions in each scenario. In all scenarios, three parameters were estimated:

Total distance travelled (TDT) by the city inhabitants:

$$TDT = \sum_{j=1,2} \sum_{\forall h} ITH_j \times DTpTM_{j,h}. \tag{9}$$

Proportions of each transport mode (% $TM_{j,h}$) in the total distance travelled:

$$\%\, TM_{j,h} = \frac{ITH_j \times DTpTM_{j,h}}{TDT}. \tag{10}$$

Total emissions in the city (TEC):

$$TEC = \sum_{j=1,2} \sum_{\forall h} ITH_j x\ DTpTM_{j,h} \times E_h + \sum_{j=1,2} \sum_{h=1,2} ITH_j x\ DTpTM_{j,h} \times EP_h. \tag{11}$$

4. Results

In this section, we present results of potential changes in GHG transport emissions brought about by individuals engaging with car sharing, and the GHG emissions from each of the scenarios at the city level. We modelled changes in travel habits among car-dependent and car-free individuals after engaging with car sharing, as well as adaption of technology and implementation of transport policies.

4.1. GHG Emissions from Individuals Changing Travel Habits

The potential annual GHG emissions relating to personal mobility in Amsterdam were calculated at an individual level with different travel habits, Equations (5) and (8). Figure 2 shows that the effects of car sharing depend on individuals' transport emissions. Annual reductions in emissions are 68.68% and 69.92% when people migrate from car-dependent to P2P or B2C car sharing, respectively (Figure 2a). When individuals with car-free travel habits engaged with car sharing, their annual emissions increase by 11.63% and 12.51% (B2C and P2P, respectively) (Figure 2b). Regardless of travel habits, the implementation of the Clean Air Action Plan reduces emissions by 18.40% and 4.88% for individuals with car-free and car-dependent travel habits, respectively.

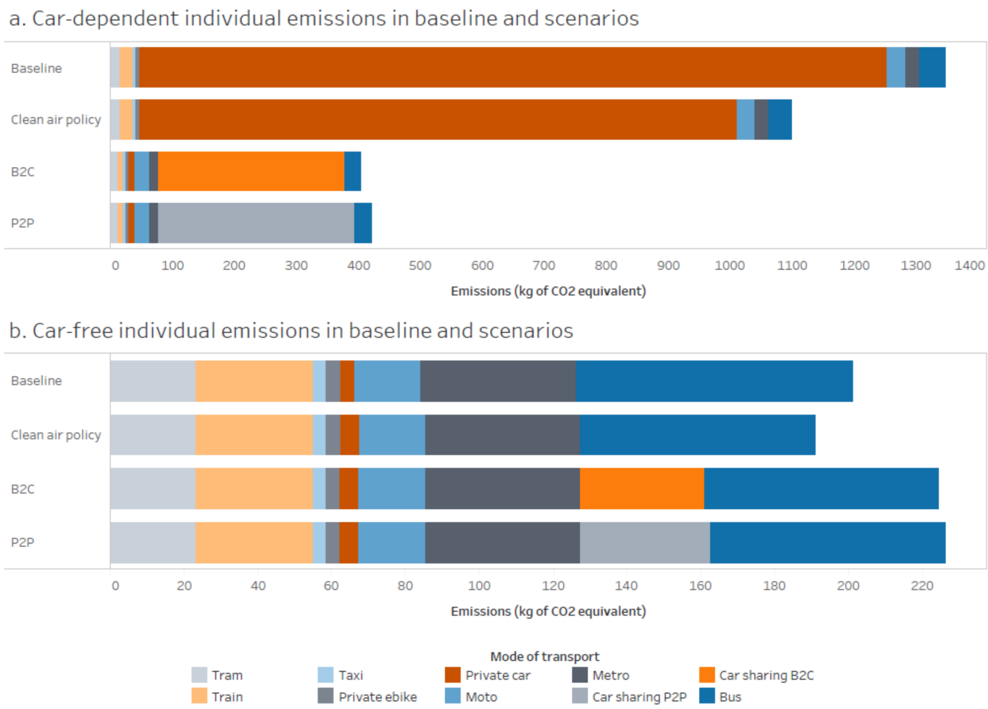

Figure 2. Annual GHG emissions of individuals with car-dependent (**a**) and car-free (**b**) travel habits (ITE_j) (Equation (8) differentiating between modal share ($DpTM_{j,h}$) (Equation (5)). Emissions include four different scenarios: Baseline, Clean Air Action Plan, B2C car sharing, and P2P car sharing. P2P—Peer-2-peer. B2C- Business-to-consumer. Note the difference between the x-axis scales on the graphs.

The savings in emissions from individuals who migrate from car-dependent to car-sharing are clearly higher than the increase in emissions from individuals who migrate from car-free to car-sharing travel habits. Forty individuals would have to migrate from car-free to car sharing to offset the emissions saved from individuals migrating from car-dependent to car sharing (Table 4).

Table 4. Impact of changes in travel habits on GHG emissions (Column 3). Number of individuals needed to migrate from car-free to car sharing to offset the emissions savings from car-dependent to car-sharing travel habits (Column 4).

Scenarios	Change in Travel Habits	Changes in Emissions (kg CO_2-eq.)	No. of Individuals with Car-Free Travel Habits Needed to Offset Emissions from Car-Dependent Travel Habits When Both Migrate to Car Sharing
2	From car-free to car sharing From car-dependent to car sharing	−25.16 941.45	37
3	From car-free to car sharing From car-dependent to car sharing	−23.39 924.80	39

4.2. Emissions at City Level

We obtained a more comprehensive understanding of the effects of car sharing by quantifying its implications at the city level (Equations (10) and (11)). Emissions from passenger transport can vary due to changes in individuals' travel habits, different policies, or technological adaptation. When these happen simultaneously, the potential reductions of GHG emissions are the highest (Figure 3), specifically 14.8%, 24.8%, and 24.9% in scenarios 1, 2, and 3, respectively, compared to the baseline.

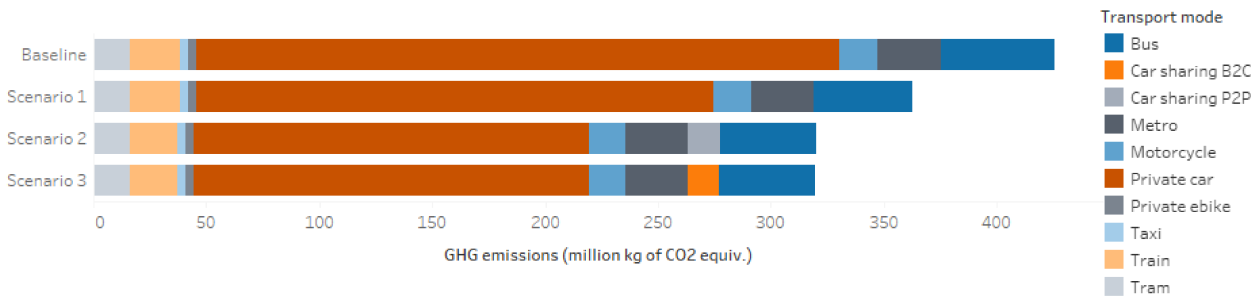

Figure 3. Total transport emissions in each of the scenarios (TEC) (Equation (11)). All scenarios include the implementation of the Clean Air Action Plan, while scenario 2 and scenario 3 include changes in travel behaviour due to B2C and P2P car sharing. B2B—Business-to-consumer and P2P—Peer-to-peer.

Private vehicles accounted for most of the emissions in all scenarios, followed by bus, metro, and train (Figure 3). These transport modes account for most of the passenger-km travelled in all scenarios (Table 5). Although they emitted the most in all scenarios, they also presented the highest reductions in emissions in each scenario compared to the baseline (Figure 4). The annual emissions of private cars decreased in approximately by 20% in scenario 1 and by 38.6% in scenarios 2 and 3.

Table 5. Annual p-km (passenger-kilometres) travelled in Amsterdam (TDT). Percentage of the annual p-km travelled per transport mode in each of the scenarios (% $TM_{j,h}$) (Equation (10)).

	Baseline	Scenario 1	Scenario 2	Scenario 3
TOTAL (million p-km)	4395.6	4395.6	4304.71	4304.71
Bus	8.25%	8.25%	8.31%	8.31%
Metro	7.69%	7.69%	7.76%	7.76%
Train	12.84%	12.84%	12.71%	12.71%
Tram	4.90%	4.90%	4.93%	4.93%
B2C car-share	0.00%	0.00%	0.00%	3.55%
Motorcycle	2.77%	2.77%	2.78%	2.78%
Private e-bike	3.84%	3.84%	3.85%	3.85%
Private car	59.38%	59.38%	55.78%	55.78%
P2P car-share	0.00%	0.00%	3.55%	0.00%
Taxi	0.33%	0.33%	0.33%	0.33%

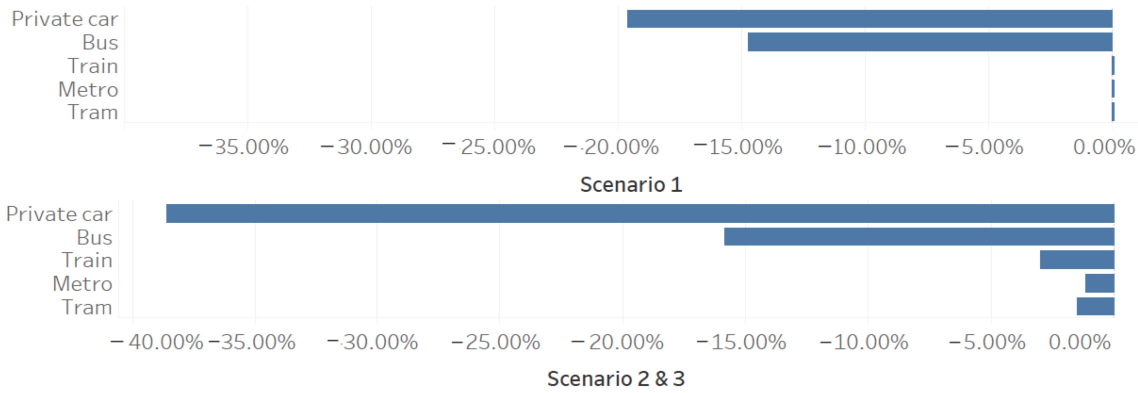

Figure 4. Percentage difference in total emissions between baseline and scenarios 1, 2, and 3 in some transport modes.

4.3. Emissions from Different Car Sharing Business Models

Scenarios 2 and 3 incorporate B2C and P2P car sharing respectively as part of the transport modes available for individuals. In both scenarios, car sharing accounted for the same amount of kilometres (Table 5). Emissions from the two modalities of car sharing differ by 5% (Figure 3), due to the characteristics of the vehicle fleets. Cars in B2C fleets are more fuel efficient (e.g., newer, smaller size) than in P2P, which is similar to the average national fleet (older, larger).

5. Discussion

5.1. Effects of Car Sharing on Emissions at Individual Level

Once individuals engage with car sharing, they tend to adjust their travel habits [7,9,22,39,40]. People might reduce their annual distance travelled by car, replacing journeys with more emission-efficient transport modes and thereby reducing total emissions [11,40]. Nonetheless, findings from our research indicate different consequences in transport emissions when individuals engage in car sharing. Individuals shifting from car-dependent to car-sharing travel habits reduce their emissions, while those shifting from car-free to car sharing increase them. Nijland and van Meerkerk [22] reported that car-share users travelled 960 km in shared vehicles that they would not have travelled if they did not have access to car sharing. These additional kilometres may affect transport emissions at the individual level. Consequently, to evaluate the effect of car sharing on emissions at an individual level, the travel habits need to be assessed before and after engaging with it.

Emissions savings from people who migrate from car-dependent to car sharing appear to be significant—a reduction of about 68% of the WTW, which can be attributed to disposing of owned vehicles and consequently a modal shift. Gleave [39] reported that 16% of the members of car-sharing clubs in the UK sold their first or second vehicle after joining a sharing scheme. Similar results were reported in Berlin and Munich, where 15% of the members of car-sharing schemes were willing to sell their car [25]. Variations in car ownership have been associated with subsequent changes in modal splits [37,41].

Chen and Kockelman [42] and Amatuni et al. [11] also reported a reduction in GHG emissions due to the use of car sharing and reduction in car ownership—about 50% and 3–18%, respectively. In our estimates, the reduction was about 68%. Our results are higher because they also account for savings from the implementation of the Clean Air Action Plan and the use of more emission-effective technologies, which assumes emission improvements in vehicle fleets, while Amatuni et al. [11] only simulated changes in individual travel behaviours.

When individuals with car-free travel habits engage with car sharing, their transport emissions increase, but it is also possible that these individuals will never buy a vehicle or will postpone buying one. This has been reported in several studies. Le Vine and Polak [43] estimated that 30% of the car-sharing users in London chose not to purchase a vehicle because of the availability of shared cars. This is in line with Gleave [39], who found that 34% of car-sharing club members avoided vehicle purchase. Emissions savings from decreased vehicle ownership are not only from the use phase, but also due to avoided emissions from production and end-of-life phase [11,44].

5.2. Effects of P2P and B2C Car-Sharing Fleets on Emissions

The findings in our study show a difference in WTW emissions between B2C and P2P car sharing, since B2C fleets are more fuel efficient and have a higher percentage of low- or zero-emission vehicles. So far, our results only cover the use phase and do not consider the impacts caused by vehicle production, maintenance, and end-of-life. In other studies, the use phase of vehicles has been identified as the most critical in terms of GHG emissions, so our results are still relevant [45].

A more comprehensive evaluation at the city level should include other life-cycle phases and assess how car-sharing organisations operate. One aspect is that most vehicles in B2C car sharing models are replaced more often than private vehicles. It may be argued that certain car-sharing business models may facilitate the supply of used cars into the second-hand market. The degree to which environmental impacts of such cars should be attributed to sharing is an interesting methodological question for systemic analysis.

5.3. Effects of Car Sharing at City Level

Changes in emissions at the city level are brought about by changes in individual travel habits and the adaptation of technology and transport policies [4]. Our findings suggest that travel behaviour combined with technology adaptations results in highest emission reductions. In our model, we simulate the effects of policies, such as the Clean Air Action Plan, which designates zero-emission areas [46]. The implementation of this policy will most likely lead to the adoption of technology such as electrical vehicles (EVs); in 2018, the municipality of Amsterdam started procuring buses to facilitate this transition [47].

Clear differences in the results for individuals underline the importance of modelling at the city level and the effects of car sharing on facilitating local sustainability targets. Especially important is to understand how the overall mobility system is affected and what the trade-offs are between individual gains and losses. Our results suggest that car sharing helps to decrease GHG emissions, providing there are fewer people disposing of owned cars or delaying a purchase than individuals with car-free travel habits who gained access to a car through car sharing.

Another relevant aspect is that mobility solutions offered in a city need to be flexible enough to adapt to individual needs. There are clear differences between the needs of urban vs. rural inhabitants, people with disabilities, etc. Urban mobility systems need to be flexible enough to cater to a wide spectrum of mobility needs. Sustainable transport systems should not only limit environmental impacts but also need to be socially and economically viable.

5.4. Sensitivity Analysis

Modelling the effects of individual factors on emissions in a city can shed light on highly sensitive variables in the model. So far, our scenarios have shown the impacts of simultaneous changes of travel habits and technological development variables on the transport emissions, so in this sensitivity analysis, we explored the variation of the transport emissions due to changes in one single variable (Table 6).

Our results show that variations in travel habit variables are sensitive. For example, a reduction of 10% in the annual distance travelled could decrease total emissions in the city by 26%, and changes in the modal share can result in a 20% reduction. Other variables affecting GHG emissions at the city level are also sensitive, such as the proportion of people who change their travel habits. If 10% of people migrate from car-depending to car-free travel habits, the reduction in emissions is approximately 20%.

Variables corresponding to technological development proved to be no less sensitive to variations compared to variables related to travel habits. The results of this sensitivity analysis can indicate which measures are more useful and have the greatest effect on total emissions of the city.

Table 6. Variables changed in the sensitivity analysis, the magnitude of these changes, and the variations generated in the GHG emissions of passenger transport.

Variable Changed (One at a Time)	Arbitrary Change of the Variables	Variations of the GHG Emissions of Passenger Transport
Annual distance travel by individuals with car-dependent and car-free travel habits	10% decrease	26% reduction
Modal share travel of private car by individuals with car-dependent travel habits	10% decrease	20% reduction
Number of individuals with car-dependent travel habits	10% decrease	21% reduction
Fuel consumption by bus per passenger kilometre	10% decrease	1% reduction
Fuel consumption due to increase in vehicle weight	10% decrease	0% reduction

5.5. Limitations

Although still marginal, new transport modes like car sharing have wider socio-economic effects, such as the production of vehicles and fuels, as well as the development and maintenance of infrastructure. Our assessment is limited to WTW system boundaries, since the use phase of cars represents the bulk of the lifecycle impacts (especially GHG) of vehicles [45]. Our approach, capturing a snapshot of a mobility system in a city, is largely an attributional LCA [48]. Although consequential assessment methods have wider system boundaries and are more dynamic, they might not be feasible for capturing complex mobility systems [44]. We therefore consider an attributional approach to serve the purposes of this study.

Likewise, our study is limited to only direct effects, namely GHG emissions, related to use. Other environmental effects should also be considered, along with the indirect effects of shared mobility and changes in consumption brought about by additional income or savings generated through the use of shared mobility. Capturing these would enable further understanding on how different modalities of shared mobility (B2C and P2P) translate into sustainability outcomes of personal mobility.

Our analysis was based on a mix of empirical and secondary data, such as national statistics and case studies reported in peer-reviewed literature. The latter are often based on self-reported surveys that are prone to under- or over-estimations. In our approach, where possible, we attempted to verify various data sources, and deemed small variations acceptable for the nature of our study. However, our models are based on scenarios built of informed assumptions.

Finally, we excluded from our scenarios the possible changes in travel habits caused by COVID-19. This is because there is not enough data available about any such changes and there is no certainty about how permanent the changes will be.

6. Conclusions

We assessed changes in GHG emissions from transport at individual and city level, brought about by changes in transport habits of citizens through engagement in two modalities of car sharing, namely B2C and P2P. We modelled car-free and car-dependent individuals who changed their travel habits after engaging with car sharing. We used a WTW approach to assess GHG emissions, differentiating between transport modes such as B2C, P2P, public transport, and private vehicles. We also simulated the effects of some environmental policies enacted in Amsterdam as a case study.

This study identified that, at the individual level, the use of car sharing has various consequences for transport emissions. Previous car owners engaging with car sharing tend to travel less and use low-emission transport modes, which results in lower GHG emissions. Car-free individuals, on the other hand, may travel more and use more emission-intensive transport modalities than before, which leads to the opposite effect. Emissions savings when individuals migrate to less emission-intensive travel habits and reduce travel distances seem to be more significant than the emissions increase of those whose travel distances increase due to the availability of car sharing options. Depending on the characteristics of the shared fleets, the emissions will vary, with B2C fleets tending to have lower emissions per passenger-km than P2P.

The results at the city level suggest that a greater reduction in emissions can be achieved when green technology adoption (e.g., more fuel-efficient cars in sharing systems) is combined with behavioural changes (e.g., disposal of cars and more use of public transport), rather than implementing one of them. Such strategies can be enabled through appropriate environmental policies.

Our results suggest that B2C and P2P car sharing can have positive effects on transport emissions, providing they encourage changes in the travel habits of individuals, such as migration to lower-emission transport modes and reductions in vehicle ownership. The various effects of car sharing at the individual level must be considered when city governments are designing transport policies. Policies that focus on restricting parking in the city stimulate alternatives to vehicle ownership or delay purchase. Such policies would facilitate the use of public transport and shared mobility in a way that would reduce emissions in the city.

Further research is needed to analyse the environmental effects of shared mobility, including assessments of other pollutants, material intensities, additional lifecycle stages, and the use of space. One important aspect to consider is the indirect effects of sharing, such as the impacts from changes in disposable income and re-spending. Other areas to be explored are the attributes of different business models in shaping user behaviour and the characteristics of the shared assets.

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