Conceptualizing environmental effects of carsharing services: A system thinking approach

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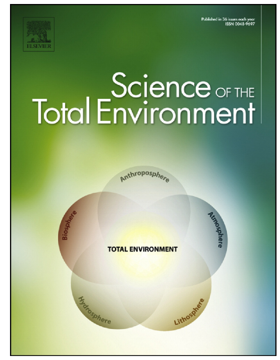

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Conceptualizing environmental effects of carsharing services: A system thinking approach

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Abstract

Emerging carsharing services and their interconnections with other modes of urban transport, regulations, car manufacturing and population have affected the dynamics of energy consumption, environmental pollution and greenhouse gas emission within a complex system. However, although some aspects of environmental impacts of transport sector have been investigated in the literature, well-deserved studies on the environmental effects of carsharing services following a system thinking approach is missing. This research aims at providing a comprehensive conceptual framework to systematize the interconnections between carsharing services and their environmental effects. To do this, system dynamics (SD) modeling, as a tool to simulate complex and dynamic systems, is applied and the proposed framework model is illustrated by using a causal-loop diagram (CLD). Along with analyzing the main identified causal loops within the presented CLD, relevant strategies are proposed to reduce the negative environmental effects associated with the carsharing services, considering the whole lifecycle of a shared vehicle. The proposed framework can help environment policy makers and shared mobility practitioners in long-term strategic decision-making.

Moreover, it can be applied by the researchers as a basis for future research, not only for SD modeling but also other simulation and analysis structures.

keywords: Car Sharing, Causal-loop diagram (CLD), Environmental pollution, Greenhouse gas emission, System Dynamics, Urban transport.

1. Introduction

The population of urban areas worldwide is estimated to experience a rise of 72% from 2011 to 2050 and reach 6.3 billion, embracing 67% of the total population in the world (IEC, 2014). The growing trend of urbanization is pushing the cities towards many challenges that they had not faced before. A significant challenge in this regard would be the increasing demand for transportation in urban areas resulting from the increase in urban population density that would lead to large volumes of traffic and congestion. However, congestion and waste of time, energy and money are not the only negative outcomes of urban transportation, but serious environmental impacts arise from these activities that deal with the people's well-being. Running exhaust emission (including CO, HC, NO_x, CO_2, PM and Mobile Source Air Toxics (MSAT), running loss evaporative emissions (including volatile organic compounds (VOC), non-exhaust emission (including PM_{10} and $PM_{2.5}$), as well as noise pollution are the main environmental impacts of vehicular transportation (Vidhi and Shrivastava, 2018).

Based on the report of the International Energy Agency (IEA) in 2019, the world total CO2 emissions from fuel combustion in 2017 was 32,839.9 million tons. Transport sector, with its 2% annual increase in the CO2 emission at the global level during the period 2000 to 2017, captured a share of 8,039.9 million tons from this amount. Almost three quarter of the CO2 emissions in this sector, that constitute 5,958.3 million tones, refer to road transport, mostly for passenger travel (IEA, 2019a). Besides, CO_2 emission resulting from the activities in the transportation sector worldwide in 2017 was reported to be 24% of the direct emissions, experiencing a rise of 0.6% compared with 2016 (IEA, 2019b).

It is believed that the recent concerns about the urban air quality and the emission of pollutants and GHG can support the growth of carsharing schemes (Wells et al., 2018b) and carsharing services can improve the urban life quality and traffic conditions (Sanvicente et al., 2018). Carsharing, enjoying the sharing economy business model (Luna et al., 2020; Ranjbari et al., 2018), is introduced as a new way of transportation which has a positive impact on the transport sustainability (Clewlow, 2016; Papu Carrone et al., 2020; Ranjbari et al., 2019a). Carsharing provides to individuals the opportunity to enjoy the benefits of a private vehicle without owning it and therefore, is shifting the private mobility from ownership to service use. However, the shared use of cars in the carsharing systems are not through sharing the trips – as in ridesharing in which commuters with similar patterns agree to share a ride –, but instead, through sharing the vehicles by different drivers at different times (Rodenbach et al., 2018b). Therefore, users are connected to available vehicles and provide the mobility service themselves, which is in contrast with the ride hailing services in which a trip by a driver is generated to suit the purpose of the user (Wells et al., 2020). Carsharing services can be provided through the peer-to-peer (P2P) system that makes a link between two consumers via a digital intermediary platform, or through carsharing platforms in which vehicles are owned by an organization and are being put into a short-term access by different consumers in one-way, two-way or round-trip forms (Business-to-peer (B2P)). Different forms of carsharing serve different mobility needs and have different impacts in terms of market penetration and substitution potential of privately-owned cars. Nevertheless, due to the emerging importance of carsharing services in the past few years, many researchers, such as Chicco et al. (2020), Vasconcelos et al. (2017) and Nijland and van Meerkerk (2017) have considered environmental aspects of these services. Research shows that carsharing definitely lowers the number of cars in the cities, without decreasing the individual mobility, since one shared vehicle can replace up to fifteen privately owned vehicles, being more intensively utilized to serve the same number of trips (Mounce and Nelson, 2019).

From the lens of environmental impacts, the vehicles fuel consumption and their travels increase the negative environmental outcomes, while the car manufacturing industry adds to the environmental pollutions and GHG emissions for the vehicle production. However, the automotive industry can affect the environmental aspects of carsharing services by its contribution in designing smaller and more efficient fleets that consume less pollutant energy sources. As a result, many legislations and action plans supporting the environment have been imposed in the recent years that would affect car manufacturing industry and the technology being used in the new vehicles, such as Directive 2009/33/EC of the European Parliament and of the Council of 23 April 2009 (EC, 2009a), and Directive 2014/94/EU of the European Parliament and of the Council of October 2014 (EC, 2014a). Therefore, in order to efficiently define transport policies to minimize the drawbacks and maximize the benefits of carsharing services, beside the growth of carsharing fleets and the consumption behavior of the people, its effects on the environment should be strictly well-thought-out.

Putting all together, to better analyze the environmental effects of carsharing services, a complex system including carsharing and other transport modes, environment, regulatory and legislative bodies, car manufacturers and citizens should be considered. Understanding the interrelationships within the structure of this system provides an aggregated strategic view on analyzing all the aspects of carsharing that affect the total environment, which is crucial for the respective decision-makers. Such a holistic map is presently absent in the literature, and most of the scholars have limited their research to focus only on some of the interconnections. An appropriate approach to capture the causality relationships among the variables in such a complex system is System Dynamics (SD), which has been widely used for modeling the environmental effects of transportation domain such as GHG emission (Batur et al., 2019; Luna et al., 2020; Vilchez and Jochem, 2020), air pollution (Vafa-

Arani et al., 2014) and carbon tax on road passenger transport (Gupta et al., 2019), and is also applied in the present research.

The main purpose of this research is to develop a comprehensive conceptual framework for analyzing the environmental effects of carsharing services following a system thinking approach. To do this, the study employs a two-phase methodology. First, a detailed literature review is conducted on the research applying SD for analyzing or quantitatively simulating carsharing services, keeping an eye on its environmental impacts. Besides, to enrich the literature review in this phase, an overview of the other transport-related issues applying SD modeling considering environmental impacts is performed. In the second phase, to provide the comprehensive framework, the outcomes of the first phase are put together for analyzing the interconnections between carsharing services and other important elements in the considered system boundary. A causal-loop diagram (CLD), as a system thinking tool that is widely applied in SD, is built to clarify the interconnections among the identified variables and finally, a conceptual comprehensive framework for the environmental effects of carsharing services is presented. This framework denotes the interconnections among the main players of the described system and can be utilized by the researchers and policymakers to better analyze the causalities linked with the positive or negative environmental effects of carsharing services.

The remaining parts of the paper are as follows. Section 2 discusses the methodology applied, introducing the two-phase process considered to conduct the research. Section 3 presents the results of the comprehensive literature review conducted to identify the footprints of environmental effects on the SD models designed for carsharing services and the other transport modes. Section 4 presents the CLD to visualize the cause and effect relationship between the variables. Section 5 discusses the foremost loops identified in the designed CLD and provides the comprehensive framework. Finally, section 6 concludes the paper and recommends guidelines for further research.

2. Research methodology

In order to provide a conceptual framework for a system thinking perspective, which is the main objective of this research, a two-phase process is followed. Each phase is designed to address one of the research questions as the following:

RQ1: What are the main drivers of carsharing services environmental effects from a system thinking perspective?

RQ2: How to conceptualize the environmental effects of carsharing services with a system thinking approach?

In phase 1, correspondent with RQ1, a comprehensive literature review on the scientific materials applying SD for modeling carsharing services with an environmental impact consideration is conducted. This phase entails 2 steps, namely material collection and document analysis, and aims at identifying the main elements of carsharing services that can affect the environment with a system thinking approach.

To fulfill the material collection step, the main search keywords are defined, the related materials for the analysis are collected through keyword and snowball search, and finally, the collected materials are checked for validation. The main keywords considered in this research include "carsharing", "car club", "shared mobility", "shared cars", "shared vehicles", "system dynamics", "causal loop diagram", "system thinking", "environment" and "transportation". We have also searched "car sharing" and "car-sharing" as many articles use such different writings for the same meaning. We have tried to find all the papers that had used qualitative or quantitative SD for modeling carsharing services, but since the number of papers are significantly low, we have extended our search to cover papers applying SD for transportation issues that have touched upon any environmental impacts.

Phase 2, which tries to answer the second research question, contains the main contribution of this research by providing a comprehensive system thinking framework for carsharing services and their underlying environmental impacts. To do this, a mixed stepwise method adopted from Vennix (1996) and Sterman (2000) is used. The steps followed include (1) boundary selection and definition of problem variables, (2) detecting cause and effect relationships, and (3) identifying feedback loops. Finally, a comprehensive framework is suggested, which captures the main identified feedback loops in the system and facilitates the analysis of the potential managerial strategies.

SD, as a fundamentally interdisciplinary approach, follows the System thinking principles that tries to truly understand a certain event by seeing things as a whole instead of several parts. It uses the theory of nonlinear dynamics and feedback control to show the behavior of complex systems (Sterman, 2000). When the map of the causal structure for the SD is developed, a deeper insight about the whole map of the system is provided, assisting the researcher or decision maker to better analyze the interconnections and relationships in the system.

The map of the causal structure in this research is developed by applying a CLD, which is an appropriate tool to illustrate the causalities among the variables to better analyze the interconnections and relationships in the system. In the CLDs, the network of variables within the border of the system are connected by using headed arrows starting from the cause and pointing to the effect. Therefore, the causal structure of the system is mapped through it. The positive or negative polarity of the relationships are also indicated, helping to identify reinforcing and balancing loops that lead to dynamics in the system behavior over time (Elsawah et al., 2017; Ranjbari et al., 2019b).

Vensim PLE software is utilized to build the CLD in this research. Moreover, to present the final proposed comprehensive system thinking framework, a subsystem diagram is designed, which is another system thinking tool (Sterman, 2000).

3. Identification of environment footprints in carsharing services

Following the methodology described for phase 1 of this research, scientific works focusing on the application of SD and system thinking for carsharing services and their associated environmental issues were collected. No time horizon was considered for this search and the search was refined and updated by March 21, 2020. After filtering and validating the materials, only 3 papers were found to be specifically applying SD for a research focusing on carsharing and its environmental effects. Although this group of 3 papers were the target for this search, 2 other groups of papers were formed, one using SD for a problem regarding carsharing with no concern about environmental effects and the other, applying SD for a transportation problem with a concern of environmental effects and no highlighted effect of carsharing services. These two groups comprise of 5 and 40 scientific publications, respectively.

Figure 1 illustrates the distribution of selected publications in the specified 3 groups. As it can be seen in this figure, the application of SD in transport-related problems has been growing up, mainly from 2010 and the focus of publications applying SD for environmental issues in transportation had a significant growth in 2019. This may point out the growing attention of the researchers towards environmental issues associated with the transportation systems from a system thinking perspective and also the suitability of SD for modeling and analyzing such problems.

Figure 1 is located here.

Furthermore, publications applying SD for carsharing services emerged from 2011, while environmental impacts have been the concern of such research activities from 2014. This highlights the attention of researchers towards the environmental effects of the innovative and technology-driven modes of transport, the worldwide concern about the global warming and pollution, and the complexity behind such analysis that can be shown and modeled by applying the system thinking approach.

According to the distribution of papers applying SD for modeling the complex systems dealing with transportation issues and specifically carsharing illustrated in Figure 1, it can be realized that SD modeling is attracting a growing popularity in this field. However, since carsharing is rather a new way of transportation (Ferrero et al., 2018), the number of research works concentrating on the SD simulation of such services are not high, and the ground is left for conducting system thinking-based research in this field.

3.1. System thinking approach towards carsharing environmental effects

This part of the literature review provides an informative and focused evaluation of the papers that have applied SD for modeling carsharing services among other modes of transportation, and have an attention towards their environmental effects. Table 1 provides an overview of the research that have applied SD for an analysis or simulation regarding carsharing services. As specified in the last column of the table, only 3 of the mentioned papers have considered the interconnections between carsharing services and environmental effects in their research, which are the focus of attention in this section.

Table 1 is locate here.

The most recent research applying SD for modeling the effects of carsharing services on carbon emissions among the presented papers in Table 1 is published by Luna et al. (2020), in which the case of Fortaleza, Brazil is studied. In this research, an e-carsharing scheme is focused on and its impact on both carbon emissions and on electric vehicle adoption is modeled. A simplified model structure is presented that illustrates the general stock-flow diagrams (SFD) for CO2 emissions and EV adoption. The rate increasing the CO2 stock is mainly affected by the CO2 emissions from vehicles with ethanol, gasoline, natural gas and ethanol-gas, and the market share of each vehicle type as well as the stock related to conventional vehicle fleet that is constructed in the SFD of the electric vehicle adoption. The results obtained through the simulation of CO2 emission show that the growth policy is an important factor towards the reduction of carbon emissions.

Menon and Mahanty (2015) focused on energy efficiency improvement policies in India and considered GHG emissions in personal transport sector. They accounted for carbon tax imposition, carsharing, car scrappage and a combination of the three in the scenarios they tested in the simulation model. The conclusion was that although the combined policy provides the best result in terms of fuel consumption and GHG emission levels, carsharing scenario performs best with regard to the direct rebound effect. They considered dynamics related to fuel efficiency improvements, vehicle ownership, travel behavior and social impact, and presented four SFDs to simulate their policies. To lower the GHG emission level, they suggested the adoption of a combination of carbon tax imposition, carsharing and car scrappage along with the improvement of fuel efficiency in India.

Geum, Lee, and Park (2014) tried to evaluate the environmental, social and economic aspects of carsharing services in Korea by applying a hybrid method, combining technology road-map and SD to support scenario planning. In their research, SD simulation was applied to evaluate the scenarios in terms of external environment, internal strategies, and their relationships. Their results showed that the increase in the usage of carsharing services leads to the reduction of environmental burden up to a certain level. It also improves the traffic environment and decreases energy consumption.

3.2. System thinking approach towards transportation environmental effects

In order to extend the reliability of the research scope, beside the list of papers presented in Table 1, a group of papers applying SD modeling for a transportation-related problem considering the environmental impacts is identified as well in

Table *2*. As shown in this table, the number of researches in this list is rather significant. However, only a few papers have roughly pointed to any form of shared mobility. As an example, Jia, Liu, and Yan (2019) simulated and assessed the effect of air pollution charging fee policy on the traffic and the emissions of the general transport system in Beijing considering various scenarios, but without noticing carsharing services. While providing recommendations, they pointed to bike-sharing mechanism and subsidy for the improvement of the supply level of public traffic.

Table 2 is located here.

Most of the reviewed research in

Table *2* have applied SD models without integrating it to other models. However, limited research made an exception in this regard since they have added agent-based modeling (Pasaoglu et al., 2016; Shafiei et al., 2013) and logarithmic mean divisia index (Gu et al., 2019) to their methodology.

The vast application of SD for modeling an environment-oriented issue in the transportation field, which is shown in

Table 2, highlights the complexity of the system if various stakeholders are to be considered. It also shows the suitability and usefulness of system thinking for modeling such a system. Carsharing as a new mode of transportation has added more complexity to the system and hence, SD is a suitable tool for the analysis and/or simulation of the underlying system, too.

Although the number of papers using SD for modeling the environmental impacts of carsharing services is still scarce in the literature (see Table 1), the initial attempts in this regard are successfully made. However, a holistic system thinking framework that considers the critical players and captures their role in the system is still lacking. In sections 4 and 5, the big map and comprehensive framework of the complex system entailing carsharing services and their associated environmental impacts are presented and discussed in details.

4. Results

While considering carsharing as a part of the urban passenger transport system, many players in the business environment can affect or being affected by it. These players include (1) people who demand transportation (Luna et al., 2020; Ramos et al., 2019), (2) other modes of transportation that compete with carsharing or complete it (Ceccato and Diana, 2018; Diana and Ceccato, 2019; Wells et al., 2018b), (3) car manufacturers who provide the supply of cars to carsharing platforms (Melis et al., 2019; Wells et al., 2018a), (4) regulators and policy makers who put restrictions and regulations for the activities in the business environment (Gupta et al., 2019; Menon and Mahanty, 2015), and finally, (5) environment, which is mainly affected by the activities of the mentioned players (Chicco et al., 2020; Geum et al., 2014) but can affect some of the decisions made by the players in the business environment, as well (EC, 2014a, 2009a).

However, analyzing the papers discussed in section 3, we came to know that putting the systems provided in this few number of papers cannot provide the framework of the system that holistically considers almost all environmental impacts of carsharing within the described business environment framework. Therefore, other research papers and reports available in the literature that can provide a clue to build the big system were used to provide a comprehensive framework in this research. These research works were considered without the constraint of applying a system thinking approach.

Following the second phase of the methodology, a CLD is built to put all the identified players of the system together. This CLD shows the interconnections among the system variables and illustrate the reinforcing and balancing loops, as in

Figure 2. In the presented CLD, carsharing services, car manufacturing industry, environment, and the main transportation and environmental regulations are put at the core of the system and special attention is devoted to the interconnections among them. However, only the important details and variables are shown to avoid complexity and confusion. Among different modes of transportation, only using personal cars is shown in the system due to its similarities with the utilization of carsharing services and the link between car ownership and using carsharing services (Chicco et al., 2020; Mounce and Nelson, 2019).

All the identified environmental effects of carsharing services, including air pollution, water and soil pollution, GHG emission, noise pollution and land use are put in a green box in

Figure 2 for the simplification of the presented model. However, any activity associated with carsharing services may have its own level of environmental impact, leading to improve or worsen the situation. In addition, some of the variables are highlighted in blue to facilitate tracking the loops discussed in the discussion section. A general causal loop referring to the population subsystem is illustrated by a dashed arrow, indicating that more details can be added between the two mentioned variables. The potential variables include city population.

Although the presented model contains many loops addressing environmental impacts, in order to provide more visibility, only the key loops are specified in the figure and will be discussed in the next section.

Figure 2 is located here.

5. Discussion

The CLD in

Figure 2 illustrates the causal loops and causality chains that lead to air, soil, water and noise pollution and climate change. In this section, from among the identified loops in the model, a selection of the loops and their related causality chains that carry the most important messages about the environmental effects of carsharing services are discussed. These loops are introduced in

Table 3 with a name conveying the main message of the loop. For each loop, the related variables are listed, along with the environmental impacts resulting from the chain. Besides, some of the important causality chains that are not within the specified loop but are linked with it are mentioned, as well as their resulting environmental outcomes. In the final column of the table, some managerial strategies are suggested to get the most out of the expansion of carsharing services regarding the reduction of negative environmental impacts. The plus and minus signs in the table imply the increase and reduction in the variables, respectively.

Table 3 is located here.

Loops R1 and B1: Carsharing: to use or not to use?

Carsharing is a transport demand management (TDM) strategy that among various economic, social and environmental benefits, can help the reduction of the congestion in cities (Litman, 2015). These services can be easier to apply for denser areas to replace many private cars with fewer shared vehicles. Therefore, congestion in high density areas lead the people to choose carsharing as an 'improved transport option' (Litman, 2003). If the shared vehicles are available at the time and place required by the members of carsharing systems and they succeed to use this service to make their trip, the congestion would reduce. The described loop to reduce congestion by using carsharing services is named "Carsharing rocks!" in the balancing loop B1 to illustrate the positive effect of carsharing services in the reduction of air pollution, noise pollution and GHG emission arising from the congestion. Moreover, although not included in the loops, carsharing platforms lean towards using smaller size vehicles compared with the average size of the vehicles in the market (Wells et al., 2018b), that can affect both the parking place and congestion.

However, loop R1 portrays a negative upshot of the expansion of carsharing services in terms of congestion level, to alarm the transport policy makers to "Beware of the rocks!". As it happens, the growth of carsharing services, which follows the sharing economy principles, provides the ground for access-based consumptions and can change the allocation of spending by the people (Verboven and Vanherck, 2016). Besides, changes in the built environment to simultaneously limit the private parking places and provide access to carsharing services can also incentivize people to modify their travel behavior. As a result, by the change of the people's lifestyle and consumption behavior over time and the growth of demand for shared vehicles, the carsharing service providers require more vehicles to expand their fleet and supply the demand of their customers. If no limitation for the expansion of carsharing fleets is considered by the regulators, considering the fixed road capacities, the growth of carsharing fleets used by the people would result in more congestion. It is worthwhile mentioning that in case of the deployment of fully autonomous vehicles as a part of carsharing systems in cities, the congestion may experience an increase due to the growth of demand coming from the previously excluded users, such as disabled or elderly people and children (Wells et al., 2018a).

Loops B2 and B3: The sustainable twins

In connection with the more utilization of shared vehicles, stepping towards more circular economy in transportation through using shared vehicles is highlighted by loops B2 and B3.

Although inconsistent perspectives exist about the complementary or competing role of carsharing services towards other modes of transport including public transportation, the competition between carsharing services and personal car usage is almost agreed upon (Ceccato and Diana, 2018; Geum et al., 2014; Wells et al., 2018b). Loop B2 focuses on the potential carsharing users that do not own a personal car. If carsharing services are available to be used by this group of customers at the time and place that they require them, the probability of using shared vehicles for making their trip increases and they may choose carsharing as their transportation mode. If they find carsharing as a good replacement for personal cars, their utilization of shared vehicles increases and the demand of this users for a new car reduces. Lower demand for car manufacturing results in the consumption of less resources and production of less pollution by the car manufacturers.

Meanwhile, car-owners' behavior in terms of using carsharing services may differ from the ones who do not own a car. They may be more motivated to use their own car that they have previously paid for, instead of using carsharing services (Mounce and Nelson, 2019) or more inspired to live with fewer cars (Chicco et al., 2020). Loop B3 indicate that if car-owners decide to use carsharing services, the more they utilize shared vehicles for their trips, the less their personal cars are used.

Therefore, their personal car is kept safer in terms of maintenance requirement, depreciation and accident. As a result, the vehicle reaches its end-of-life (EOL) in a longer time and the demand for a new car to replace the old one is postponed. Beside the pollution and GHG emission that are considered for the car manufacturing process, various negative environmental impacts are considered for vehicle EOL processes (Anh et al., 2020) that has led to the setting of many directives and guidelines in this regard. Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of life vehicles (EC, 2000) and Directive 2005/64/EC of the European Parliament and of the Council of 26 October 2005 on the type-approval of motor vehicles with regard to their reusability, recyclability and recoverability (EC, 2005) are some examples to be mentioned for EOL management of the vehicles.

Loop B4: Drive green!

Decision to initiate or expand carsharing services requires the carsharing platforms to make shared vehicles available for their potential customers. Car manufacturers have a significant role in the supply of vehicles to carsharing fleets (Wells et al., 2018b) and therefore, the type of the vehicles presented by the car manufacturers to the carsharing market can affect their fleet composition.

Due to the growing concerns towards environmental issues, car manufacturers are pushed by the regulations towards producing more environment-friendly vehicles (EC, 2009a). Regulations targeting the decrease of CO_2 emissions from light duty vehicles and new passenger cars make all the car manufacturers in the EU to respect limitations regarding the amount of CO_2 emitted per kilometer by each new car manufactured. The average CO_2 emission of each new passenger car sold by the manufacturers in the market from 2020 onwards is set to be 95 g CO_2/km and failure to comply with the regulations by the manufacturers would require them to pay a penalty of 95 € per each gram of extra emission of CO_2/km for each fleet being manufactured, that would be "Excess emissions × 95 €/g CO_2/km) × number of new passenger cars" (EC, 2014b, 2009b). Therefore, many attempts by the car manufacturers are taking place in the direction of the production of less pollutant vehicles, such as fuel cell vehicles powered by hydrogen, battery electric vehicles and hybrid electric vehicles.

Depending on the energy source that the vehicle uses, the amount of Well-to-Tank (WTT) GHG emissions that are generated during the production phase of the fuel are different. Besides, the mileage traveled by the vehicle affects the Tank-to-Wheel (TTW) emissions and therefore, Well-to-Wheels (WTW) GHG emissions that refer to the whole lifecycle of the fuel production differ for various cases. Likewise, the amount of vehicle air pollution depends on the type and amount of energy consumption. For the low or zero emission vehicles (ZEVs), the main source for the power generation is mainly responsible for such emissions. As an example, for battery electric vehicles, which shift their emissions to the location of the electricity generation, the type of energy source for the electricity production should be considered. However, research shows that electric shared vehicles have less global warming potential compared with the fully thermic engine shared vehicles in their lifecycles (Ding et al., 2019).

Although the scale of carsharing services in the EU are very small, the share of electric vehicles in their fleets, which is on average 10%, is much higher than the average of the overall car market (Wells et al., 2018b). According to recent research (Rodenbach et al., 2018a), more than 60% of a representative sample of carsharing operators across Europe had at least some electric vehicles in their fleets, and one quarter of the latter group operated an almost completely electrified fleet. This figure is much higher than the corresponding diffusion of electric vehicles in private cars.

Loop B4 notices the replacement of up to fifteen personal vehicles by only one shared vehicle with a higher utilization rate (Mounce and Nelson, 2019) leading to the reduction of congestion, and highlights the role of car manufacturers in supplying less pollutant cars for carsharing platforms to make remarkable environmental improvements.

Synchronizing the discussed dimensions of carsharing services and also their associated proposed managerial strategies can be well established through the system thinking lens, which is capable of modeling the complexity behind the system. As can be seen in

Figure 2, and according to the discussions provided in this section, the various interconnections between shared vehicles applications and all aspects of environment result in a complexity that makes all parts of the system to react to a single change in any part of the system. While a single decision can target a specific loop or variable, skipping its effects on the other parts of the system may lead to inefficiencies and even adverse effects on the environment. Therefore, managerial strategies regarding the limitation and expansion of carsharing services should be well analyzed and balanced before putting into action. Moreover, decisions about applying other sources of energy than fossil-fuel should also be well explored considering the discussed loops, because of their potential impacts at the vehicle manufacturing and disposal stages. Such inclusive decisions can be made referring to the interconnections between the players in the system, which make the system complex by nature. Failure to consider these interactions result in decisions which improve a part of the system but may have an undesirable effect on the other players and possibly lead to a negative overall outcome in terms of environmental impacts in the whole system.

In order to clarify the important players within the discussed complex system and their main interconnections, a conceptual framework is developed and presented in section 5.1.

5.1. The proposed conceptual model

Considering the presented CLD and the discussions provided regarding the causal loops, Figure 3 presents a comprehensive framework for a system thinking approach towards the environmental effects of carsharing services. Five subsystems are put within the borders of the big map of urban transport system, as transportation, environment, car manufacturing, population, and regulation and administration. The transportation subsystem comprises of two other subsystems as carsharing, which was the focus of this study, and other modes of transportation, among which car ownership was pointed out in the CLD. The proposed framework, which is presented in the form of a subsystem diagram, shows the interconnections and flow of affections in the whole system.

Figure 3 is located here.

Focusing on the general interactions between transportation and population subsystems, the demand of the population for transportation services should be satisfied through supplying these services by the transportation subsystem. Affected by the TDM strategies, various transport options along with different strategies are proposed, one of which can be carsharing. Using carsharing services is a decision that is made by the population and follows different patterns in different areas due to the differences in consumption behavior (Ceccato and Diana, 2018; Chicco et al., 2020; Diana and Ceccato, 2019). Considering the interaction of environment subsystem with these subsystems, in one hand, depending on utilization level of each transportation mode and the type of energy source consumed by it, air pollutants and GHG can be emitted. Moreover, the traffic volume and congestion can result in noise pollution and in some cases, there may be a requirement to change the land use pattern to control some part of the traffic. On the other hand, negative environmental changes can affect the health and life of the people. In fact, the vehicular emission of pollutants such as HC, NOx, CO and PM to the atmosphere can directly affect human health, while CO2 as a GHG can contribute to global warming (Silva et al., 2006). Noise pollution can also be responsible for health problems including increased distress, high blood pressure issues and heart problems (Kopelias et al., 2020). These negative life quality and health impacts can affect the population and the level of their demand for transportation in an area.

Transportation and car manufacturing subsystems exchange the demand and supply of vehicles to be used in the transportation system. As a result, the more efficient and smaller the vehicles produced by car manufacturers, the more environment-friendly the transportation activity becomes. Since a higher proportion of electric cars manufactured are purchased by the carsharing platforms compared with the personal car owners, and carsharing platforms lean towards using smaller size vehicles compared with the average size of the vehicles in the market (Wells et al., 2018b), the developments in the carsharing services market can push the whole system towards more sustainability. This positive movement would not only refer to the improvements in transport energy consumption, congestion and parking places, but also to the less materials required for car manufacturing and improved EOL processes.

Negative environmental effects resulting from the manufacturing and EOL of the vehicles including air, soil and water pollution, GHG emission, noise pollution and land use (mainly for landfilling) have attracted the attention of policymakers and regulators to provide guidelines or put restrictions to reduce the harm to the environment (e.g. EC (2000) and EC (2009a)). Therefore, the regulation and administration subsystem receives the environmental alarm and tries to manage the level of negative environmental impacts in the car manufacturing industry. Additionally, negative environmental impacts resulting from the transportation activities add to the concern of policymakers and make them decide about appropriate TDM strategies to push the transportation system towards sustainability. Carsharing is one of the TDM strategies that can change the usage pattern of other modes of transportation, including personal vehicles (Ceccato and Diana, 2018; Diana and Ceccato, 2019; Kopp et al., 2015; Wells et al., 2018b), and move towards surviving the environment.

The presented framework provides a holistic view on the interconnections among the main players of the system when deciding to analyze the environmental effects resulting from the utilization of carsharing services. This framework presents an inclusive overview of the causes of negative environmental effects in the whole lifecycle of a shared car and provides ideas on where to look for the solutions to reduce these negative effects. Moreover, considering all the relationships and feedbacks mentioned in the framework helps the policymakers and analysts to have a complete map of the interactions in their mind and more realistically predict and analyze the outcome of a decision made in accordance with any part of the whole system.

6. Conclusion

The development of carsharing services, using technology as an enabler, is affecting the transport system in different areas and leads to significant environmental effects over time. This research highlighted the importance of the system thinking approach for analyzing the environmental effects of carsharing services and presented a system thinking framework as a source for modeling its relevant interconnections. Although the results are in line with the prior research conducted by Luna et al. (2020), Menon and Mahanty (2015) and Geum et al. (2014), the presented framework has a much broader view towards the environmental effects of carsharing services compared with the prior research. In fact, while the mentioned studies have focused just on the carbon emission resulting from the utilization of carsharing services, the current research addressed five main subsystems including (1) population, (2) transportation, (3) car manufacturers, (4) environment, and (5) regulations and administration, applying a system thinking approach. Besides, it captured the role of each subsystem in affecting the environment in terms of water, noise, soil and air pollution, GHG emission and land use. The interconnections between these subsystems were initially analyzed in a

CLD, which was then translated into a subsystem diagram to illustrate a comprehensive system thinking framework to be used as a guideline. The built CLD and the presented conceptual framework can help strategic decision makers to track the causes of changes in the level of environmental impacts and the effects of changing each of the variables involved in the system. This is done by viewing all the involved subsystems and their main variables as well as their causal relationships in a single map.

While elaborating on the key identified loops in the provided CLD, appropriate managerial strategies were proposed to support positive outcomes of the utilization of carsharing services and reduce its negative environmental impacts at the same time. The main directions that the proposed strategies show are (1) the support to expand carsharing services while controlling the number of fleets to avoid environmental rebound effect, (2) the utilization of less pollutant cars or ZEVs in the carsharing fleets, and (3) using renewable energy sources for the electricity production for EVs. Following a system thinking approach, and according to the constructed CLD, the result of applying each strategy affects the behavior of the whole system in terms of the environmental effects over time and therefore, any single change in the system variables should be analyzed in the context of the whole system. Therefore, an integrated and holistic view of the system through a system thinking lens is required for the analysis of the environmental effects of shared vehicles usage, which was provided in this research.

Contributing to the literature, the current research is the first study that provides a holistic view on the environmental effects of the expansion of carsharing services by applying a CLD, as a tool to illustrate the causal structure of the system as a whole, and provides suitable strategies accordingly. The presented CLD reflects the complexity behind the system, which should be taken into account when making a decision in terms of each of the system players or draw conclusions on the environmental analysis of the shared vehicles lifecycle.

The presented framework is flexible to be used for modeling the environmental effects of the activities conducted in any of the presented subsystems. It can also be used as a basis not only for system dynamics modeling, but also for any analysis and simulation dealing with system thinking approach, such as agent-based modeling. Besides, transportation and environment policy makers can use this framework in order to better analyze the interactions between the main players of the urban transportation to see the potential conflict of interests among the stakeholders while making decisions to reduce the environmental concerns.

However, although the provided framework portrays a big map of transportation environmental effects in an urban area, it does not consider the diffusion of private and shared autonomous vehicles and their impacts on the whole system. It also does not deeply investigate the effects of each form of carsharing services separately. Therefore, further studies are suggested to be conducted on the interconnections between various modes of transportation and their relevant environmental effects.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Figure 4. Distribution of selected papers applying SD for transportation issues

Figure 5. the proposed CLD to illustrate the map of causalities between carsharing services and environment

Figure 6. the proposed comprehensive conceptual framework for the analysis of environmental effects of carsharing services from a system thinking perspective

Table 4. overview of the studies found in the literature using the system thinking approach for carsharing problems

Title	Author(s) and year	Case study	CLD	Quantitative SD modeling	Concentration	Hybrid method	Considering environmental impacts
The influence of e-carsharing schemes on electric vehicle adoption and carbon emissions: An emerging economy study	Luna, Uriona-Maldonado, Silva, & Vaz (2020)	Fortaleza, Brazil	✓	✓	E-carsharing impact on carbon emissions and electric vehicle adoption	-	✓
Assessment of the Development of Time-Sharing Electric Vehicles in Shanghai and Subsidy Implications: A System Dynamics Approach	Zhou, Hu, & Dai (2020)	Shanghai, China	✓	✓	Time-sharing electric vehicles	-	-
Market development of autonomous driving in Germany	Kaltenhäuser, Werdich, Dandl, & Bogenberger (2020)	Germany	Yes, but only the main framework is presented	✓	Autonomous vehicles	-	-
Towards a quantitative method to analyze the long-term innovation diffusion of automated vehicles technology using system dynamics	Nieuwenhuijsen, Correia, Milakis, van Arem, & van Daalen (2018)	Netherlands	✓	✓	Diffusion of automated vehicles-carsharing is considered in the model	-	-
Assessing the Long-term Effects of Autonomous Vehicles: A Speculative Approach	Gruel & Stanford (2016)	-	✓	-	Shared autonomous vehicles	-	-
Assessing the Effectiveness of Alternative Policies in Conjunction with Energy Efficiency Improvement Policy in India	Menon & Mahanty (2015)	India	✓	✓	Energy efficiency and GHG emission	-	✓
Combining technology roadmap and system dynamics simulation to support scenario-planning: A case of car-sharing service	Geum, Lee, & Park (2014)	Korea	✓	✓	Energy consumption and environmental burden	technology roadmap and SD	✓
A New System Dynamics Framework for Modeling Behavior of Vehicle Sharing Systems	Papanikolaou (2011)	-	yes, but not presented	✓	Resource allocation in a vehicle sharing	-	-

system

Table 5. Overview of the selected studies considering the interaction between transport systems and environment using the system thinking approach

Title	Author(s) and year	Case study	CLD	Quantitative SD modeling	Concentration	Hybrid method	Noticing shared mobility
Powertrain technologies and their impact on greenhouse gas emissions in key car markets	Vilchez & Jochem (2020)	China, France, Germany, India, Japan, and the US	✓	✓	Electric vehicle technologies	-	Carsharing is suggested to be considered in future research.
A Study of Urban City Traffic Congestion Governance Effectiveness Based on System Dynamics Simulation	He & Li (2019)	Chongqing, China	✓	✓	Urban traffic congestion	-	Carsharing rate is considered in the model.
A system dynamics model for emissions projection of hinterland transportation	Liu, Liu, Du, & Mu (2019)	Caofeidian port, China	✓	✓	Hinterland transportation	-	-
Coupled LMDI and system dynamics model for estimating urban CO2 emission mitigation potential in Shanghai, China	Gu, Fu, Thriveni, Fujita, & Ahn (2019)	Shanghai, China	✓	✓	Residential and urban transportation sectors	logarithmic mean divisia index (LMDI) and SD	-
Causes and effects of suburban traffic dynamics: A case study in a municipality close to Munich	Cullen (2019)	A suburban municipality of Munich, Germany	✓	-	Suburban traffic dynamics	-	Ridesharing and shared autonomous vehicles are touched upon.
Measuring effectiveness of carbon tax on Indian road passenger transport: A system dynamics approach	Gupta, Bandyopadhyay, and Singh (2019)	India	✓	✓	Carbon tax on road passenger transport	-	-
Effect of APCF policy on the haze pollution in China: A system dynamics approach	Jia, Liu, & Yan (2019)	China	✓	✓	Air pollution charging fee (APCF) policy	-	Bikesharing is noticed in policy implications and recommendation.
Impact assessment of supply-side and demand-side policies on energy consumption and CO2 emissions from urban passenger transportation: The case of Istanbul	Batur, Bayram, & Koc (2019)	Istanbul, Turkey	✓	✓	Energy consumption and CO2 emissions of urban motorized passenger transport system	-	-

Investigating the impact of e-bikes on modal share and greenhouse emissions: A system dynamic approach	Astegiano, Fermi, & Martino (2019)	Europe	Yes, but not presented	✓	E-bikes	-	Carsharing is considered as a transport mode.
Dynamic Feedback Analysis of Influencing Factors and Challenges of Dockless Bike-Sharing Sustainability in China	Yang, Li, Zhou, & Zhang (2019)	China	✓	-	Dockless bikesharing	-	-
The Brazilian urban mobility policy: The impact in São Paulo transport system using system dynamics	Fontoura, Chaves, & Ribeiro (2019)	São Paulo, Brazile	✓	✓	Urban transport system	-	Shared trips and carsharing are introduced as examples of mobility management strategies to improve transport options.
System dynamics model of taxi management in metropolises: Economic and environmental implications for Beijing	Wang et al. (2018)	Beijing, China	✓	✓	Taxi system	-	-
A Review of Electric Vehicle Lifecycle Emissions and Policy Recommendations to Increase EV Penetration in India	Vidhi & Shrivastava (2018)	New Delhi, India	Yes, but only the main framework is presented	-	Electric vehicle lifecycle emissions	-	Shared mobility is considered in policy recommendations.
A system dynamics model for CO2 emission mitigation policy design in road transport sector	Barisa & Rosa (2018)	Latvia	✓	✓	Road transport sector	-	-
System Dynamics Simulation of Income Distribution and Electric Vehicle Diffusion for Electricity Planning in South Africa	Pilla (2018)	South Africa	✓	✓	Electric vehicle diffusion and electricity planning	-	-
The Traffic Congestion Charging Fee Management Model Based on the System Dynamics Approach	Jia et al. (2017b)	Shanghai, China	✓	✓	Traffic congestion charging fee	-	-
Assessing the impacts of electric vehicles uptake: A System Dynamics approach	Caroleo, Pautasso, Osella, Palumbo, & Ferro (2017)	Piedmont, Italy	✓	✓	Electric vehicles	-	-
A system dynamics-based simulation model to evaluate regulatory policies for sustainable transportation planning	Sayyadi & Awasthi (2017)	-	✓	✓	Regulatory policies	-	Trip-sharing is focused on.

Describing and explaining urban freight transport by System Dynamics	Thaller, Niemann, Dahmen, Clausen, & Leerkamp (2017)	Berlin, Germany	✓	-	urban freight transport	-	-
A comparative, simulation supported study on the diffusion of battery electric vehicles in Norway and Sweden	Testa (2017)	Norway and Sweden	✓	✓	Battery electric vehicle diffusion	-	-
A System Dynamics Model for Determining the Traffic Congestion Charges and Subsidies	Jia, Yan, Shen, & Zheng (2017a)	Shanghai, China	✓	✓	Traffic congestion	-	-
Investigating carbon footprint reduction potential of public transportation in United States: A system dynamics approach	Ercan, Onat, & Tatari (2016)	USA	✓	✓	Public transportation	-	Ridesharing is suggested to be considered in future research.
A system dynamics-based market agent model simulating future powertrain technology transition: Scenarios in the EU light duty vehicle road transport sector	Pasaoglu et al. (2016)	EU	✓	✓	EU powertrain technology transition	Agent-based modeling and SD	-
Analysis of supply-push strategies governing the transition to biofuel vehicles in a market-oriented renewable energy system	Shafiei et al. (2016)	Iceland	✓	✓	Market development of biofuel vehicles	-	-
A system dynamics approach to scenario analysis for urban passenger transport energy consumption and CO2 emissions: A case study of Beijing	X. Liu, Ma, Tian, Jia, & Li (2015)	Beijing, China	✓	✓	Urban passenger transport	-	-
Comparative analysis of hydrogen, biofuels and electricity transitional pathways to sustainable transport in a renewable-based energy system	Shafiei, Davidsdottir, Leaver, Stefansson, & Asgeirsson (2015)	Iceland	✓	✓	Hydrogen, biofuels and electricity transitional pathways to sustainable transport	-	-
Evaluation of sustainable policy in urban transportation using system dynamics and world cities data: A case study in Isfahan	Haghshenas, Vaziri, & Gholamialam (2015)	Isfahan, Iran	✓	✓	Urban transportation	-	Carsharing and carpooling are considered in scenarios in a general way.
A system dynamics modeling for urban air pollution: A case study of Tehran, Iran	Vafa-Arani, Jahani, Dashti, Heydari, &	Tehran, Iran	✓	✓	Urban transportation and air polluting	-	-

	Moazen (2014)				industries		
Integrated Agent-based and System Dynamics Modelling for Simulation of Sustainable Mobility	Shafiei, Stefansson, Asgeirsson, Davidsdottir, & Raberto (2013)	Iceland	✓	✓	Diffusion of alternative fuel vehicles	Agent-based modeling and SD	-
System dynamics modeling for urban energy consumption and CO2 emissions: A case study of Beijing, China	Feng, Chen, & Zhang (2013)	Beijing, China	✓	✓	Urban energy consumption	-	-
Dynamic and multidimensional measurement of product-service system (PSS) sustainability: a triple bottom line (TBL)-based system dynamics approach	Lee, Geum, Lee, & Park (2012)	Seoul, South Korea	✓	✓	Public bicycle system	-	-
A System Dynamics Model for Urban Low-Carbon Transport and Simulation in the City of Shanghai, China	Lei, Zhang, & Li (2012)	Shanghai, China	✓	✓	Urban transportation	-	-
Factors affecting future demand for electric vehicles: A model-based study	Shepherd, Bonsall, & Harrison (2012)	UK	✓	✓	Demand for electric vehicles	-	-
A Systems Dynamics Approach to Explore Traffic Congestion and Air Pollution Link in the City of Accra, Ghana	Armah, Yawson, & Pappoe (2010)	Accra, Ghana	✓	-	Traffic congestion	-	-
Impact assessment in the automotive industry: mandatory market introduction of alternative powertrain technologies	Walther, Wansart, Kieckhäfer, Schnieder, & Spengler (2010)	California, USA	✓	✓	Customer demand for alternative powertrains and regulatory compliance	-	-
A System Dynamics Energy Model for a Sustainable Transportation System	Armenia, Baldoni, Falsini, & Taibi (2010)	EU countries	✓	✓	Road transport sector	-	-
A system dynamics model of CO2 mitigation in China's inter-city passenger transport	Han & Hayashi (2008)	China	✓	✓	Inter-city passenger transport	-	-
System Dynamics Model of Urban Transportation System and Its Application	J. Wang, Lu, & Peng (2008)	Dalian, China	✓	✓	Urban transportation system	-	-
Simulating a combination of feebates and scrappage incentives to reduce automobile	BenDor & Ford	-	Yes, but only the	✓	Financial incentives to promote the sale	-	-

emissions	(2006)		main framework is presented		and use of cleaner vehicles		
Sustainable Transportation System: A System Dynamics Approach	Yevdokimov (2002)	-	No (only framework)	-	Sustainable transport system	-	-

Table 6. Selected main identified loops and causality chains in the proposed CLD

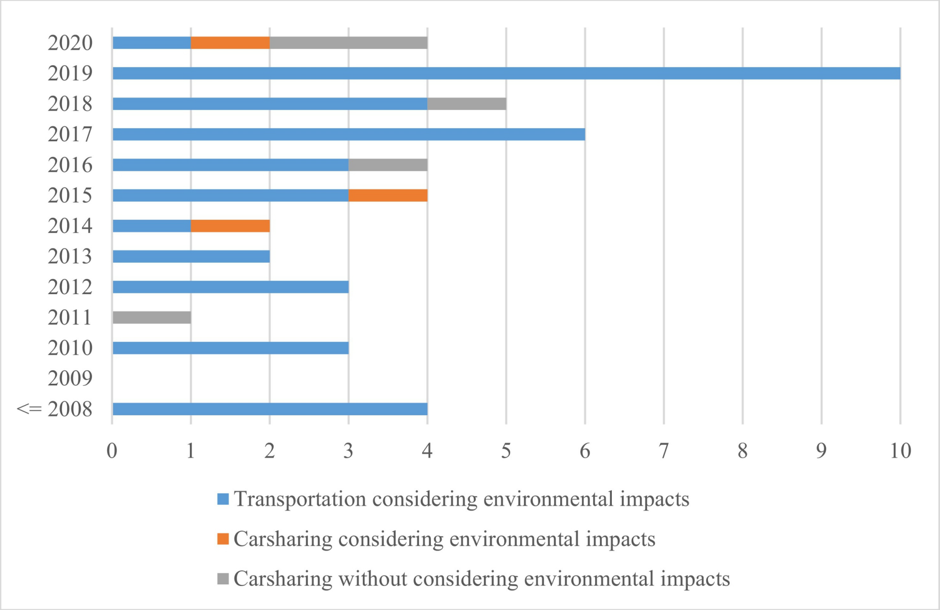
Loop no.	Loop name	Description	Environmental effect	Important causality chain(s)	Environmental effects considering causality chain(s)	Proposed managerial strategies
B1	Carsharing rocks!	Congestion + → demand for SVs + → using CS services + → congestion -	Air pollution (-) GHG emission (-) Noise pollution (-)	Availability of SVs + → using CS services +		Supporting the expansion of CS platforms
R1	Beware of the rocks!	Demand for SVs + → using CS services + → congestion + → demand for SVs +	Air pollution (+) GHG emission (+) Noise pollution (+)	Private parking place - → demand for SVs + Population consumption behavior → demand for SVs + Availability of SVs +→ using CS services + Built environment → road capacity → congestion	Change of land use patterns	Limiting the CS fleet size
B2	Towards circular economy	(strategies towards the reduction of air pollution/ GHG emission) → decision to generate or expand CS platforms + → … → using CS services + → distance traveled by FTE/GE SVs + → utilization of vehicle in its lifecycle + → demand for new PCs (by users of CS services)- → demand for new vehicles - → manufacturing FTE/GE vehicles - → air pollution/GHG emission -	Air pollution (-) GHG emission (-)	Diffusion of technology → decision to generate or expand CS platforms + Diffusion of technology (real-time information) + → availability of SVs +		Supporting the expansion of CS platforms
B3	Why too much waste?	(strategies towards the reduction of air pollution/ GHG emission) → decision to generate or expand CS platforms + → … → using CS services + → distance traveled by FTE/GE SVs + → distance traveled by FTE/GE non-shared PCs - → utilization of vehicle in its lifecycle - → need for EOL processes for vehicles - → demand for new PCs (by users of CS services) - → demand for new vehicles - → manufacturing FTE/GE vehicles - → air pollution/ GHG emission -	Air pollution (-) GHG emission (-)	need for EOL processes for vehicles - → vehicle EOL process - → air pollution/ GHG emission/ water and soil pollution/ noise pollution- / landfill capacity +	air pollution (-) GHG emission (-) water and soil pollution (-) noise pollution (-) landfill capacity (+)	Supporting the expansion of CS platforms
B4	Drive green!	Congestion + → (TDM strategies) → decision to generate or expand CS platforms + → demand for new SVs + → demand for new vehicles + → purchasing FTE/GE vehicles + → CS fleet size + → availability of SVs + → using CS services + →	Air pollution (-) GHG emission (-) Noise pollution (-)	Diffusion of technology (real-time information) + → availability of SVs + Diffusion of technology → decision to generate or expand CS platforms +	Air pollution (-) GHG emission (-)	Supporting the shift towards less pollutant vehicles and ZEVs Using renewable energies for

congestion -	Manufacturing FTE vehicles + → purchasing FTE vehicles+ → (using FTE SVs) + → air pollution/ GHG emission + Manufacturing GE vehicles + → purchasing GE vehicles+ (using green-engine SVs) + → air pollution/ GHG emission -	electricity production

Graphical abstract

Highlights

- Four drivers of environmental effects were identified and considered as subsystems
- A causal-loop diagram was built to visualize interconnections among the subsystems
- Five main causal loops were identified, and relevant strategies were suggested
- A holistic system thinking framework was presented for CSS environmental effects


2020
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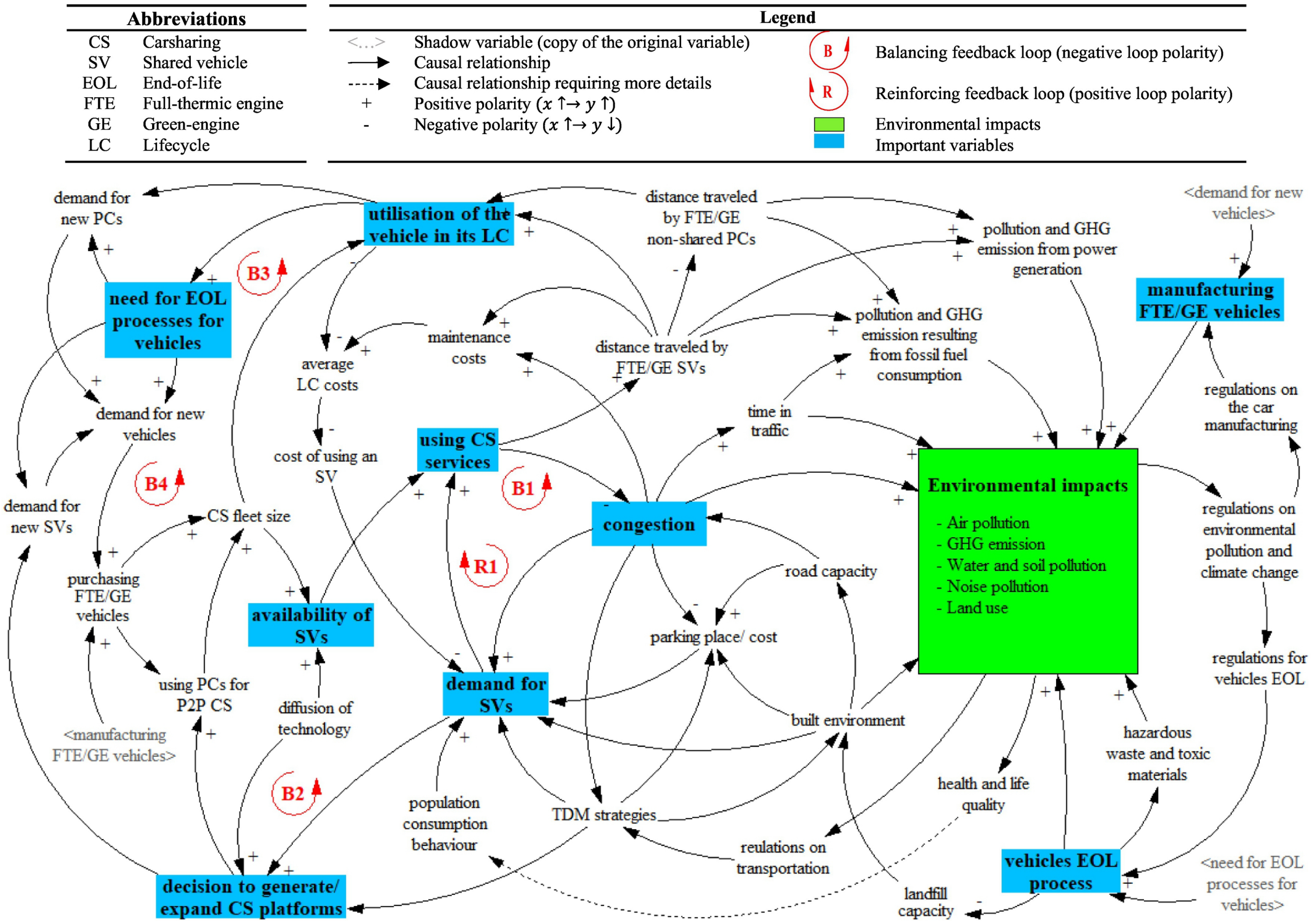
Transportation considering environmental impacts
Carsharing considering environmental impacts
Carsharing without considering environmental impacts

Figure 1



Abbreviations
CS Carsharing
SV Shared vehicle
EOL End-of-life
FTE Full-thermic engine
GE Green-engine
LC Lifecycle
Legend
<…> Shadow variable (copy of the original variable)
Causal relationship
Causal relationship requiring more details
+ Positive polarity (x ↑→ y ↑)
- Negative polarity (x ↑→ y ↓)
B Balancing feedback loop (negative loop polarity)
R Reinforcing feedback loop (positive loop polarity)
Environmental impacts
Important variables
demand for new PCs
utilisation of the vehicle in its LC
distance traveled by FTE/GE non-shared PCs
pollution and GHG emission from power generation
<demand for new vehicles>
need for EOL processes for vehicles
B3
maintenance costs
average LC costs
distance traveled by FTE/GE SVs
pollution and GHG emission resulting from fossil fuel consumption
manufacturing FTE/GE vehicles
demand for new vehicles
regulations on the car manufacturing
time in traffic
using CS services
cost of using an SV
B4
B1
Environmental impacts
- Air pollution
- GHG emission
- Water and soil pollution
- Noise pollution
- Land use
demand for new SVs
CS fleet size
congestion
regulations on environmental pollution and climate change
purchasing FTE/GE vehicles
R1
road capacity
availability of SVs
parking place/ cost
regulations for vehicles EOL
using PCs for P2P CS
diffusion of technology
demand for SVs
built environment
<manufacturing FTE/GE vehicles>
hazardous waste and toxic materials
B2
population consumption behaviour
TDM strategies
health and life quality
reulations on transportation
vehicles EOL process
<need for EOL processes for vehicles>
decision to generate/ expand CS platforms
landfill capacity

Figure 2

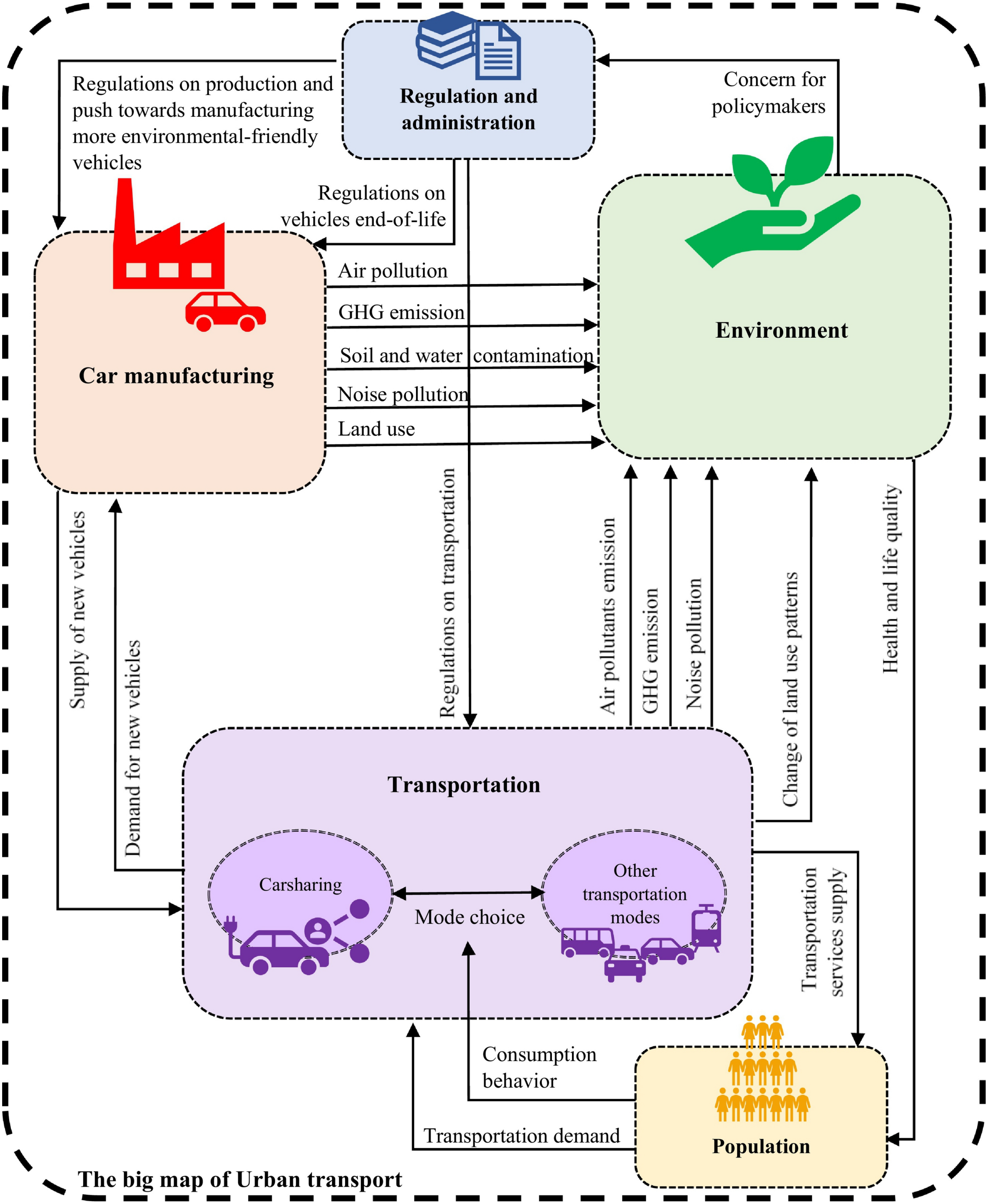

Regulation and administration
Regulations on production and push towards manufacturing more environmental-friendly vehicles
Concern for policymakers
Regulations on vehicles end-of-life
Car manufacturing
Environment
Air pollution
GHG emission
Soil and water contamination
Noise pollution
Land use
Supply of new vehicles
Demand for new vehicles
Regulations on transportation
Air pollutants emission
GHG emission
Noise pollution
Change of land use patterns
Health and life quality
Transportation
Carsharing
Mode choice
Other transportation modes
Transportation services supply
Consumption behavior
Transportation demand
Population
The big map of Urban transport

Figure 3