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Air emissions impacts of modal diversion patterns induced by one-way car sharing: A case study from the city of Turin

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A R T I C L E I N F O

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A B S T R A C T

This paper aims to understand to which extent the spread of one-way car sharing in an urban area can contribute to limit air pollutants and greenhouse gas emissions by diverting trips from existing travel means. Modal switch models informed the definition of five mobility scenarios in the city of Turin (Italy). Related emissions were quantified to understand how to maximise the positive environmental impacts of car sharing. Models' results indicate that the car sharing modal share might increase up to a maximum of 10%. The diverted travel demand is mainly subtracted from private cars, however environmental benefits are partially offset by switches from public transport and active modes. The planning scenario would lead to a reduction of the externalities related to the emissions produced by the whole transport system of 1% in terms of social costs. Such benefits can be increased up to 3.6% by promoting electric car sharing fleets.

1. Introduction

Car sharing is one of the first shared mobility services that has spread throughout European cities in the past decade. The principle of car sharing is simple: people registered to the service can access to a fleet of shared cars and pay for their use. It represents a kind of short term rental, without interaction with the service provider, since the vehicle location, the access to the car, and the billing is generally managed through a smartphone application. According to their operational characteristics, car sharing services can be grouped in three main schemes, namely roundtrip station-based, one-way station-based and one-way free-floating (Shaheen et al., 2019). In roundtrip services, the user needs to pick-up and drop a shared car in the same dedicated parking station. On the other hand, in one-way services shared cars can be picked up and dropped in different dedicated stations or any parking slots within an operative area (free-floating).

Since 2009, when car sharing was available in 14 European countries (Loose, 2010), the service has grown both in terms of geographical coverage – it was found in 25 EU countries at the end of 2017 (Rodenbach et al., 2018) – and in the number of shared vehicles and customers, as reported in Fig. 1 below.

The year 2012 marked an additional boost of such services, basically due to the introduction of the above mentioned one-way free-floating schemes in many cities.

Car sharing is expected to have positive impacts on both travel behaviours and the environment. The "pay per use" solution, without the typical fixed costs of a private car, should lead the car sharing members to reconsider the need of owning cars. More conscious of the real cost of driving, users are expected to better evaluate all the transport solutions for their travels (Cervero et al.,

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2007). Furthermore, the use of shared cars equipped with less pollutant engines (sometimes electric) compared to the average city fleet, might reduce the greenhouse gas (GHG) and air pollution emissions (Barth and Shaheen, 2002).

Car sharing impacts have been extensively analysed by researchers to help decision makers understanding whether these systems can be an effective tool to improve sustainability. Many studies report positive impacts on greenhouse emissions related to car sharing adoption, although the magnitude of such impacts may vary according to different factors – among others the study area, the built environment, the transport offer and the car sharing scheme. The reduction in greenhouse gas and air pollutant emissions are generally associated to lower car ownership level reported by car sharing members (Becker et al., 2018; Cervero et al., 2007; Ko et al., 2017; Martin et al., 2010; Martin and Shaheen, 2016). Moreover, if car sharing services are provided with electric vehicles, they contribute to decrease air pollutions emissions even strongly (Hu et al., 2018) also promoting the acceptance of private electric vehicles (Schlüter and Weyer, 2019; Shaheen et al., 2002). However, few studies have analysed the impact on emissions deriving from the modal diversion from different travel means towards car sharing, rather than from the decrease of car ownership (Rodier and Shaheen, 2003). Changes in travel demand are often reported among car sharing members (Clewlow, 2016), even with contradictory results (Ceccato and Diana, 2018; Cervero et al., 2004). In this perspective, car sharing should not erode travel demand from more sustainable modes, such as public transport and active means. Understanding the relationship between car sharing and the other travel means is therefore crucial for both policy makers, whose target is to promote sustainable travels, and car sharing providers, who aim to increase as much as possible the use of their fleets.

Some authors tried to forecast car sharing potential demand using models that allow to predict future trips (Heilig et al., 2017; Rotaris et al., 2019), albeit without considering the previously used travel modes (El Zarwi et al., 2017; Li et al., 2018), thus overlooking modal substitution patterns. Finally, modelling results sometimes are not used to quantify car sharing modal switch related impacts, such as changes in GHG and air pollution emissions, under different scenarios (Costain et al., 2012; Heilig et al., 2017).

Given the above state of the art, this paper aims to quantitatively estimate the impacts in terms of air pollution and greenhouse gas emissions related to the modal diversion patterns at the individual trip level from existing travel means to car sharing. Therefore, this paper investigates the environmental consequences of daily modal choices enabled by car sharing services, without considering car ownership changes that are likely to have an even more significant environmental impact. In particular, modal switch models calibrated on a Stated-preferences travel survey administered to a representative sample of the population living in Turin (Italy) are applied to another dataset with real trips performed in the same area. Different mobility scenarios are developed, and related air pollutants and greenhouse gas emissions are quantified to understand which conditions are necessary to reach the scenario that maximises the positive impacts of car sharing.

The city of Turin represents a good case study for two main reasons. First, the city presents one of the worst air quality in Europe (European Environmental Agency, 2019; Legambiente, 2019) due to the geographical position (Turin is located in the Po valley, surrounded on the North-Western side by the Alps) and the high motorisation rate, with a consequent high share of car trips. Second, at the beginning of 2019, there were three car sharing providers with about 900 cars and more than 181,000 members (Ciuffini et al., 2019). Two operators provide a free-floating scheme with gasoline vehicles (710 cars). The other operator provides a one-way service with electric vehicles (190 cars) and charging stations (94) distributed across the city.

The remainder of this paper is structured as follows. Section 2 presents a literature review focused on car sharing impacts on greenhouse gas and air pollutants emissions. Section 3 describes the data and methods used in this study. Scenarios and estimated emissions are presented and discussed in Section 4. Section 5 concludes the paper with potential policy implications.

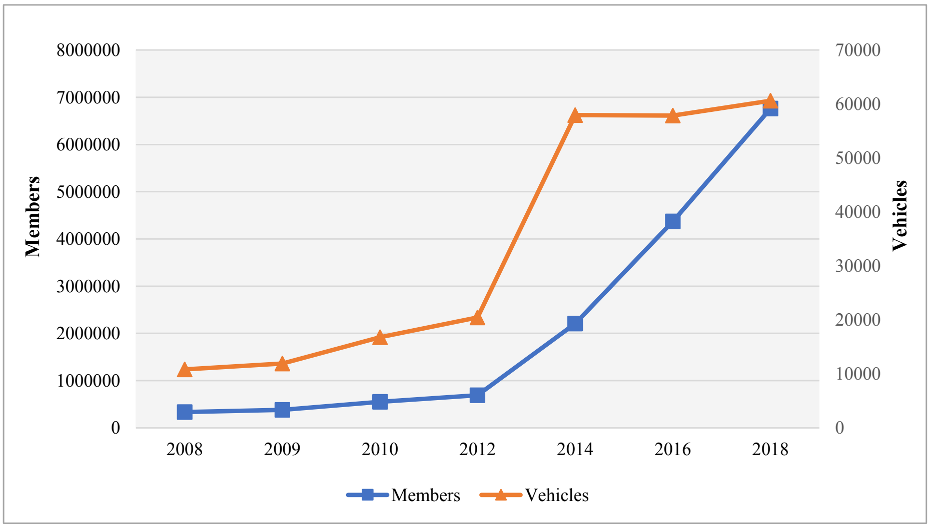

Fig. 1. Car sharing trends in European countries (27) – Data retrieved from (Loose, 2010; Shaheen et al., 2020).

2. Background

The estimation of greenhouse gas and air pollutant emissions in car sharing studies is generally associated with the reduction of the Vehicles Miles/Kilometres Travelled (VMT/VKT) reported by car sharing members (Cohen and Shaheen, 2016). The VKT reduction derives from two main impacts related to the introduction of car sharing, namely the reduction in car ownership and the shift from private motorised means towards public transport and active modes. In addition, the emissions reduction is generally associated to the characteristics of the shared fleet, since car sharing vehicles are small, equipped with more fuel-efficient and low-polluting engines (Barth and Shaheen, 2002; Cervero et al., 2007; Cohen and Shaheen, 2016; Giesel and Nobis, 2016). Therefore, car sharing impacts on emissions are ultimately depending on a wide set of factors (Shams Esfandabadi et al., 2020), including the specific operational scheme among the previously mentioned ones (basically, roundtrip versus one way). Different studies that we review in the following are focusing on some specific aspects.

Martin and Shaheen (2011) evaluated the annual changes in GHG emissions considering the changes in vehicle ownership and travel patterns reported by roundtrip car sharing members in United States and Canada. They found that most of the households, which were car-free before joining car sharing, increased their emissions afterwards by gaining access to a car. On the other hand, the remaining households decreased their emissions by reducing car ownership levels and VMT. The estimated emission reductions outweigh the small emission increases, therefore the overall effect was an average reduction of 0.58 tons of GHG per year per household (0.84 considering also foregone vehicle purchases). A similar result was found by the same authors in a more recent study about the impacts of a free-floating car sharing service, car2go, in five North American cities (Martin and Shaheen, 2016). They found a minority of car sharing members who shed a car and drove less after joining car sharing. These actions produced a reduction of the VMT that exceeded the additional driving of car-free members. Therefore, because of the reduction of car ownership and VMT, the authors estimated a decreasing of GHG emission ranging from 5.5 to 12.7 tons per year per shared vehicle.

Another study carried out in the Netherlands aimed to quantify the effects of car sharing car ownership, car use and CO_2 emissions (Nijland and van Meerkerk, 2017). They found that members reduced their VKT after joining car sharing of 15–20%. Such reduction was mainly ascribed to the decrease in car ownership. Through a well-to-wheel (WTW) analysis the authors estimated a reduction of CO_2 emissions ranging from 0.24 to 0.39 tons per user per year.

Within the longitudinal study on City CarShare members in San Francisco, California, Cervero et al. (2007) observed that the biggest environmental benefit of roundtrip car sharing derives from reduced gasoline consumption, which was related to a decline of about 67% of the VMT by members of the service over the longer term (2001 to 2005). Such reduction was attributable to a combination of shifts to green modes, shorter travel, and to relatively high occupancy levels for private car trips.

Following a more holistic approach, Chen and Kockelman quantified the life-cycle reduction in energy and GHG emissions of shared cars compared to private vehicles, as a result of selected travellers adopting car sharing in United States (Chen and Kockelman, 2016). Their calculations considered the changes in car ownership and related changes in parking infrastructure demand, the shift to alternative modes, VKT changes, and fuel efficiency improvements of the car sharing fleet. They estimated a reduction of about 51% of the transportation energy use and GHG emissions per member, highlighting that the major contribution was given by the avoided private-vehicle VKT.

Some authors adopted a simulation approach to quantify car sharing effects on GHG emissions. For instance, Firnkorn and Müller (2011) developed a model to forecast the car sharing environmental impact using data from a mobility survey administered to car2go members in Ulm, Germany. Considering changes in car ownership, VMT and modal shift, they obtained a decreasing of CO_2, on a year base, ranging from 0.15 to 0.31 tons per member of the free-floating service.

Rabbitt and Ghosh (2013) estimated the market potential of car sharing in Dublin, Ireland, using multiple alternative scenarios. Applying such scenarios to the travel information of the Irish population, they predict a reduction of 86 kt of CO_2 per year (895 kt with appropriate policies and financial support for car sharing). A different approach was used by Baptista et al. (2014). They estimated energy and environmental impacts of car sharing in the city of Lisbon, Portugal, by considering a possible technology change in car sharing engine rather than considering a change in the travel demand. They found that replacing the existing car sharing fleet with hybrid electric vehicles (HEVs) or with electric vehicles (EVs), annual CO_2 emissions can be reduced by 35% and 65%, respectively.

Rodier and Shaheen (2003) used a travel demand model to evaluate potential effects of car sharing, real-time transit information services, and car-free housing policy in the Sacramento region. In particular, they quantified travel, emission, and economic benefits in three "innovative mobility scenarios", forecast to 2025. Considering the car sharing scenario (without the effects of the other interventions) they found a modest reduction in vehicle trips and VMT, to which corresponded a reduction of CO, NO_x, and PM emissions of 0.1%, 0.04%, and 0.2%, respectively.

Differently from the above studies that largely evaluate environmental effects of car sharing services on members only, with the present work we attempt to measure the environmental effects in terms of GHG and air pollution emissions using modal switch models, therefore considering the relationship among car sharing and other modes at the more disaggregate trip level.

This approach can be used to estimate the potential travel demand that can be satisfied with car sharing on the city population, not only among individuals participating to car sharing. Moreover, the approach is independent from any car ownership reduction assumption. Once predicted the travel demand for different travel means, the subsequent travelled distances, and environmental impacts can be evaluated.

3. Data collection and methods

3.1. Study area

The area under investigation is the city of Turin, a municipality located in the North-Western part of Italy. Turin is one of the largest cities in Italy, with about 900,000 inhabitants living on about 130 square kilometres (Agenzia per la Mobilità Metropolitana e Regionale, 2015).

The study area is characterised by one of the highest motorisation rates in Italy: in 2018, there were 653 private cars per 1000 inhabitants (ISFORT, 2019). On the other hand, the offer of public transport is made up of one metro line, 83 bus lines, and eight tram lines (Gruppo Torinese Trasporti S.p.a., 2016). 34.4% of the trips starting in Turin is performed with public transport (Agenzia per la Mobilità Metropolitana e Regionale, 2015), while the highest share of trips is performed with private cars, with consequences in terms of congestion and air pollution. In order to tackle such problems, among other solutions, the city administration enlarged the traditional transport offer with shared mobility services, such as bike sharing, car sharing, and more recently, e-scooter sharing.

In 2015 two free-floating services started their operations (car2go and Enjoy) with gasoline vehicles; the offer was enlarged with a full-electric one-way station-based service (Bluetorino) in 2016. In 2019, the car sharing offer in Turin was composed of 720 gasoline vehicles in free-floating (provided by ShareNow – previously car2go - and Enjoy) and about 190 electric cars distributed in 94 charging stations. The operational areas and the stations of the car sharing services operating in Turin are shown in Fig. 2 below. It can be noted that both station-based and free-floating services currently operate in a inner city area of Turin, which roughly cover the 40% of the whole surface of the Turin municipality (130 km^2).

The customer base has steadily grown since 2015. At the end of 2018, the electric car sharing of Turin accounted for 3000 members, whereas the two free-floating schemes jointly reported having about 181,000 members (Ciuffini et al., 2019). Additionally, according to the official statistics reported by the two free-floating services, in 2018, Turin members made some 1,642,360 rents and drove about 8 million kilometres (Ciuffini et al., 2019). Such information will be properly considered in the definition of the base scenario that is detailed in paragraph 3.4 below.

3.2. Survey activities

As mentioned in the introduction, to develop this study two datasets containing trip level information were considered. The first one comes from an existing Stated-preferences survey (SP) (Ceccato and Diana, 2018) to evaluate the potential of car sharing in attracting the travel demand. The second considered a dataset from a Revealed-preferences survey (RP) specifically carried out in the same area for the purposes of the present research. The analysis here presented is based on the combination of two different surveys due to the need to limit the length of the questionnaire and reduce the respondent burden, which would not have allowed us to gather all the required information at once.

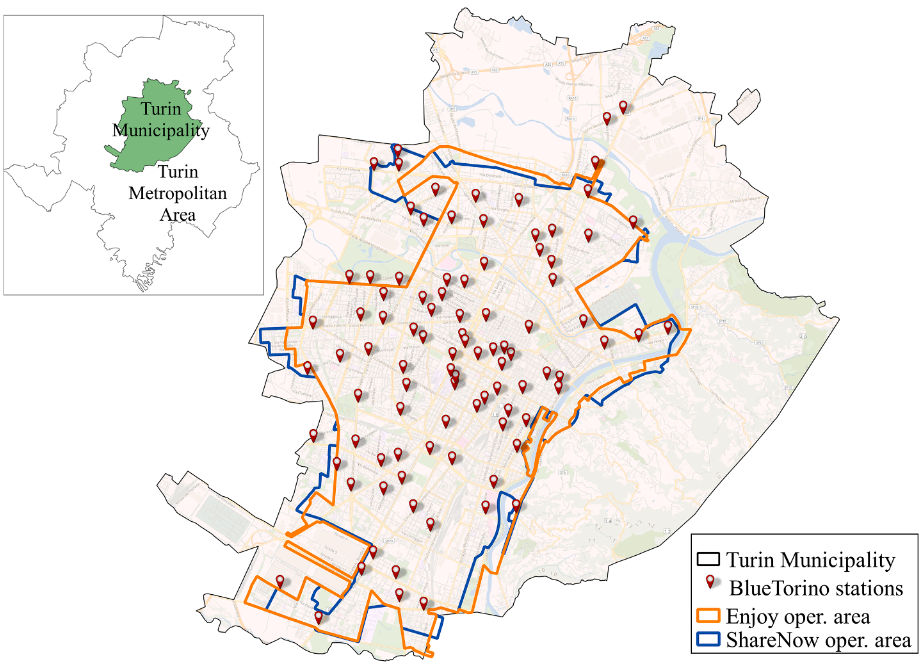

Fig. 2. Operational areas and stations of the car sharing services operating in Turin.

3.2.1. Stated-preferences survey

An extensive travel survey was administered in the city of Turin through both Computer Assisted Web Interviewing (CAWI) and Computer Assisted Telephone Interviewing (CATI) protocols, seven days a week in three different 4-weeks periods (September–October 2016, February 2017, and June 2017), to a representative sample of the population living in the Turin metropolitan area. The data collection activity ended with 4466 complete questionnaires collected. In this study however, only 2293 (51.3%) observations were retained since respondents living outside the urban area of Turin, those who did not travel the day before the interview or had only trips longer than 50 km were not considered. Along with a complete travel diary and questions about socioeconomic characteristics of the respondents and of their households, one section of such survey focused on a randomly selected trip among those listed in the travel diary. Attitudinal questions on that trip and stated-preference (SP) experiments were used to investigate related mode switching attitudes. Since car sharing was one of the alternative modes proposed in the SP experiments, it was possible to evaluate the attributes that influence the switching intentions towards car sharing. In particular, respondents were asked to state their willingness to switch to car sharing from the "base mode", represented by the currently used mode, to car sharing considering a given variation of trip cost and travel times compared to the base mode. The reader is referred to (Ceccato & Diana, 2018) for additional details on this survey.

3.2.2. Revealed-preferences survey

The RP survey was run in the city of Turin between the 13th and the 28th of May 2019, as one of the activities of the European project STARS (http://stars-h2020.eu/). Incidentally, the same survey was also fielded in Milan, however related results are not considered here. The survey format followed the cross-sectional travel survey standard practice (BMVI, 2019; Cornick et al., 2019; Ortúzar and Willumsen, 2011), with the addition of specific car sharing questions in line with some existing studies (Ceccato and Diana, 2018; Schreier et al., 2018).

The survey was aimed at understanding the differences between car sharing users and non-users in terms of mobility habits (e.g., frequency of usage of different transport means, public transport and bike sharing subscriptions), but also the changes in car ownership and in the use of different modes to perform within-city trips (Chicco et al., 2020b). Additionally, interviewees were asked to provide information on the last trip performed using either car sharing (users) or any other mode (non-users). Trip characteristics were properly enriched using information from Google Directions API (e.g., distance, in-vehicle and walking time, waiting time at transit stop), public transport agencies, and car sharing providers. Finally, socio-demographic information at both the household (e.g., number of members, workers, cars, income) and the individual (education, occupational status) level were collected.

The survey was administered to a representative sample of licensed drivers living in the city of Turin, with the help of an external poll firm that could rely on more than 60,000 panellists in the whole Italy. Sampling and weighting methods were employed to match citywide individual population distributions on two key demographic variables, namely gender and age. Both computer-assisted web interviews (CAWI) and computer-assisted telephone interviews (CATI) were used to maximise the coverage.

Along with those respondents who declared of being enrolled in a car sharing service that was encountered by chance during the survey distribution (about 24% of the respondents), car sharing members were oversampled to obtain a more consistent group. As a result, 436 completed questionnaires were collected: 181 respondents declared of being registered to a car sharing service whereas 255 did not. The complete dataset can be found on Zenodo (Chicco et al., 2020a).

Since the aim of the paper is to estimate the car sharing impact on emissions related to the switching intention from the mode used to car sharing in performing different within-city trips, only 255 non-members interviews were considered to estimate such switches, while the remainder were analysed to understand what would happen if car sharing were not any more available, which is one of the below introduced scenarios.

3.3. Modal switch models and trip-level analyses used to define mobility scenarios

Following the methodology described in Ceccato and Diana (2018), the SP dataset was used to calibrate binomial logit models that predict switching intentions from the currently used mode to car sharing. Both socioeconomic characteristics of the respondent, of her household, and trip characteristics (distance, duration, generalised cost, purpose) were considered as potential explanatory variables.

Four distinct binomial switching models were developed by separately considering four main travel means, namely walk, bike, car, and public transport (PT). It is in fact necessary to take a multimodal perspective in the study of car sharing switching intentions to provide sound policy indications (Diana and Ceccato, 2019). Trip diverted from private car to car sharing are desirable, due to the worse environmental performances of the former, whereas switching trips from public transport or active means to car sharing should be discouraged.

Each model was specified also using a stepwise selection of the initial list of explanatory variables. In particular a forward selection was used, therefore each model started with no variables and at in each step the addition of one variable was tested using a chosen model fit criterion. The variable was retained if it produced the most statistically significant improvement of the fit. The final models were then estimated again only retaining the significant variables; their specification along with the final estimation results are reported in the following Table 1.

Intercept values were not significant for the three models with the smallest sample size and in many instances of the fourth model as well, when it was estimated with a subsample whose dimension is comparable with that of the previous three. Therefore intercepts are not estimated in all four final models for better consistency.

The reader is referred to Chicco et al. (2020b) for additional details about the modelling phase. In general terms, concerning the interpretation of the results, the signs of the coefficients of the explanatory variables are in line previous research findings. We omit

Table 1
Binomial logit estimation for switching intention from different transport modes trips to car sharing - significant coefficients and statistics.

Variable	Walk to CS	Bike to CS	Car to CS	PT to CS
Age	−0.538***	−0.042**	−0.014***	−0.477***
Gender (ref: Male)				−0.672*
Educ. – Master's degree or PhD (ref: High school diploma)			0.377*	
Empl. – Work at home (ref: Student)				−0.925*
Number of household's members		0.954*		
Number of children (<18 years)	0.597†		0.220*	
Number of household's workers	0.754**	−1.380*		
Avg. household's monthly income [k€]		0.769†	0.147**	
Number of cars per driving licence			−0.748***	−0.853*
Number of household's cars	−1.240**	−1.710*		
Bike sharing subscription (ref: No)				1.550*
Public transit pass (ref: No)		1.860		
Bike monthly use frequency			0.038**	
Car monthly use frequency		0.108**		0.064***
PT monthly use frequency		−0.055†		
Trip purpose – NHB (ref: HBW)		−1.600		
Destination within a LTZ (ref: No)			−1.360†	
Holiday (ref: No)				0.767†
Current mode trip cost [€]			−0.318***	−0.401*
Current mode trip distance [m]		−3.21E−04*		−3.65E−05*
Current mode trip duration [min]	−0.059**			
Current mode waiting time [min]				−0.032†
Current mode walking distance [m]		−0.002†		
Car sharing trip cost [€]	−0.859†	−0.785†	−0.522***	−0.387*
Car sharing walking duration [min]	−0.071**			
Statistics				
Sample size	347	79	1329	538
Init. log likelihood	−240.52	−54.76	−921.19	−372.91
Final log likelihood	−74.61	−39.00	−743.06	−214.15
Likelihood ratio test for the init. model	331.83	31.51	356.26	317.53
Rho-square for the init. model	0.69	0.29	0.19	0.43
Akaike Information Criterion	165.21	102.00	1504.12	450.30
Bayesian Information Criterion	196.01	130.44	1550.85	497.46

Significance codes:
*** $p < 0.001$.
** $p < 0.01$.
* $p < 0.05$.
† $p < 0.10$.

thorough comments on the effect of each explanatory variable on the outcome of different switch models, since they are not the focus of the present paper.

The above models provided trip-level switching probabilities from each of these four modes to car sharing as a function of the above mentioned characteristics of both trips and travellers. Considering then the trips observed in the RP surveys as a representative sample of the trips made in the study area, the application of such switching probabilities gave an estimation of the number of trips of the sample that could be diverted from each traditional means to car sharing.

The last step involved aggregating the results and expanding them to the universe of trips in the study area. To this effect, the number of average daily trips per person (2.3 according to Turin metropolitan mobility agency report (Agenzia per la Mobilità Metropolitana e Regionale, 2015) was multiplied times the number of Turin inhabitants aged 18 or more according to the stratified sampling procedure.

The population-level modal split of Turin resulting from the RP survey was compared to existing statistics[1] to check for consistency. A good match was found, albeit the RP survey recorded a larger proportion of walk trips, probably because these trips are traditionally under-reported in official statistics (Agrawal and Schimek, 2007; Westat, 2019).

3.4. Definition of mobility scenarios

The above introduced modal switch models were used to estimate the potential travel demand that can be satisfied with car sharing, from which changes in distance travelled with different travel means and related emissions can be derived. In particular, the knowledge of the exogenous variables influencing the switching probabilities allowed us to test the combination of different

[1] http://www.epomm.eu/tems/result_city.phtml?city=279&map=1 (EPOMM - Turin modal split) - Accessed July 7th, 2020

interventions that a public authority might carry out to maximise the number of switching trips from private cars towards car sharing, and to minimise those from other more sustainable modes (e.g. public transport and active modes). Additionally, some scenarios were directly created from the survey data, rather than through the application of switching models, since they represent either the observed situation or a hypothetical situation with no car sharing services are available in the city.

Five scenarios were defined and evaluated in this study.

3.4.1. Base scenario

This scenario is informed only by the RP survey dataset, where observed mobility patterns of the sample are expanded to the universe of daily trips in the study area. However, car sharing trips would have been missed since we did not consider the oversampled responses from car sharing members (see above). Therefore, the daily number of car sharing trips made in the city of Turin was added to the base scenario by considering published statistics on car sharing usage (Ciuffini et al., 2019). Considering the time point to which both the RP dataset and the published statistics can be referred, the base scenario can be considered as a representation of the mobility situation in Turin at the beginning of 2019.

3.4.2. Growth scenario

This scenario is the result of the application of the switch models to the daily trips performed by non-members survey respondents, then expanded to the universe of daily trips of Turin. Therefore, it assumes that the car sharing offer would be expanded until all trips in the study area can be served with the same levels of service of that of private cars, both in terms of travel times including walk times to/from the parking spots at origins and destinations and costs. These latter two conditions are clearly not (yet) met in reality, mainly because existing car sharing systems cannot provide the pervasiveness of private cars in the whole city to be economically viable. In this scenario, no policy intervention is made to shape the car sharing demand.

We do not observe the same level of demand for car sharing services in the base and in the growth scenario since its performances are much lower in the former one. In other words, the growth scenario can be seen as an estimation of the maximum number of trips potentially served by car sharing. According to the configuration that such services might take in the future, such market share could indeed be lower, and this ceiling never reached.

It is also well known that SP surveys overestimate the actual behavioural change that would take place if the hypothetical choice under analysis would really be available. Concerning the latter point, it is however worth mentioning that the research design was based on a stated modal diversion concerning a trip that was really taken by the respondent, rather than developing an abstract modal choice task as commonly done. This was done also in light of reducing such respondent bias, as discussed in (Diana, 2010).

3.4.3. Planning scenario

Although the previous growth scenario provides an upper bound for the market share of car sharing services, it does not necessarily lead to a maximisation of its benefits in terms of reduction of the externalities of the transport system in a city. As already mentioned, the latter depends on the switching patterns between different modes and car sharing, where a maximisation of diverted trips from private cars and a minimisation of diverted trips from PT and active means is desirable.

The planning scenario is defined as the scenario that maximises the overall car sharing environmental benefits, expressed in terms of greenhouse and pollutants emissions reduction. Among the explanatory variables coming out from the modal switch models calibration, two were selected to run a sensitivity analysis and check how the car sharing demand is affected. The first variable is the cost of car sharing, directly linked with the car sharing fee: its increase should reduce the overall number diverted trips, especially those performed with null-cost modes (at least in terms of out of pocket cost), namely walk and bike. However, the increase of car sharing fare should also impact on the number of trips that might be diverted from both PT and private cars. Although the reduction of switches from PT is desired, the one from private cars is not. In this perspective, it would be advisable to act on a second variable that might help to decrease the attractiveness of private cars, namely its cost.

The actual cost of car sharing was determined by averaging the operators' tariffs in Turin, which are all based on a per time fare (0.22 €/min on average) for trips shorter than 50 km. The resulting car sharing costs for each trip were then increased according to the above mentioned sensitivity analysis to find out how modal diversion patterns would be affected.

The actual average cost of a private car trip in Turin was estimated considering perceived out-of-pocket rather than real costs, since the former rather than the latter shape the travel demand for such mode. The sum of fuel parking (if any), toll roads (if any) and pass costs to enter the limited traffic areas (if any), was used. Coming to the sensitivity analysis, only parking costs were considered as potentially changing, since they are under direct control of the city administration. Indeed, the limited traffic zone (LTZ) in Turin is currently designed to block access to private vehicles in certain hours of the day, except for residents[2]. The city administration is currently considering to introduce an access fee, but plans were not yet finalised at the time of this research and therefore this option was not considered in this study.

In order to evaluate the potential effects of an increase of both car sharing and parking costs on diverted trips to car sharing from different modes, the two costs were both varied in a range from 0% (growth scenario settings) up to 100% of increase with 5% increasing steps, therefore leading to 21x21 possible combinations. Concerning this sensitivity analysis, (Chicco et al., 2020b) note that, "*although the considered modelling framework assumes a fully compensatory choice protocol, thereby assuming that any variation in the*

[2] http://www.gtt.to.it/cms/ztl/permessi-di-circolazione-ztl – Accessed July 7th, 2020

*costs of the alternatives has an impact on the probability that the individual is making a choice, it advisable to limit the range of cost variations when defining realistic policy scenarios [...]. On the one hand, there is a threshold below which changes are not perceived and therefore no behavioural changes are observed, leading to a well-known habit or behavioural inertia phenomenon. On the other, too sharp increases in parking costs might be considered unrealistic by respondents and, in any case, they would not be implemented by the relevant stakeholders. Given the fact that an hourly parking fare consists in a relatively small amount of money in absolute terms, previous research (*Tsamboulas, 2001*) has shown that an increase of up to 50% had little effect in changing behaviours, while the effect became substantial for increases of around 100%. Therefore we retain the latter as an upper bound, considering that policy-makers are probably not willing to increase costs even more than that but only to a (much) smaller amount. To sum up, we simulate the effect of increasing parking fares from 0% to 100% to study what would happen in a realistic policy scenario, however anticipating that cost changes of less than 50% would probably produce no effect independently on the modelling results."*

Travelled distances, the quantity of each pollutant mentioned above, GHG, and respective costs were assessed for each of the above mentioned combinations, following the methodology reported in Section 3.5 below. Then, to identify the maximum impact scenario, a cost evaluation of the related externalities was carried out by considering the coefficients reported in Table 3 of Section 3.5.2. The combination that minimises the sum of the monetary costs of greenhouse and pollutant emissions identified the planning scenario.

3.4.4. Fully electric planning scenario

This scenario is derived from the planning scenario by assuming a fully electrified car sharing fleet, rather than the current car sharing fleets composition in terms of engine characteristics and emission standards. Travel demand invariance is assumed, which seems reasonable since electric vehicle performances are comparable to internal combustion engine ones in a free-floating scheme in urban areas, where trip lengths and rental durations are limited. Actually, a recent study found that members would switch to car sharing with electric vehicles if possible, after having tried it out (Schlüter and Weyer, 2019). Differently from the planning scenario, electric car sharing fleets would not produce tailpipe exhaust emissions. Therefore, increasing modal switches from any other mode would never correspond to an emissions' increase. Eventual emissions related to the production of electricity are not considered in this study.

3.4.5. No car sharing scenario

This scenario was evaluated to understand how current car sharing users would change their travel choices in case of absence of car sharing services. Indeed, several systems ceased their operations in many cities around the globe in recent years, and the trend could also accelerate given the COVID pandemics in 2020 that jeopardised the business model. Decision-makers should therefore also consider what would be the consequence of a service suspension or even shut-down to eventually take appropriate actions. For instance, an undesired opposite switch from car sharing to more pollutants' modes may take place.

Respondents enrolled in a car sharing service were asked to indicate what they would have done if car sharing had not been available for the specific trip that they reported in the survey, by using a 5-points Likert scale (1 strongly disagree – 5 strongly agree) related to a set of different strategies including performing the same trip with different travel modes. Descriptive statistics related to such answers are used to define this scenario.

It is worth noting that the predicted number of switches in different scenarios does not refer to any specific time point. Hence, understanding "when" such scenarios could take place was not addressed in the present research. Additionally, the nature of the switch models used in this study allows us to predict changes in the travel demand among existing modes, but not to forecast increases in the overall travel demand. Therefore the overall travel demand in the city is considered constant in all designed scenarios.

3.5. Evaluation of mobility scenarios

The evaluation of the above defined scenarios was based on a partial application of standard methods for the evaluation of externalities in the transport sector (European Commission, 2019), considering data availability and the specific framework of the present research. In particular, emissions of pollutants and greenhouse gases were quantified and monetised through unit costs, and the optimal planning scenario was identified on the basis of these externalities.

3.5.1. Estimation of greenhouse gas and pollutants emissions in scenarios

Trip distances obtained through the RP survey dataset and the Google Directions API were used to estimate the exhaust emissions of both GHG and some pollutants, by multiplying such distances times the exhaust emission coefficients (expressed in [g/km]) which are available in the literature according to different vehicles characteristics. A Tank-To-Wheel (TTW) analysis was carried out, therefore considering only tailpipe emissions of both CO_2 and pollutants without the contribution related to the energy production and distribution. The pollutants considered in this study are those typically used in the estimation of the external costs of transport, which are reported in (European Commission, 2019), namely non-methane volatile organic compounds (NMVOC), particulate matter under 2.5 μm ($PM_{2.5}$), nitrogen oxides (NO_x) and ammonia (NH_3).

Exhaust emission coefficients were calculated by considering the fleet composition of both car sharing and private fleets in terms of number of electric and conventional cars (typically petrol ones). The average emissions of different car models composing the fleet were weighted by the number of private cars belonging to each emission class. Concerning the car fleet composition of 2018 (reference year in the base scenario), we rely on the annual statistics produced by the *Automobile Club d'Italia* (ACI)[3]. City car fleet was segmented according to EURO emission standards, type of fuel, and year of first registration. Pollutants' exhaust emissions coefficients for conventionally fuelled cars are the limit values defined by the European Environment Agency (EEA) (Ntziachristos et al., 2018); electric vehicles were assumed to have no tailpipe emissions.

Through such method, average exhaust emission coefficients were estimated for both car sharing and private car fleets in the city of Turin, which will used to compute emissions in our scenarios. Indeed, it might be argued that emissions in real traffic conditions are different from such values that are obtained through standard driving cycles (Fontaras et al., 2017). However, it is important to note that in our framework what matters are the differences between scenarios, and the same approximation is consistently introduced in all these.

Finally, since there is not a direct link between EURO categories and CO_2 limit values, the CO_2 exhaust emission coefficients for private cars were evaluated considering the year of registration of the cars (ACI[4]) and the average value of CO_2 of the vehicles produced in Europe in that year, according to the information reported in "Monitoring of CO_2 emissions from passenger cars – Regulation 443/2009" (European Environment Agency, 2019). The reader is referred to Appendix 9 of Chicco et al. (2020b) for additional details about the coefficients calculation. To sum up, car sharing and private car fleets exhaust emission coefficients used in this study are summarised in Table 2 below.

Concerning the other used modes of transport reported in the RP survey trips, the CO_2 and pollutant emissions produced were assumed negligible. This is true when trips performed by bicycle or on foot are considered. Concerning public transport, since this service usually operates regardless of capacity utilisation (Martin and Shaheen, 2011), the offer was assumed constant in all scenarios, therefore an additional person switching to car sharing would not decrease the public transport emissions.

3.5.2. Economic evaluation of air pollutions and greenhouse gas externalities

Since the effects that CO_2 and air pollutants have on human health and the environment are significantly different, their impacts cannot be evaluated by directly comparing the estimated produced quantities. In order to correctly evaluate the impact of each pollutant to the overall balance and therefore understand which scenario may lead to the maximisation of the benefits for the city, all the emissions quantified were converted in monetary terms, following the cost benefits analysis workflow. Therefore, a cost evaluation of the externalities due to emissions in all scenarios was carried out by considering the cost coefficients determined by the European Commission (European Commission, 2019), which are reported in Table 3 below.

4. Results and discussion

The estimation of the potential travel demand that can be satisfied by car sharing in different scenarios and the subsequent changes in distance travelled with different travel means and related emissions are first introduced. Then, a comparison of the estimated emissions and related economic evaluation among scenarios is presented.

4.1. Trips and emissions quantification in mobility scenarios

4.1.1. Base scenario

The figures for the base scenario are reported in Table 4. The considered mode, the number of daily trips, and the sum of the trip lengths are reported in the first three columns, whereas the last five columns report the estimated quantity CO_2 and air pollutants considered in the study. According to our framework, emissions related to public transport are not depending on travel demand and therefore they are not reported.

About 1.3 million trips are estimated on a daily base in Turin and this number is not changing across scenarios (see the above methodology section). In the base scenario, most of these trips are performed using private cars (53.7%) and about one third the public transport of the city. Car sharing satisfies a tiny portion of the daily travel demand (0.4%).

4.1.2. Growth scenario

The growth scenario maximises the travel demand served by car sharing under the base conditions, therefore without any dedicated policy. The diverted daily trips from different travel means of the base scenario to car sharing, the resulting growth scenario modal split, and the estimated emissions are reported in the below Table 5.

Observing the percentages of diverted trips to car sharing (reported in the second column), trips performed with private cars have the highest value (59.6%), followed by public transport trips (28.8%), and active modes (9.7% and 1.9% for walk and bike trips, respectively). These results confirm that trips carried out within an urban area by both car and public transport, have characteristics that can be met by car sharing services (Ceccato and Diana, 2018). On the contrary, switches from non-motorised modes are lower since probably trips characteristics such as distance, time, and cost are different.

Results coming out from the application of switch models show that, globally, car sharing has the potential to attract 116,424 additional daily trips, which represent 9.5% of the current daily travel demand. Considering that, on average, 4500 daily trips in 2018

[3] http://www.opv.aci.it/WEBDMCircolante/ – Accessed May 15th, 2020

[4] http://www.opv.aci.it/WEBDMCircolante/ – Accessed May 15th, 2020

Table 2
Car sharing and private car fleet emission coefficients in Turin.

	Avg. CO2 exhaust emission [g/km]	Avg. NMVOC exhaust emission [g/km]	Avg. NOx exhaust emission [g/km]	Avg·NH3 exhaust emission [g/km]	Avg. PM2.5 exhaust emission [g/km]
Car sharing fleet	87.9	0.043	0.047	0.009	0.001
Private car fleet	146.9	0.177	0.437	0.019	0.009

Table 3
Average Italian air pollution costs in 2016 (European Commission, 2019).

CO2 [€/ton]	NMVOC [€/kg]	NOx transport city [€/kg]	NH3 [€/kg]	PM2.5 transport city [€/kg]
100.0	1.1	25.4	21.6	132.0

Table 4
Estimated daily trips, CO_2 and air pollution emissions in the base scenario.

Mode	Daily trips	(%)	Trips length sum [km]	Daily CO_2 emission [t]	Daily NMVOC emission [t]	Daily NO_X emission [t]	Daily NH_3 emission [kg]	Daily $PM_{2.5}$ emission [kg]
Walk	192,856	(*15.1*)	332,002	–	–	–	–	–
Bike	27,735	(*2.2*)	92,717	–	–	–	–	–
Car	684,452	(*53.7*)	13,496,372	1,982	2.39	5.89	253	122
CS	4,500	(*0.4*)	22,805	2	≈ 0	≈ 0	≈ 0	≈ 0
PT	364,532	(*28.6*)	3,782,642	–	–	–	–	–
Total	**1,274,075**	**(*100*)**	**17,726,539**	**1,984**	**2.39**	**5.89**	**253**	**122**

Table 5
Estimated daily trips, CO_2 and air pollution emissions in the growth scenario.

Mode	Diverted trips to CS	(%)	Daily trips	(%)	Total trip length [km]	Estimated daily emission				
						CO_2 [t]	NMVOC [t]	NO_X [t]	NH_3 [kg]	$PM_{2.5}$ [kg]
Walk	11,266	(*9.7*)	181,590	(*14.3*)	306,244	–	–	–		–
Bike	2,157	(*1.9*)	25,578	(*2.0*)	84,928	–	–	–		–
Car	69,442	(*59.6*)	615,010	(*48.3*)	13,031,078	1914	2.31	5.69	244	118
CS	–	–	120,924	(*9.5*)	924,370	81	0.04	0.04	9	1
PT	33,559	(*28.8*)	330,973	(*26.0*)	3,356,660	–	–	–		–
Total	**116,424**	**(*100*)**	**1,274,075**	**(*100*)**	**17,703,280**	**1,995**	**2.35**	**5.73**	**253**	**119**

were performed with shared cars in Turin, the car sharing demand predicted through the application of switch models is 26 times higher in terms of trips and sums up to 120,924 trips.

The growth scenario thus represents an ideal scenario under the base conditions for car sharing operators, because it maximises the switching trips from all transport modes and consequently the usage of the fleet (hopefully increasing the turnover rate of each car) and the profitability of car sharing organisations; on the other hand, this strong increase might be challenging for the operators in terms of fleet management.

It is however interesting to observe that the total trip length of the growth scenario is smaller than the one in the base scenario, albeit the number of daily trips is, according to the assumption of travel demand invariance, constant. An explanation to such value can be done by considering trips diverted from public transport: the path connecting origin and destination might be, in many cases, longer than the one chosen when driving a shared car (and estimated here through the Google Directions API).

This interpretation is also supported by the total CO_2 emissions estimated in the growth scenario, which are higher than the one estimated in the base scenario. As explained in the above Section 3.5.1, the reduction of trips performed by public transport (and consequently their distances) does not produce positive effects in terms of CO_2 and pollutant emissions, since public transport offer is supposed invariant as well.

Finally, observing the estimated quantity of CO_2 emissions it can be noted that the reduction of CO_2 emissions produced by the trip diversion from private car to car sharing (1914 tons in the growth scenario against 1982 tons in the base one) is not completely eroded by the increase of CO_2 emissions produced by car sharing trips which were previously performed by walk, bike and public transport (81 tons against 2 tons). A more detailed comparison among scenarios will be presented in the following.

4.1.3. Planning scenario

As explained in the methodology, the planning scenario considered in this study aims to maximise the positive impacts of car sharing in terms of both greenhouse and air pollutant emissions. Therefore, it is necessary to maximise the switches from private car towards car sharing and to minimise those from other sustainable travel means. The best combination of joint changes in car sharing fares and private vehicles parking fares that was studied through the above introduced sensitivity analysis led us to identify that the minimisation of the costs related to emissions is obtained when there are no changes in car sharing fares and an increase of 100% of parking fares. The estimated number of diverted trips, distance travelled and GHG and air pollutant quantities are reported in Table 6.

The number of trips diverted from active modes and public transport is the same as the growth scenario, since the car sharing fare is unchanged. However, the total number of daily trips switching towards car sharing is higher than the one in the growth scenario due to the increased number of diverted private car trips. The modal switch models application shows that, in the planning scenario, car sharing has the potential to attract 122,530 daily trips out of 1,274,075, which represents 9.6% of the current daily travel demand estimated from respondents. Therefore the application of mobility policies aimed to make citizens more conscious about the real costs of driving (in specific, the increase of the parking costs in the city) might even increase the demand for car sharing services.

Detailed comparisons across different scenario will be later done, however it is worth anticipating here that there seems to be no practical difference between growth and planning scenarios in terms of emissions. This is mainly due to the fact that only modal diversions towards car sharing are here studied. It is, on the other hand, clear that an increase in parking costs might also produce a shift from private car use to an increased use of public transport and active modes. However such additional effects are not considered in the present research, whose focus is on the environmental impacts of car sharing.

4.1.4. *Fully electric planning scenario*

This scenario presents the same modal shares and number of kilometres travelled of the above planning scenario, but assuming that a fully electrified fleet is used. As a result, the fully electric planning scenario only differs from the planning one in the emission produced, since electric car sharing exhaust emissions are assumed equal to zero (Table 7).

4.1.5. *No car sharing scenario*

The no car sharing scenario estimates how the travel demand that is served by car sharing services in the base scenario would redistribute in a hypothetical scenario, in which car sharing ceased its operations. Differently from the other scenarios, the no car sharing scenario is based on the preferences for alternative travel means for the reported trip that were expressed by car sharing members in the RP survey. The results are summarised in Table 8 below. The reader is referred to Section 5.1.5 of Chicco et al. (2020b), for further details about the computational procedure.

Although the substitution effect of car sharing trips with private car is quite high (33.2%), 42.1% of respondents stated that they would have used public transport if car sharing had not been available.

The potential modal split of the no car sharing scenario is obtained by applying the percentage breakdowns observed in the above table to the daily trips of the base scenario. The results are summarised in Table 9 below.

Differently from the previous scenarios, in the no car sharing scenario a very small proportion of trips are assigned to taxi because some respondents stated that they would use a taxi if car sharing were not available for the reported trip. This mode was not present at all in the previous scenarios since there were no observed trips by taxi in the SP survey that was used to calibrate the switching model, nor observed trips by taxi in the RP survey. Despite the methodological difference in deriving such scenarios we believe that such discrepancy is negligible since the number of trips by taxi that appears in the no car sharing scenario is of the same order of magnitude of the approximation errors.

4.2. *Comparison of mobility scenarios and related emission costs*

Table 10 summarises the estimated quantities of GHG and air pollutants in each scenario from the preceding subsections and their respective percentage variation compared to the base scenario, to ease a more systematic assessment of the results.

In general, it can be observed that the quantified CO_2 emissions follow a different trend compared to the other pollutants. On the one hand, both growth and planning scenarios show a higher quantity of greenhouse gas emissions (+0.55% and +0.52% compared to the base scenario, respectively). On the other hand, CO_2 emissions are lower in the no car sharing scenario.

On the contrary, the estimated quantities of all the other pollutants are lower in the planning scenario and higher in the no car sharing scenario. The different trends between greenhouse gases and other pollutants are due to the fact that the increment of the emissions related to trips diverted from more sustainable modes to car sharing is not fully compensated by the reduction of CO_2

Table 6
Estimated daily trips, CO_2 and air pollution emissions in the planning scenario.

Mode	Diverted trips to CS (%)		Daily trips (%)		Total trip length [km]	Estimated daily emission				
						CO_2 [t]	NMVOC [t]	NO_X [t]	NH_3 [kg]	$PM_{2.5}$ [kg]
Walk	11,266	(*9.5*)	181,590	(*14.3*)	306,244	–	–	–	–	–
Bike	2,157	(*1.8*)	25,578	(*2.0*)	84,928	–	–	–	–	–
Car	71,048	(*60.2*)	613,404	(*48.1*)	13,031,078	1,912	2.31	5.68	244	118
CS	–	–	122,530	(*9.6*)	924,370	82	0.04	0.04	9	1
PT	33,559	(*28.4*)	330,973	(*26.0*)	3,356,660	–	–	–	–	–
Total	**118,030**	(***100***)	**1,274,075**	(***100***)	**17,703,280**	**1,994**	**2.35**	**5.72**	**253**	**119**

Table 7
Estimated daily trips, CO_2 and air pollution emissions in the fully electric planning scenario.

Mode	Diverted trips to CS (%)		Daily trips (%)		Total trip length [km]	Estimated daily emission				
						CO_2 [t]	NMVOC [t]	NO_X [t]	NH_3 [kg]	$PM_{2.5}$ [kg]
Walk	11,266	(*9.5*)	181,590	(*14.3*)	306,244	–	–	–	–	–
Bike	2,157	(*1.8*)	25,578	(*2.0*)	84,928	–	–	–	–	–
Car	71,048	(*60.2*)	613,404	(*48.1*)	13,031,078	1,912	2.31	5.68	244	118
CS	–	–	122,530	(*9.6*)	924,370	0	0	0	0	0
PT	33,559	(*28.4*)	330,973	(*26.0*)	3,356,660	–	–	–	–	–
Total	**118,030**	**(*100*)**	**1,274,075**	**(*100*)**	**17,703,280**	**1,912**	**2.31**	**5.68**	**244**	**118**

Table 8
Declared alternative modes for the recorded trip in absence of car sharing.

Mode	Respondents (%)
Walk	10 (*7.9*)
Bike	12 (*9.2*)
Car as a driver	43 (*33.2*)
Car as passenger	3 (*2.1*)
Taxi	7 (*5.5*)
PT	54 (*42.1*)
Total	**128 (*100*)**

Table 9
Estimated CO_2 and air pollution emissions in the no car sharing scenario.

Mode	Diverted trips from CS (%)		Daily trips (%)		Total trip length [km]	Estimated daily emission				
						CO_2 [t]	NMVOC [t]	NO_X [t]	NH_3 [kg]	$PM_{2.5}$ [kg]
Walk	357	(*7.9*)	193,213	(*15.2*)	333,557	–	–	–	–	–
Bike	413	(*9.2*)	28,148	(*2.2*)	94,349	–	–	–	–	–
Car	1591	(*35.3*)	686,043	(*53.8*)	13,505,353	1,984	2.4	5.9	253	122
Taxi	246	(*5.5*)	246	(*0*)	–	–	–	–	–	–
PT	1893	(*42.1*)	366,425	(*28.8*)	3,793,281	–	–	–	–	–
Total	**4500**	**(*100*)**	**1,274,075**	**(*100*)**	**17,726,539**	**1,984**	**2.4**	**5.9**	**253**	**122**

Table 10
Estimated emissions of mobility scenarios.

Scenario	Estimated daily emission (*% variation from the base scenario*)				
	CO_2 [t]	NMVOC [t]	NO_X [t]	NH_3 [kg]	$PM_{2.5}$ [kg]
Base	1984	2.39	5.89	253	122
Growth	1995 *(+0.55)*	2.35 *(−1.90)*	5.73 *(−2.73)*	253 *(−0.03)*	119 *(−2.41)*
Planning	1994 *(+0.52)*	2.35 *(−1.90)*	5.72 *(−2.79)*	253 *(−0.03)*	119 *(−2.41)*
Fully electric planning	1912 *(−3.62)*	2.31 *(−3.56)*	5.68 *(−3.54)*	244 *(−3.60)*	118 *(−3.55)*
No car sharing	1984 *(≈ 0)*	2.40 *(+0.03)*	5.90 *(+0.04)*	253 *(≈ 0)*	122 *(≈ 0)*

emissions deriving from the reduction of private car trips, while pollutants emissions are more than compensated through such switching patterns. In turn, this happens because pollutants emission coefficients of car sharing fleets are of one order of magnitude smaller than those of private vehicles, whereas CO_2 emission coefficients are "only" halved (see Table 2). In all cases however, the changes in the quantity of the emissions produced are negligible if compared to the base scenario (variations range from about −3.62% to +0.55%). Nevertheless, we believe it is important to observe and comment such results because they allow to better understand the intertwined relationships between modal diversion patterns and variations of emissions due to car sharing systems.

Focusing on the comparison between the base and the planning scenario, the modest increase of CO_2 emissions might appear counterintuitive. However, as explained in methodology, the maximisation of the positive impacts of car sharing has been evaluated by considering the overall external costs of different emission kinds. Therefore, a scenario that produces a better result in terms of CO_2 emissions might not be the best one for other pollutants.

Finally, it is worth observing that impacts on emissions would be more positive if current car sharing fleets would be substituted with electric ones (Fully electric planning scenario). Electric vehicles would not produce exhaust emissions according to the assumption of the analytical methods used. Therefore the increasing use of car sharing deriving by the switch from other modes would not correspond to an increase in the emissions.

To evaluate the overall impact of car sharing in the mobility scenarios for the city of Turin, the total external costs of both different pollutants and GHG emissions of each scenario are computed. The results are reported in Table 11 below.

The base scenario, which is characterised by the modal split individuated in the above Section 4.1.1, is producing an overall cost for the city of Turin quantifiable in about 372,000€ per day.

The estimated modal switches from different travel modes towards car sharing can be evaluated in economic terms as a reduction of the total daily cost in both the growth and the planning scenario. Being the latter an optimisation of the former scenario, the maximum expected reduction in the daily total cost is about 3606€ (less than 1% of the daily total cost in the base scenario). Such reduction derives from the savings produced by the reduction of pollutants' emissions and the additional cost deriving from the increase in CO_2 emissions.

These relatively small benefits are clearly bigger when considering the fully electric scenario, where the daily cost for the city of Turin is quantified in 358,984€, with a saving of 13,333€ per day (i.e., a variation of about 3.6%).

On the other hand, for the no car sharing scenario, costs would practically be the same given the low market share of car sharing in the base scenario.

5. Conclusions

In this paper, the modal diversion patterns at the individual trip level from existing travel means to car sharing are assessed to quantitatively estimate car sharing impacts in terms of air pollution and greenhouse gas emissions and related external cost. In particular, five mobility scenarios are developed to understand which conditions are necessary to reach the scenario that maximises the positive environmental impacts of car sharing. The base scenario, which represents the mobility situation of the city of Turin in 2019, is compared with a growth scenario, a planning scenario, and the hypothetical no car sharing scenario. The growth scenario represents an hypothetical future mobility situation that would occur after a wide diffusion of car sharing among Turin inhabitants with no specific supporting policy measures, while the planning scenario represents a situation that can be obtained only with specific policy measures to encourage modal diversion from private cars.

According to the models' results, the potential car sharing demand might increase from about 1% of the daily travel demand served in the base scenario, up to about 10% estimated in the planning scenario. The travel demand satisfied with car sharing is mainly subtracted from private cars, however the application of the switching models shows diverted trips also from public transport and active modes. This produces different results when either the greenhouse gas or the air pollutant emissions are considered. On the one hand, we observed that the reduction of CO_2 emissions produced by the trip diversion from private car to car sharing is completely offset by the increase of CO_2 emissions produced by car sharing trips which were previously performed by walk, bike, and public transport. Therefore car sharing might produce a negative effect in terms of CO_2 emissions, albeit the increase is negligible if compared to the total amount produced in the base scenario (about +0.5%). On the other hand, less pollutant engines of car sharing fleet would reduce the overall amount of pollutant emissions, meaning that the reduction deriving from the substituted private car trip outweighs the increase deriving from the substitution of public transport and active modes. However, also in this case, the reduction is negligible compared to the quantities produced in the base scenario (almost always below 4% for the considered pollutants), especially considering the ambitious policy targets concerning the reduction of emissions in the transport sector (European Commission, 2011; WHO, 2005).

To evaluate the overall impact, the estimated quantities are converted in monetary terms. We found that the planning scenario would lead to a reduction of the externalities related to the greenhouse gas and air pollution produced by the transport system in the city, which corresponds to a saving of 1% in terms of related social costs. Such benefits can be increased up to 3.6% by promoting electric car sharing fleets.

To the best of the Authors' knowledge, it is the first time that an attempt is made to quantify the emissions related to modal switch towards car sharing without assuming a change in car ownership levels, but rather through a trip-level analysis. Clearly, changes in car ownership levels would also have an impact on overall emissions, as discussed in the introduction, which is probably much more substantial than the one analysed here, at least for some operational variants of car sharing services. However, this more tactical perspective focusing on daily mobility rather than on long-term choices can provide guidance to policy makers to understand which kind of intervention can lead to an increased use of car sharing while maximising environmental benefits, thus by subtracting travel demand from private travel means. Moreover, local authorities can evaluate impacts in terms of emissions to address financial resources to support car sharing operators that are pursuing the electrification of their fleets.

This study presents some limitations. Trip level information collected in the RP survey focuses only on one trip, rather than on all

Table 11
External costs of pollutants and GHG emissions in scenarios.

Scenario	Daily external costs [€] (% variation from the base scenario)
Base	372,317
Growth	368,877 (−*0.92*)
Planning	368,711 (−*0.97*)
Fully electric planning	358,984 (−*3.58*)
No car sharing	372,327 (≈ *0*)

trips completed in a given time period (full travel diary). Another limitation is related to the application of the average emissions factors, which do not take fully into consideration the real driving conditions. Future investigation should be developed by using simulation tools, which can provide accurate estimates but that require more input.

CRediT authorship contribution statement

Andrea Chicco: Conceptualization, Methodology, Software, Formal analysis, Writing - original draft, Visualization, Writing - review & editing. **Marco Diana:** Conceptualization, Methodology, Writing - review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

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.

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Availability of data** and **materials

The RP dataset used and analysed in the current study is available at the platform Zenodo with embargoed access until March 1st, 2021.

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