Carsharing: panacea or everlasting promise

Simulating the effect of car sharing policies on the modal split in Amsterdam

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ABSTRACT

Roads in and around cities are jammed, the air quality in some streets is sickening and more and more public space is consumed by unused cars. Car sharing is promoted as one of the solutions for these urban problems, but the dynamics that determine demand and its implications for these problems are hardly known. This firstly uses system dynamics modeling to assess the demand for car sharing. Five policies that aim to promote car sharing are simulated. Four of these policies are decreasing the cost of car sharing, increasing the costs of a private car, creating parking restrictions and increasing the number of car sharing vehicles. As a fifth policy, the three most sensitive policies are combined. It turns out that the number of car sharing vehicles heavily restrains the increase of carsharing. Without a proper public transport system, the car sharing demand initiates mostly from public transport. Most importantly, combining different policies is necessary to decrease the number of cars.

1. INTRODUCTION

Urban areas all over the world are suffering from similar problems. Congestion and occupancy of public space by parked cars are causing cities to come to halt. Pollution by exhaust gasses further reduce the liveability of cities. According to Deloitte and Statistics Netherlands (CBS) [17], traditional solutions to mobility will not keep up with the rapid urbanization. They argue that to keep our cities liveable we need a less vehicle-centric approach to mobility.

Goodall et al. see Mobility as a Service (MaaS) as a possible solution to these urban mobility problems [17]. According to them service models add more variability to the available means of transportation. Supporting mobile technology, in theory, should allow MaaS solutions to be more effective, because they are data driven and are thus better adaptable to a changing environment. Car sharing is the most prominent example of MaaS.

The idea of car sharing as solution to contemporary urban mobility questions has found a willing ear in national and local governing bodies, such as the municipality of Amsterdam [11]. Car sharing is adopted by the municipality. The city of Amsterdam is now actively supporting commercial car sharing companies by providing them with cheap parking permits, while at the same time increasing parking restrictions for car owners.

However, in the literature two conflicting perspectives on this theme can be found. One strand of research confirms that larger adoption of car sharing will reduce the number of cars owned as well as the miles driven with cars [14, 23, 27, 6]. On the opposite side there are studies that argue that car sharing-services are used by people who do not own cars and previously made use of public transport modes as tram, bus or metro [13, 9, 32].

Taking this last perspective in consideration, it is not self-evident that broader adoption of car sharing will always lead to less cars on the streets. Something similar happened with the disruption of the taxi branch by companies as Uber and Lyft. While people assumed traffic would be more efficient thanks to these services, research shows that their adoption actually had severe unexpected consequences for traffic in the United States, and the distance travelled by cars increased significantly because of these innovations[5].

1.1 Research question

Most likely both outcomes are possible, depending on the context of the situation. Therefore the aim of this paper is to identify the dynamics that influence the demand for different transport modes, i.e. the modal split, in the city of Amsterdam, and to model the consequences of different policies on the number of cars owned in the city. The answer to this is paramount for the success of the car sharing policies of the Amsterdam municipality.

The method used in this research will be macro modelling using a System Dynamics simulation. This method should give more understanding of the behaviour of the system as a whole. The causal relations used in micro simulation is used to develop the system dynamics model. The structure of this paper mirrors this approach. In the related work, features that influence car sharing demand are discussed, and influential models are compared. Next, the modeling choices are discussed and a causal loop and stock and flow diagram are developed. The model is then calibrated for the case of the Amsterdam modal split and policies are simulated.

2. RELATED WORK

This section gives a short definition of car sharing and explains which form is most relevant for this research. Then different attempts at modelling car sharing and their implications on the methodology are discussed. Lastly, an overview of characteristics of car sharing users is provided as this might support building the model

2.1 car sharing

car sharing is not new, but has become more popular since it is provided as innovative service. In Amsterdam there are at least 5 different companies active that all provide a slightly different service. Three of them are highlighted to explain the different forms.

Greenwheels is the largest car sharing company in Amsterdam. They provide station based cars that members can reserve and use. After use they have to return the car to the car sharing station. Car2go is the second largest car sharing company in Amsterdam and they provide free floating car sharing vehicles. Their fleet can be picked up and dropped of anywhere within the urban area of Amsterdam, allowing one way trips. Snappcar does not provide own cars but instead provides an online platform and insurance to enable car owners to share their vehicles.

One-way free-floating car sharing-services are thought to be the most promising, as it is most flexible for users. They are not bound to returning the car at the departing station. According to Barth and Shaheen one way car sharing allows more types of journeys than round trips and therefore has more potential than the latter [3, 38].

2.2 Car sharing demand and simulation

The users of car sharing services are extensively surveyed in order to predict demand and thus a detailed "persona" of a typical user can be given. However, attributes such as age, household-size, environmental awareness and income, are less interesting to this research. The aim is to model demand beyond the current users, and data that describes current car sharing users most likely describes early adopters [32]. Therefore personal details are less relevant to make statements about potential adoption by a larger audience. The relevant features are summarized below.

- Low vehicle ownership (although this might also be caused by car sharing) [27, 6, 36]
- Many parking limitations/restrictions [1]
- Access egress time [10, 12, 39]

One of the first models of car sharing is given by [32], it showed that car sharing demand for 50% comes from people who previously use the public transport system, only 40% comes frome private car owners. In [24] regression models are used to estimate a modal split that includes car sharing for specific areas. However, the authors did not account for travel time and kilometric costs. With the approach an initial modal split can be estimated, but predictions on policies cannot be made. A third mode-choice model is developed by [25]. It focuses on stated preference experiments and emphasizes the importance of costs and rental conditions in demand predictions.

An agent based simulation discussed in [9, 8, 19], uses econometric utility functions based on cost and travel time to re-plan mobility behaviour of agents in a certain area. These papers focus on peak times for car sharing and the exchange in demand with other transport means to estimate car sharing demand. In [9] it was shown that in Berlin less than 35% of the potential demand for car sharing comes from private car drivers. The rest of the demand comes from people using public transport, cyclists and even people who before walked to their activities.

The first relevant system dynamics approach to model demand was used to model congestion and pollution in the Ghanian capital Acra. Their work is useful as it assesses the exchange between the number of cars and the use of public transport in Acra. Another system dynamics model that simulates the use of private cars and public transport systems was given by [2]. A key understanding from this research is that the "entire state of the modal share in a city would be the collective reflection of the mode choice behaviour of individuals" [2] and that to change behaviour, the attractiveness of owning a car needs to be addressed. In [31] the modal split for cars, walking and public transport is modeled using the theoretical principles of microeconomics. The core of his model is again a time-price model. Furthermore, it was concluded that car ownership is positively related to more car trips, despite of increasing traffic.

Although the demand for car sharing services is already simulated, this is not yet done on the macro scale. Conventional models of transport mode-choice use the system dynamics approach, but these simulations do not yet include car sharing. Lastly, [20] states that the relation between the availability of car sharing and its demand is still underexposed.

2.3 Local car sharing policies

Governing bodies, nationally or locally, are welcoming car sharing companies to support their goals and give them an innovative image. This section gives a short overview of the current car sharing policies that are active or initiated in Amsterdam.

In march 2019 the local Amsterdam government announced that they will be restricting the number of public parking spaces in Amsterdam [22]. From the summer of 2019, the municipality strives to remove 1500 parking spaces each year. The goal is to remove 11.200 parking spaces in total. This measure is aimed at discouraging car ownership.

Related to the restriction of the number of parking spaces is a price increase for paid parking in Amsterdam. From April 2019 parking costs in the city center increased by 50% from €5.00 to €7.50 per hour. Outside the city center parking also became more expensive. In the more peripheral neighborhoods paid parking will be introduced [37]. This increases the average costs of car ownership for Amsterdam residents.

Earlier in 2019 the municipality also announced that they want to increase the available permits for free floating car sharing vehicles in the city from the current 750 permits to 2500 in 2020. The idea behind this goal is that the number of car sharing cars at this moment provides not enough spatial coverage, i.e. users cannot always get a vehicle if they want to.

Other car discouraging measures in literature are aimed at making alternatives such as car sharing cheaper, or creating spatial barriers for car users [26]. The latter can be done by making it harder to reach a destination by car, for example by slowing traffic flows artificially. Though these measures would probably discourage car sharers as well.

3. MODEL DESCRIPTION

Activity-based or agent-based simulations and system dynamics modeling lie at different ends of the simulation scale spectrum. Nevertheless, both methods do share some practical features when the same phenomenon is modeled. Causal relations that exist on micro scale are also in effect on macro scale. In this paper a system dynamics macro model is developed based on utility functions that have proven to be valid in micro simulations. System Dynamics is to the best of our knowledge not yet used to model the effect of transportation policy on the modal split. It is used to assess the

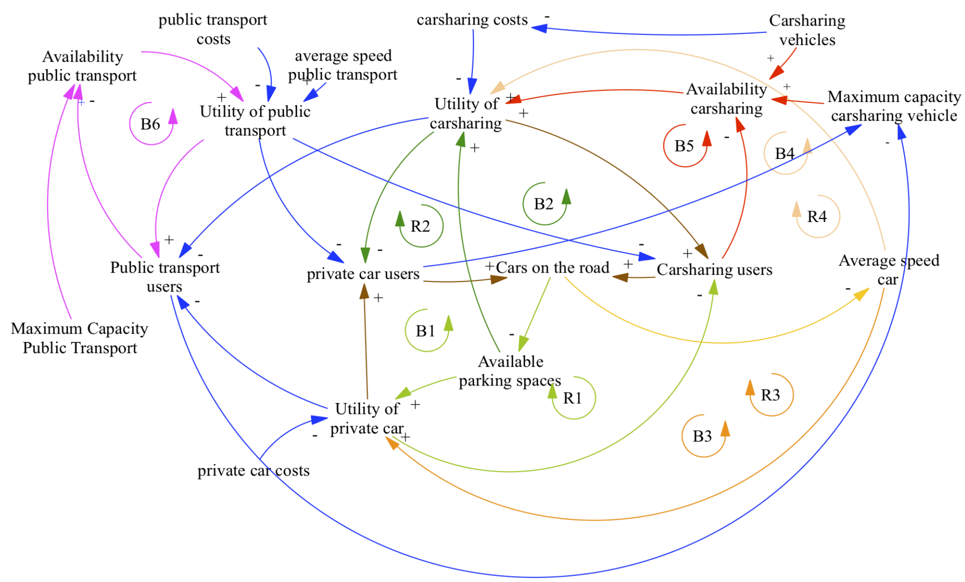

Figure 1: Causal Loop Diagram that models the causal relations that define the transport modal split

consequences of the discussed policies on a more abstract level and to get more insight in the dynamics that inhibit adaption of car sharing.

3.1 Causal loop diagram

The causal loop diagram in fig. 1 models the assumed causal relations that define the demand for private car travel (PC), public transport (PT), and car sharing (CS) services. Bicycle and walking are left out as modes, because based on the literature it can be expected that only a small part of the demand comes from these modes. Correlations based on personal features are left out of the model, as explained in section 2.2.

The choice for a specific transport mode is based on the expected utility of travelling for all modes [19]. It is thought that everyone tries to optimize his or her utility. The expected utility is based on the monetary and time bound costs and on the experienced availability of the specific modes. The costs are not independent, both travel time and monetary expenses are functions of distance. The relation between them is implicit in the causal loop diagram, but will be made explicit in the stock and flow diagram in section 3.3 and in the case description in section 4.

Demand can decrease as well as increase, therefore four of the balancing loops (B1-4) in the diagram, have a reinforcing counterpart (R1-4). Each of these pairs is marked with the same colour. The four brown arrows are part of all these four loops and also of balancing loop B5. Loop B1 and R1 explain how the available parking spaces influence the utility of owning a car, while loops B2 and R2 do the same for the utility of car sharing. Loops B3, R3, B4 and R4 model the influence of congestion on the travel time. Loop B5 represents the effect of changes in demand on the availability of car sharing. Lastly, loop B6 introduces a carrying capacity for public transport into the model.

In this causal model it is assumed that people using the different transport means are rational agents, who base their decisions on economic motivations such as the price per km, travel time, and availability of transport modes. In reality this will not always be the case. The model is based on exchange of demand between the different transport modes. If the demand for one mode increases, this requires the demand for at least one of the other two modes to decrease. The total population in the model is constant, because is is expected that it will not change significantly over the timespan of the simulation.

3.1.1 Model assumptions

The causal loop diagram contains very specific assumptions about the system that are not always completely realistic, but are necessary to develop an abstract model. The most important ones are listed below:

- The current state of the system is a stable equilibrium. Without policies the modal split does not change significantly.
- Without any balancing mechanisms, the mode with the highest utility would eventually reach monopoly.
- The population is constant, and based only on users who already use one of the three transport modes.
- Everybody in the simulation is able to choose a car as primary vehicle, e.g. everybody is able to get a driver's license and buy a car.
- Demand can change at most by 10% per time unit.
- Trains are not included in public transport because the focus of the model is local traffic, while trains are used primarily to travel between different cities or countries.

3.2 Dynamic hypothesis

In section 3.1 it is mentioned that the costs and travel time of the modes depend on distance. In this model the different modes are compared for an average (median distance) travelled within a certain area. As mentioned in section 3.1.1, it implies that the system is in stable equilibrium for this distance; an assumption that is not ideal, but necessary for a system dynamics model that is structured like this [31].

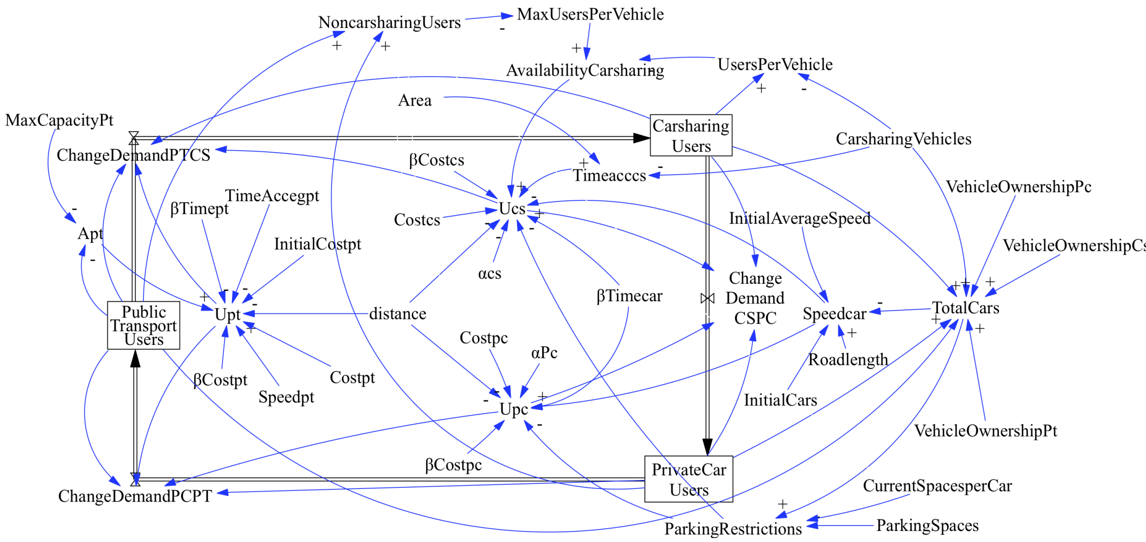

Figure 2: Stock and Flow diagram modelling the relations between the demand for different transportation means

In reality, one of the three transport modes has the best utility for the average distance used. Without balancing loops this mode would aggregate all demand. Thus the system is hold in balance by the negative feedback loops that represent the availability of the different modes. As a consequence, changing one of the variables will cause the system to seek a different stable equilibrium.

3.3 Stock and flow diagram

The structure of the stock and flow diagram in fig. 2 is derived from the utility functions proposed in [29] and the implementation of the utility functions is also inspired by [31].

The time unit in the current model is one month, because it is thought that this time unit gives the right amount of abstraction to interpret changes in the modal split. The stocks in the model represent the demand for the specified modes. Someone is seen as car sharing user as someone uses carsharing during a specific month, even when this is only for a few rides. Public transport users main transport mode for a month is public transport, private car users are defined similarly. In all cases it does not mean that they will exclusively use this mode.

3.3.1 *Utility functions*

The utility functions are based on the idea that one travels to an activity. This activity has a certain utility, in this case 1, and travelling reduces the utility of the activity. Traveling is thus actually seen as disutility as it decreases the utility of the activity travelled to [29]. The linear equations that represent the disutility of travelling proposed in [29] are taken as core of our model. The resulting utility scores drive the change in demand between the different populations.

$$\begin{aligned} U_{pt} = 1 - \alpha_{pt}\beta_{Cost,pt} * Cost_{pt}(d) \\ -\beta_{Time,pt} * TT(d) - A_{pt} \end{aligned} \tag{1}$$

$$\begin{aligned} U_{pc} = 1 - \alpha_{pc} - \beta_{Cost,car} * Cost_{pc}(d) \\ -\beta_{Time,pc} * TT(d) - PRestr \end{aligned} \tag{2}$$

Equation 1 and 2 describe the utility for PC and PT. The utility functions are linear equations, based on the cost, travel time (TT) and availability or parking restrictions (PRestr). Both cost and TT have distance as intervening variable. A closer look at the trip distance distribution for Amsterdam in figure 3 and in table 4 (see the appendix for the table), reveals that both modes cover different distance categories, although the distributions overlap.

To achieve linear behaviour, in which each mode covers a specific distance category, the utility functions contain a mode specific constant α. It represents the (psychological) barriers or costs that cannot be caught in the other terms of the equation, such as transfers necessary when travelling with public transport, the responsibilities that come with car ownership, the preconditions for using a car such as getting a drivers licence. The cost and TT terms are scaled and calibrated using β_{mode} weights to have an outcome between 0 and 1 , where 0 represents worst and 1 perfect utility.

The travel time TT(d) is determined dividing the distance by the average speed of a mode ($\frac{distance}{Speed_{mode}}$). For cars, the average speed depends on the number of cars on the road. This dependence is further explained in section 3.3.2. The equation for the public transport system also incorporates the average access and egress time as a constant.

The costs in eq. 1 and 2 are determined using the formula $cost * d$. For public transport a starting tariff is added to this equation. The utility equation for PC is extended with a term for parking restrictions, as [1] states that one of the factors influencing demand for car sharing is the degree of parking restrictions within the operating area. A similar balancing feedback loop is implemented for the capacity of the public transport system. The fuller busses, trams and metros are, the less convenient it will be to travel with the public transport system. The equations for these variables

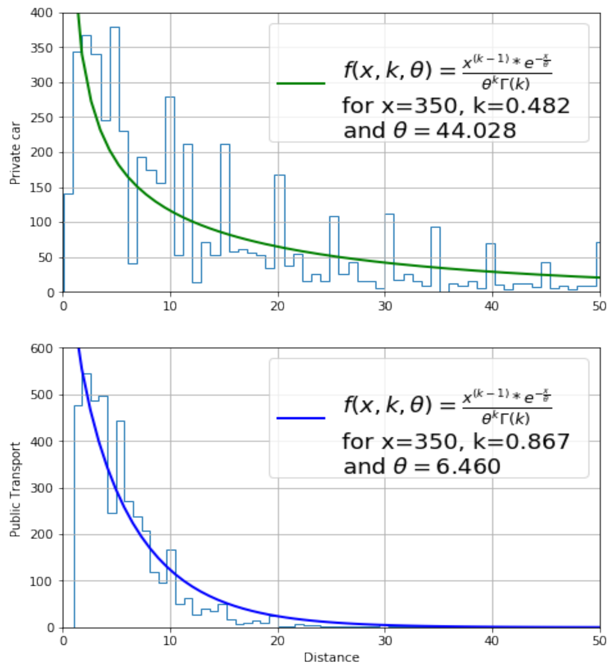

Figure 3: Histogram of the distance distributions for car and public transport. The gamma shaped trend line represents the probability density function for the distances. Source: Statistics Netherlands [34]

are discussed in section 3.3.4 and 3.3.3.

Equation 3 represents utility of car sharing trips and is based on [7]. Next to the mode specific constant, it again contains a term for the cost per hour. The costs are per hour instead of per kilometer, though, the travel time depends on the distance. The car sharing equation also has a term for the availability of vehicles and contains the term for the parking restrictions, as free-floating car sharing depends on public parking spaces. Both variables are further discussed in section 3.3.4 and 3.3.3.

$$\begin{aligned} U_{cs} = 1 - \alpha_{cs} - \beta_{Cost,cs} * Cost_{cs}(d) \\ -\beta_{Time,car} * TT(d) - A_{cs} - PRest \end{aligned} \tag{3}$$

Travel time includes the access time for car sharing. The access time is determined in eq. 4 with the acreage of the operating area, the number of car sharing vehicles and the average walking speed of 3.6 kilometer per hour, also used by google maps. The access time multiplied by $\frac{1}{2}$, because on average only half the distance between two vehicles needs to be bridged. Egress time is not part of the equation as free floating car sharing vehicles can be dropped off anywhere. The weight for travel time is the same as for a private car, because for both modes the time is spend in a car.

$$Time_{access,cs} = \frac{1}{2} * \frac{\sqrt{\frac{area/carsharingVehicles}{\pi}}}{3.6} \tag{4}$$

3.3.2 Average speed car traffic

The more cars on the road above the optimal road capacity, the more congestion there will be, and the more congestion there is, the lower the average speed. However, there is no known direct relation between the number of cars owned and the average speed, therefore an educated guess is made using the fundamental relations between the number of cars on the road, the road kilometers and average speed described in [28]. The average speed is thought to be negatively linearly related to the traffic density, thus an increase in traffic density causes a linear decrease in average speed. Density is the number of cars per distance, in this case, the total road length in some area. This is implemented in eq. 5.

$$vcar = MAX\left(Initvcar + \frac{InitCars - Ncars}{Roadlength}, 40\right) \tag{5}$$

Instead of observed cars on the road, it is assumed that all cars in the system contribute evenly to the change in speed and are thus evenly distributed over the total road length. Furthermore, the maximum speed within the city is chosen to be cut off at 40 km/h due to speed limitations and obstacles in a city. In Dutch residential area's the maximum speed is 30 km/h, while on main city roads the maximum speed is 50 km/h.

3.3.3 Availability of car sharing and public transport

The (dis)availabilities of car sharing and public transport are implemented through the system dynamics concept of carrying capacity [35]. For carsharing the carrying capacity is the maximum number of users per vehicle. The utility decreases when the number of people having to share a vehicle increases. For some people it might even be impossible to share their car with others at all. Therefore the utility decreases already when there are two or more users. The fraction that represents the availability of car sharing vehicles (see eq.6) is positive because it is subtracted in equation 3. It is squared because it is assumed that finding a vehicle becomes increasingly harder as the number of users approaches the maximum.

$$A_{cs} = \left(\frac{UsersPerVehicle - 1}{MaxUsersPerV}\right)^2 \tag{6}$$

Furthermore the carrying capacity of car sharing is decreased by dividing the current non-car sharing demand by the initial non-car sharing demand (eq.7. This is done because the last users to switch most likely have the most urgent need for good availability.

$$MaxUsersPerV = \frac{NonCSUsers}{InitNonCSUsers} * InitMaxUsersPerV \tag{7}$$

The availability of public transport is a measure of experienced discomfort because of bustle in the public transport system. The relation between the number of people and crowdedness, as given in eq.8, is assumed to be linear, because a person occupies a (relatively) fixed space. The maximum capacity is seen as the tipping point from which travelling by public transport becomes unpleasant. The availability cannot be negative. It does not become more pleasant to travel with public transport when the bus is totally empty instead of half empty.

$$A_{pt} = MAX\left(\frac{N_{pt} - MaxCapacityPt}{MaxCapacityPt}, 0\right) \quad (8)$$

3.3.4 Parking restrictions

Parking restrictions can have two forms, either monetary or spatial. The variable parking restrictions in the discussed model will only refer to the spatial restrictions. Monetary restrictions or parking costs are included in the variable for the costs of a private car.

$$PRestr = TotalCars * \frac{CurrentSpacesperCar}{Parkingspace} - 1 \quad (9)$$

The parking restrictions are measured as a fraction, where the number of parking spaces in an area is divided by the current number of parking spaces. Because it is not known if the current number of parking spaces is the optimal number of parking spaces, the equation is allowed to become negative. The spatial nature of parking resembles that of available space in the public transport, therefore this fraction is also not squared.

3.3.5 Change in demand

In the stock and flow diagram the in- and outflows of the stocks depend on the utility scores. The flows are implemented clockwise, which leads to the transition rates from CS to PC (eq.10), frrom PC to PT (eq.11) and from PT to CS (eq.12). The stocks for car sharing, private car and public transport users in the model are represented as N_{CS}, N_{PC} and N_{PT} in the equations.

$$\frac{dCSPC}{dt} = (U_{pc} - U_{cs}) * 0.1 * [N_X]\begin{cases} N_{CS} & \text{if } U_{pc} - U_{cs} > 0 \\ N_{PC} & \text{else} \end{cases} \quad (10)$$

$$\frac{dPCPT}{dt} = (U_{pt} - U_{pc}) * 0.1 * [N_X]\begin{cases} N_{PC} & \text{if } U_{pt} - U_{pc} > 0 \\ N_{PT} & \text{else} \end{cases} \quad (11)$$

$$\frac{dPTCS}{dt} = (U_{cs} - U_{pt}) * 0.1 * [N_X]\begin{cases} N_{PT} & \text{if } U_{cs} - U_{pt} > 0 \\ N_{CS} & \text{else} \end{cases} \quad (12)$$

In contrast to the use of the scoring functions in [19], the result is not a "winner takes it all" scenario, in which only the mode with the higher score remains. This has two benefits, the first is that the change in demand can be positive as well as negative, without having to implement this in the indicator function. Second and most important, this approach damps the change in demand, preventing the system to oscillate heavily and change abruptly from one state to another. A damping factor of 0.1 is added to the equation because not all users will switch immediately, the factor is based on [19].

4. CASE DESCRIPTION

The model is calibrated with the most recent data available for Amsterdam. Section 4.2 describes how the hidden parameters or weights are established. The different policies are implemented are listed in section 4.3.

4.1 Known parameters

Table 6 in the appendix gives an overview of all the known parameters that are used. The rest of this section describes the origin of the initial values.

4.1.1 Initial modal split and Vehicle ownership

The population and factors that are used to calculate the initial modal split are based on municipality of Amsterdam population above 20 years old in 2016 [1] and the modal split in the same year [2]. Carsharing is not yet taken into account in official Dutch modal split statistics, as carsharing users are registered as car users. Car2go publishes their total number of users instead of their active users [4]. Based on this an educated guess of around 20000 is made for the starting value of carsharing users.

4.1.2 Distance, speed and cost

People tend to use different transportation means for different distances. This is related to the speed and cost of the mode used. Table 1 gives the median distance travelled by car and public transport and the median travel time for these modes. The median is used instead of the mean because the distance distributions (see fig. 3) are heavily skewed. Using these variables, the average speed is calculated. The numbers are based on the aggragated OViN censuses performed by the Statistics Netherlands between 2011 and 2017 [34].

mode	distance	travel time	speed
Car	10 km	20 min	30 km/h
Pt	4.2 km	15 min	16.8 km/h
Car and Pt	6 km		

Table 1: Median distance, travel time and speed for car and public transport

The costs for carsharing are based on the two free-floating carsharing suppliers in Amsterdam, Car2go and Fetch. Their price depends on the availability of the vehicles and neither of them charges membership costs. In the model an average minute price of €0.30 is used. The costs for an average car are taken as benchmark [30] for private cars. Though the lower bound of the kilometrage is used, because the yearly distance travelled by car is significantly lower for densely populated areas [34]. This results in a price of €0.59 per km. Parking costs of €0.05 per km are added based on the costs of a parking permit plus a small parking fee per trip for on-site parking [16]. The costs for public transport are given by the the city's public transport provider GVB [18].

4.1.3 Availability, parking spaces, car ownership

The maximum number of users is based on the average users per free floating car sharing vehicle in Germany in 2019 [33]. German numbers are taken instead of local data, because it was the only available comparable example. In the 2017 annual report GVB wrote that they already reached their maximum capacity[3]. Therefore the current number of public transport users is used as the maximum capacity.

The current number of parking spaces in Amsterdam taken as the minimal amount of parking spaces. The value of 1.75

[1] https://www.ois.amsterdam.nl/feiten-en-cijfers/amsterdam/?20050

[2] https://www.metropoolregioamsterdam.nl/document/443b0adc-d952-4545-980b-99bf68db08e8

[3] https://over.gvb.nl/content/uploads/2018/05/GVB-Activa-BV-Jaarverslag-2017.pdf

is based on the number of cars divided by the current number of parking spaces [15]. The ratios for car ownership are based on the number of cars in Amsterdam in 2017[15], and household car ownership numbers by the Kennisinstituut voor Mobiliteitsbeleid (KIM) [21].

4.2 Weights

Determining the weights through optimization with travel census data is rather problematic, due to the fact that cost and travel time are not independent. Furthermore the utility scores for the monetary costs and the travel time in the model are based on averages, while in reality both vary a lot. To overcome this, the model is manually optimized using three calibration cases with values that should all be valid according to the general rules deducted below. As a robustness check the results of the different calibrations are compared in section 5.

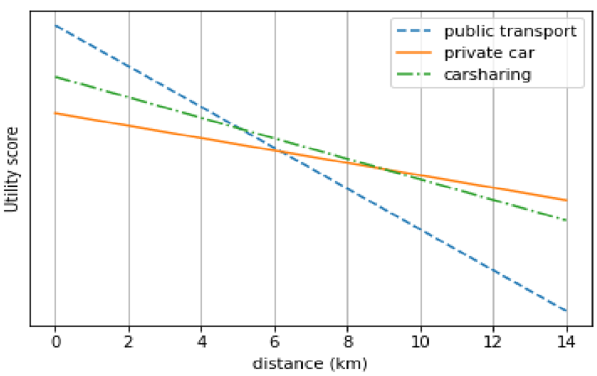

Figure 4: General form of the outcome of the utility functions

When it is assumed that the current state of the system is in equilibrium, the utility score of all three transport means should be equal and fixed for the median distance of all trips (6 km, see tab.1). Next to that the different modes are used for different distances, thus different modes should have the highest score for different distance categories. As described in section 3.3.1, the utility functions have a linear structure. With this, the general form of the two utility scores shown in fig. 4 can be suggested.

Key insights concerning the rental time imply that the average distance for which carsharing is used is somewhat less than 10 km [4]. Based on this, carsharing should have the highest utility score for a distance category between the median of carsharing (4.1 km) and the median of private car (10 km). To achieve equilibrium , the availability score for carsharing has to lower the utility that mode. Hence, the three general rules given in eq. 13 can be derived:

$$\begin{aligned} averageDistance = x\ km &\implies U_{pt} = U_{cs} = U_{pc} \\ averageDistance < x\ km &\implies U_{pt} > U_{cs} > U_{pc} \\ averageDistance > x\ km &\implies U_{pc} > U_{cs} > U_{pt} \end{aligned} \tag{13}$$

Table 5 in the appendix shows the weight values used for the three cases.

4.3 Policy implementation

Five different policy strategies are implemented based on the real policy measures discussed in section 2.3. To mark the transition before and after the implementation, each measure is implemented at time t=12.

The first policy is to subsidize car sharing in order to make it cheaper, this can either be achieved through tax benefits for car sharing companies or through tax breaks for car sharing users. In the model a 50% price reduction is implemented. Making private car ownership or use more expensive is the second policy. This can either be done through increasing parking costs, heavier taxes, or road pricing for non-shared cars. A price increase of 50% is used in this research.

The third policy is increasing parking restrictions. Just as the municipality of Amsterdam started doing in the summer of 2019. A yearly reduction for parking spaces of 1500 is used in the model. The fourth policy of placing more carsharing vehicles is aimed at improving the availability of carsharing vehicles. This is grounded in the assumption that the availability limits the growth. The last policy, is a combination of the best 3 policies. Best will be defined as the variables for which the model is most sensitive.

5. RESULTS AND DISCUSSION

In this section, the model and policy simulations are presented. First, the robustness of the model is discussed. Second the sensitivity of the model to different policies is tested. Third, the visual results of running the simulation are reviewed. The bounds used for the analysis of the three calibration cases and the response variables are listed in table 7 in the appendix.

5.1 Verification and robustness

Validating a model requires data that can be related to observed variables. Unfortunately, this data is not (yet) available for car sharing. The next best verification method is testing for robustness. This is done by comparing the results of sensitivity analysis for the different α- and β-values used in the calibration cases given in table 5. The results of the sensitivity analysis of the policies on the number of cars is shown in table 2

	1st case		2nd case		3rd case	
Variable	First index	Total index	First index	Total index	First index	Total index
Carsharing Vehicles	0.103	0.141	0.158	0.179	0.128	0.153
$Cost_{cs}$	0.002	0.002	0.001	0.002	0.003	0.003
$Cost_{pc}$	**0.118**	0.133	**0.491**	0.539	**0.507**	0.547
Parking Spaces	**0.732**	0.774	**0.0307**	0.336	**0.325**	0.352

Table 2: Sobol indices for the variables that are manipulated to promote carsharing with the total number of cars as response variable

Table 2 shows that the sensitivity of the model constant and low for the cost of car sharing, and relatively constant - all within a range of 0.103-0.158 - for the number of carsharing vehicles. The sensitivity for the cost of carsharing and the number of parking spaces shows a lot more more variation. When the costs are made more important through the β-values, an exchange of sensitivity between the cost of private car the number of parking spaces is observed.

The sensitivity of the weights is assessed in table 8. It can be found that the model is most sensitive for changes in the β-values of car sharing and private car costs, and for the public transport travel time and availability of carsharing. This indicates that the β-values for these variables cause the most uncertainty in the model, and therefore these values should be first found in future studies.

The results of the sensitivity analysis for the calibration cases and the results for the sensitivity analysis of the weights both show that the cost of a private car is one of the most sensitive parameters. However, a robustness check for extreme values still addresses a deficiency for the effect of the costs in the model. The demand for private car only approaches zero when the costs per kilometer reaches the absurd amount of €9.00. While even half that price would most likely push a lot of car owners on the verge of poverty. This implies that this relation might not be linear as assumed thus some other relations should be considered.

5.2 Sensitivity analysis

Sensitivity analysis is also done for the demand output variables and the users per vehicle to interpret the effect of the policies. The bounds used for the explanatory variables are listed in table 7 in the appendix. The third calibration case is chosen because this case puts more emphasis on the travel time and the cost for cars as compared to the number of parking spaces and number of carsharing cars. Table 1 showed already that people use the car not only for longer distances, but are also willing to travel longer with it. Despite the fact that the price per kilometer for car is higher than that of public transport.

	cs users		pt users		member/vehicle	
Variable	First index	Total index	First index	Total index	First index	Total index
Carsharing Vehicles	**0.860**	0.865	0.213	0.234	**0.533**	0.561
$Cost_{cs}$	0.020	0.024	0.007	0.014	0.064	0.078
$Cost_{pc}$	0.104	0.116	0.283	0.323	**0.357**	0.382
Parking Spaces	0.001	0.001	**0.450**	0.488	0.002	0.003

Table 3: Sobol indices for policy variables, with carsharing and public transport users and the users per vehicle as output.

Table 3 shows that the number of car sharing vehicles is now by far the most sensitive variable for the car sharing users and for the users per vehicle. The number of public transport users and the number of cars in the system, are most sensitive to the private car related policies. For all output variables, the sensitivity to the policies is larger when the policies interact with each other. Sensitivity analysis of the weights in table 8 should, and does, overlap with the analysis of policies. of the weights . It also shows that the travel time for public transport is an important variable in the model.

5.3 Policy scenarios

The behaviour of the model over the different cases is shown in fig.8-22 in the appendix. There large format charts are given for all output variables. The shape of the results in all charts is comparable, only the magnitude of the changes differs. This confirms the result of the verification in section 5.1. Let us look in detail at the charts of the third case.

The dynamics in the system are clearly dominated by negative feedback loops. This is due to the implementation of the state of equilibrium and has a lasting effect on the model. It creates seemingly deterministic behaviour in which the system will always move into a new equilibrium when policies are introduced. This relatively predictable behaviour might seem contradictory with respect to the idea of unpredictable complex systems. However the complexity does not lie in the eventual results but in the interaction between the different variables in the model.

As predicted by the sensitivity analysis, increasing the number of carsharing vehicles has the largest effect on the demand. Fig.5 (for a larger version see fig.19) shows that the new equilibrium is more than 2 times higher than for the other policies.

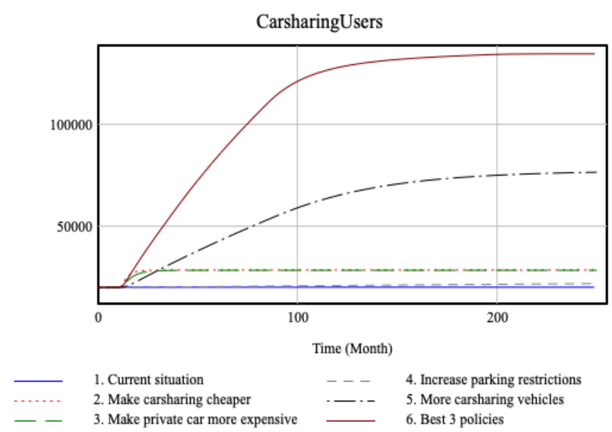

Figure 5: Policy effects on the number of people using carsharing for case 3

The increased demand for car sharing derives from private car users, but also for a large part from public transport users (see fig. 20 and 21). Therefore this measure has not much effect on the number of cars. The change in demand seems very large, but it must be noted that the number of cars becomes 7 times larger, while the other policies change the explanatory variables 50% or less. Whether the number of car sharing vehicles will soon become this high can be doubted. The municipality wrote in their car sharing agenda that they want to increase the number of permits for free floating carsharing. Though, it is not known whether that there is enough demand for the 2500 parking permits.

A closer look at fig. 6 reveals that changes in the private car cost and parking limitations indeed have the strongest effect on car ownership. Making carsharing cheaper or adding more carsharing vehicles even causes the number of cars (temporarily) to increase. Reducing the costs of carsharing seems to have more effect on public transport users than on private car users. The effect of the monetary policies seems rather limited overall, even for the third case. This confirms the idea that the implementation of the utility function might need revision.

The effect of increasing parking restrictions seems to be limited by the number of carsharing vehicles. Only when the policy is combined with adding car sharing vehicles, it has a strong effect on the carsharing users and the number of vehicles. The combined effect is actually more powerful than the effect of the individual policies added up.

The behaviour of the number of users per vehicle under

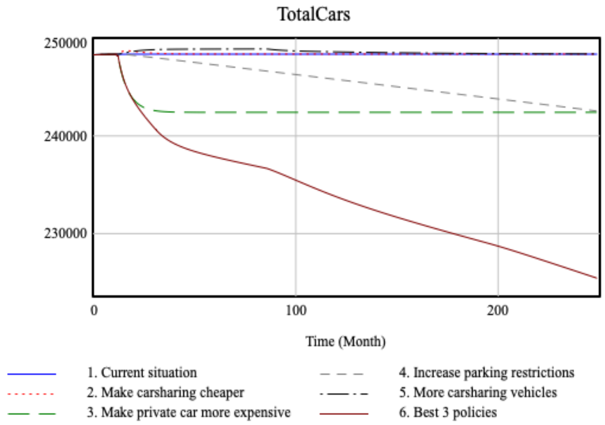

Figure 6: Policy effects on the number of cars for case 3

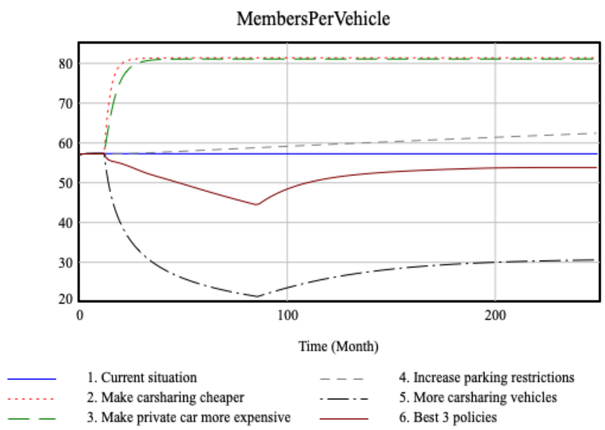

Figure 7: Policy effects on user-vehicle ratio for case 3

the different policies gives more insight in the influence of the availability of carsharing. Fig. 7 shows that there is only one policy that reduces the number of users per vehicle, while the other policies only seem to stretch the number of users per vehicle. The tipping point and overshoot that can be identified in policy 5 and 6 is caused by the delay in the change in demand.

6. CONCLUSIONS AND FUTURE WORK

One of the most important things this research has done is addressing the relation between demand and supply, which was lacking in other simulations until now [20]. Increasing the supply of car sharing vehicles turns out to be paramount in order to make the demand for car sharing increase. Increasing the number of vehicles reduces the number of users per vehicles, which on its turn improves the availability of car sharing vehicles.

The other three policies do not promote car sharing, but rather make other transport modes more expensive, thereby stretching the tolerance for in-availability of car sharing. The last persons to switch are the most dependent on their vehicle. To be able to keep addressing new users, the availability needs to improve continually. However, more car sharing vehicles on its own will have little effect on car ownership. Car sharing turns out to be an attractive alternative for public transport.

Sensitivity analysis has shown that the combined effect of the policies is larger than individual policies alone. The effect of providing more car sharing vehicles is enlarged by adding other policies. Especially the interaction between the number of car sharing vehicles and the degree of parking restrictions is promising. The most successful policy will be a combined policy.

Parking restrictions without extra car sharing vehicles will mostly persuade car owners to switch to public transport. This emphasizes the importance of a good public transport system. Another argument for a good public transport system is that all policies now have only limited effect on the number of cars. Without it, car users will probably hold on to their car next to using car sharing services.

Car sharing alone will not soon replace the private car. Even when policies are combined very radical measures are necessary to make people abandon their personal vehicle en masse. On the other hand, a mix of policies combined with an outstanding public transport system can make a lot of people change their travelling behaviour.

6.1 Future research

Modelling is simplifying reality, it requires the modeler to leave parts of the complexity of the real world out. Nonetheless the current model can be improved by adding some complexity based on future experimental studies.

The model now seems to underestimate the impact of the costs. [19] uses a variable for financial capacity of the users. The introduction of this variable might make the influence of the costs less linear. How this could be implemented is still undetermined. Three other variables that might be included are weights for the availability of car sharing and public transport and for parking restrictions. As no data about the relation between these variables and utility is yet available, the effect is now modelled without an intermediate variable.

A policy addition that future research might look into is relieving the parking restrictions for car sharing, by assigning public parking spaces to vehicles used for free floating car sharing. The exact implementation for this in the model is still open for future research, but it seems an important policy extension if the municipality does want to promote car sharing as an alternative to the private car.

As mentioned in section 2.2, two lines of thought about the relation between the adaption of car sharing and car ownership can be identified. One is that car ownership is only an indicator for mode use. The other strand of research supposes that car ownership is depends on the mode used. That is, broader adoption of car sharing will lead to lower car ownership for car sharing users. The former idea is now implemented in the model. However, seeing the results, especially the interaction between public transport and car sharing, initiates the thought that the latter holds some truth as well. People switching from public transport to car sharing are not very likely to also buy a car, hence this could lead to a decrease in the car ownership ratio for car sharing users. Future research should look into this relation more closely.

Although literature mentioned demand exchange between bicycle and car sharing, this is not implemented in the model.

Furthermore, the model would also benefit from including (shared) scooters or motors as well. Both extensions were too complicated to include in the model for the time span of this research. A last but related uncertainty of modelling demand for innovative mobility services, without data to validate certain assumptions, is that it is impossible to capture how adoption of car sharing influences the journeys people make. It is not unthinkable that people who use car sharing have other travel patterns. The number of rides is now not included in the model, but this can have a significant effect on congestion or the availability of car sharing. The implementation of both is worth looking into.

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8. APPENDIX

8.1 Acknowledgments

As with all large projects, I could not have done this without others, and there are a few that I want to name. My first examinor and supervisor Valeria Krzhizhanovskaya was very involved, always available for questions, and made sure I kept my schedule. Quinten Meertens took care of all the logistics at Statistics Netherlands, organized feedback sessions and gave a lot of feedback on my work in progress. Ton Bastein and Cees Diks were very interested in my work and gave me helpful advice. The second examiner, Frank Nack, prepared me well for the thesis during the Masters. My colleagues and in particular Carolyn Wever were very flexible, supportive and always interested. My editor Peter Kaan was very thorough and took a huge weight off my shoulders. Lastly, I want to thank my girlfriend Judith Pel who was a big support and always an understanding audience.

8.2 Tables and figures

Measure	Private car trip distance	Public transport trip distance
count	5484	4372
mean	21.24	5.60
std	30.58	6.02
min	0.1	0.1
25%	4	2.4
50%	10	4.2
75%	25	7.0
max	299	99.0

Table 4: Summary of trip distance distributions per mode

Weight	1st case	2nd case	3rd case
α_{cs}	0.1010	0.0510	0.1460
$\beta_{C,cs}$	0.0200	0.0335	0.0400
$\beta_{T,car}$	0.0100	0.0300	0.5000
α_{pc}	0.1980	0.1180	0.1945
$\beta_{C,pc}$	0.0100	0.0300	0.0300
$\beta_{C,pt}$	0.1000	0.1000	0.0600
$\beta_{T,pt}$	0.1000	0.1000	0.6000

Table 5: mode specific constant (α) and weight (β) estimations

Variable	Initial Value	**Unit**
$CarsharingUsers$	20000	Persons
$PrivateCarUsers$	200000	Persons
$PublicTransportUsers$	175000	Persons
$MaxCapacityPt$	250000	Persons
$Threshold$	100000	Persons
$distance$	6	km
$Speed_{car}$	30	km/h
$Speed_{pt}$	16.2	km/h
$Time_{acc/eg,pt}$	0.14	hour
$Cost_{cs}$	18.00	Euro/h
$Cost_{pc}$	0.64	Euro/km
$Cost_{pt}$	0.162	Euro/km
$InitialCost_{pt}$	0.96	Euro
$ParkingSpaces$	433000	Parking spaces
$CurrentSpacesperCar$	1.75	Parkin spaces/car
$VehicleOwnershipCs$	0.7	Cars/person
$VehicleOwnershipPC$	1	Cars/person
$VehicleOwnershipPt$	0.195	Cars/person
$CarsharingVehicles$	350	Cars
$Area$	220	km^2
$Roadlength$	1900	km

Table 6: Variables in the stock and flow diagram (fig. 2) and their initial values

Variable	Lower bound	Upper bound
Carsharing Vehicles	350	2500
$Cost_{cs}$	1	18
$Cost_{pc}$	0.64	2
Parking Spaces	350000	450000

Table 7: Bounds used in the Sobol sensitivity analysis of table 2 and 3

	Bounds		All policies active	
Variable	Lower bound	Upper bound	First index	Total index
$\beta_{Cost,cs}$	0	0.1	0.069	0.202
$\beta_{Cost,pc}$	0	0.1	**0.420**	0.756
$\beta_{Cost,pt}$	0	0.1	0.001	0.045
$\beta_{Time,car}$	0	1	-0.11	0.095
$\beta_{Time,pt}$	0	1	**0.120**	0.214
$\beta_{Avai,cs}$	0	1	**0.100**	0.134
$\beta_{Avai,pt}$	0	1	0.006	0.029
β_{Prestr}	0	1	0.033	0.057

Table 8: Sensitivity for the beta values in the model

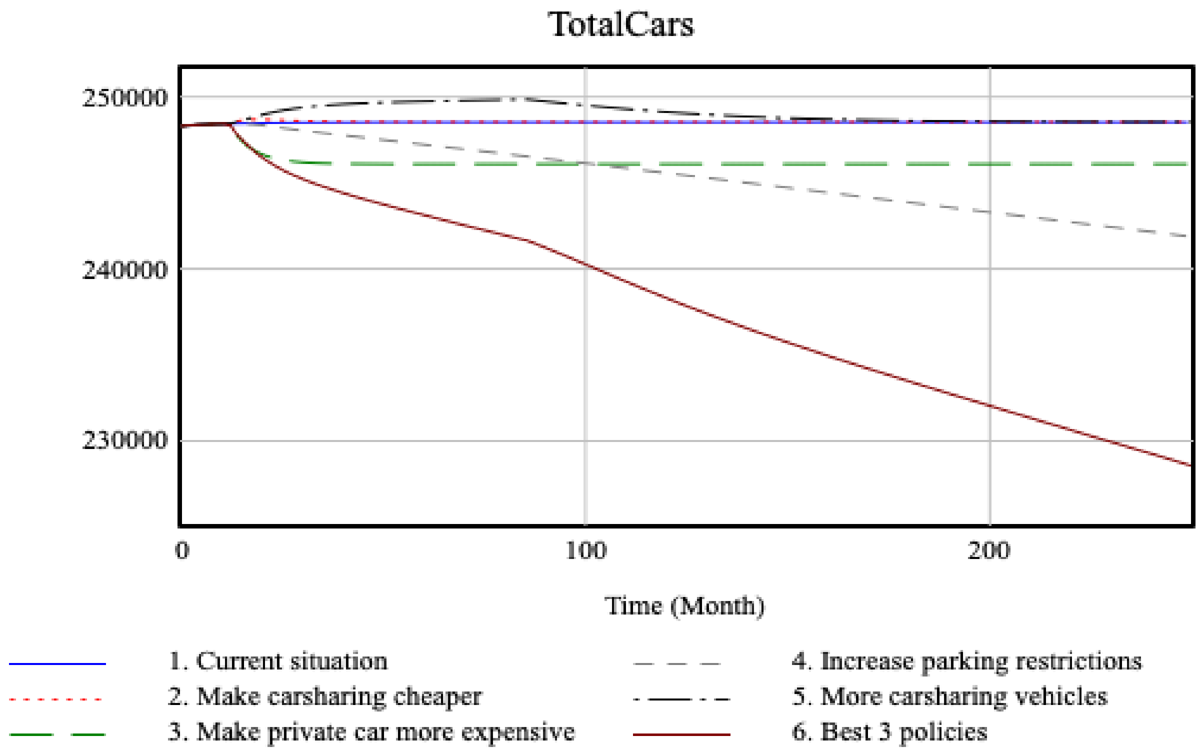

Figure 8: Policy effects on the number of cars for case 1

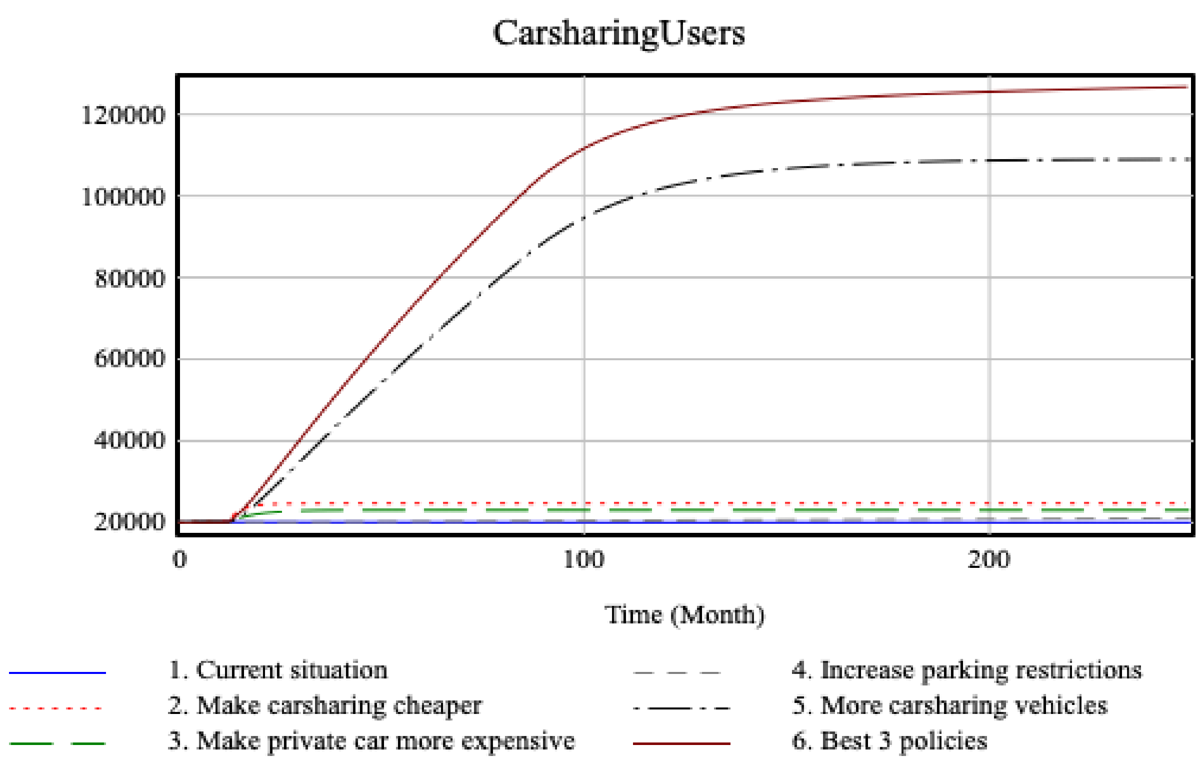

Figure 9: Policy effects on the number people using carsharing for case 1

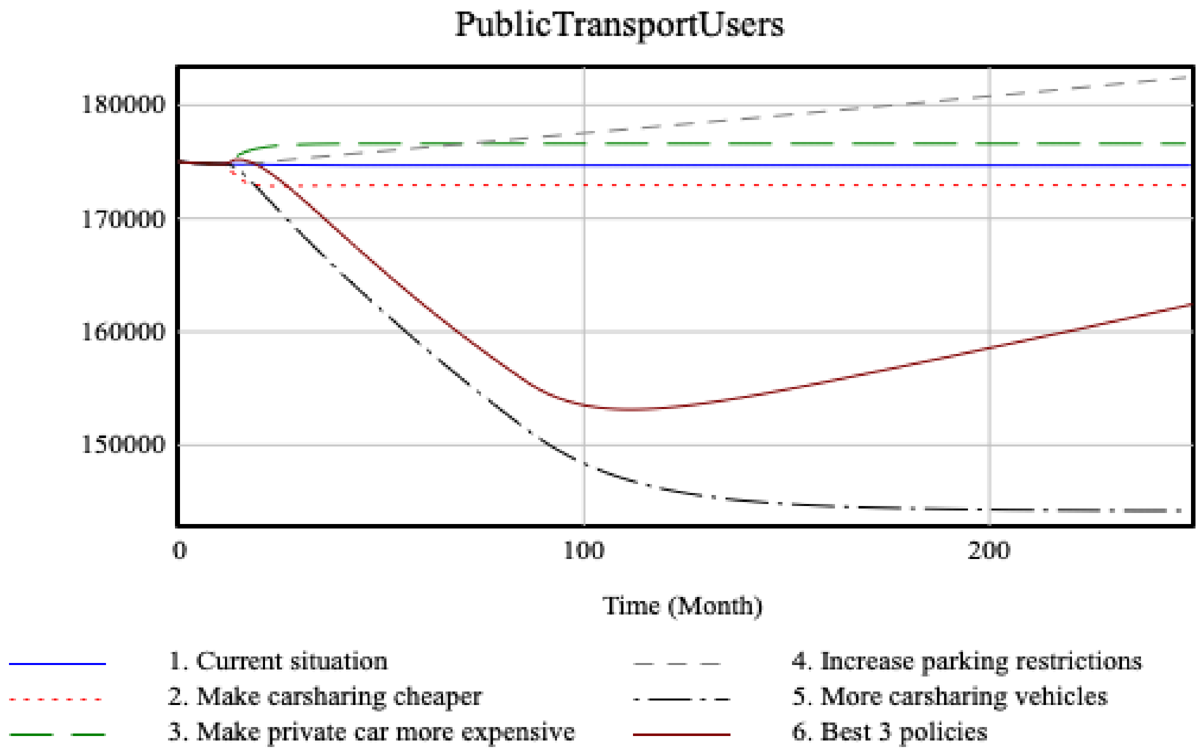

Figure 10: Policy effects on the number of people using public transport for case 1

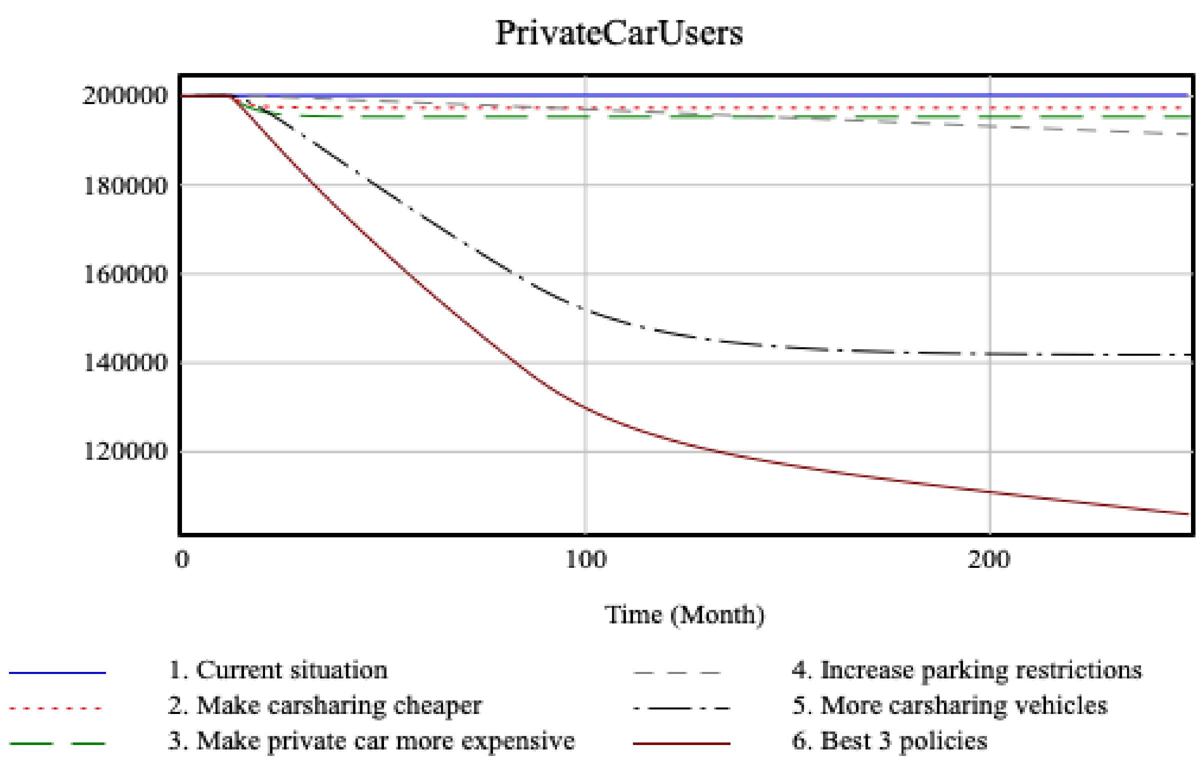

Figure 11: Policy effects on the number of people using private car for case 1

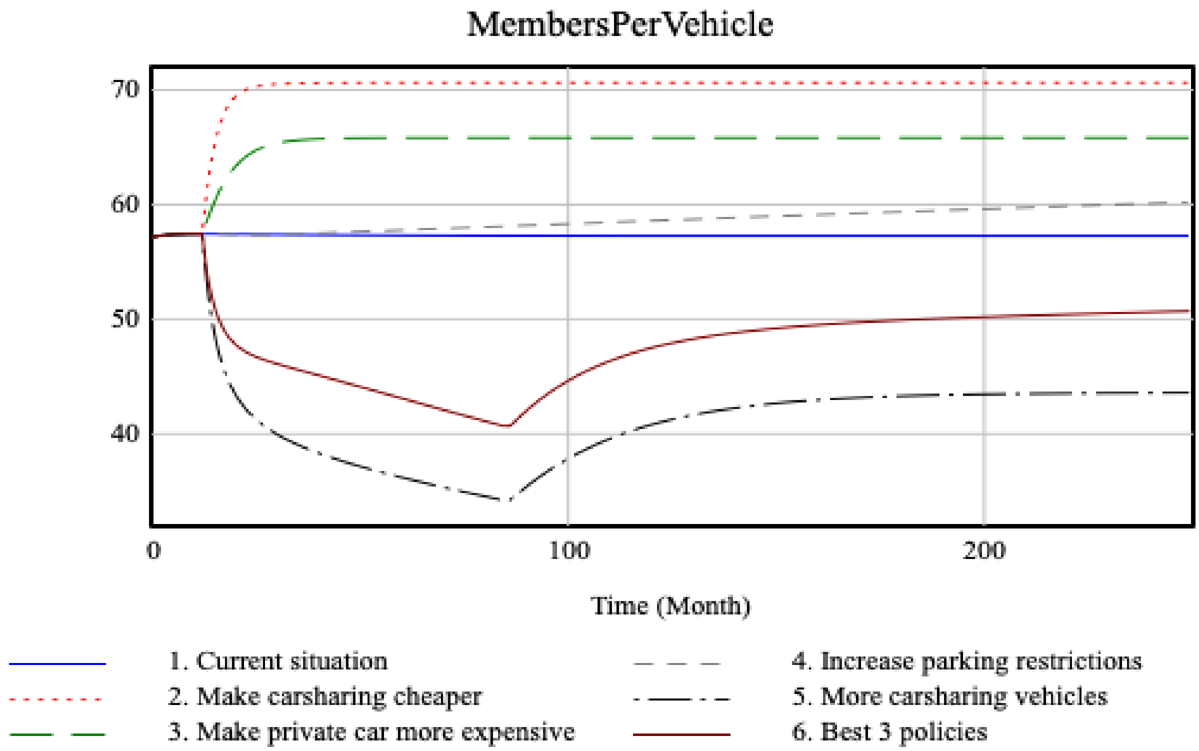

Figure 12: Policy effects on user-vehicle ratio for case 1

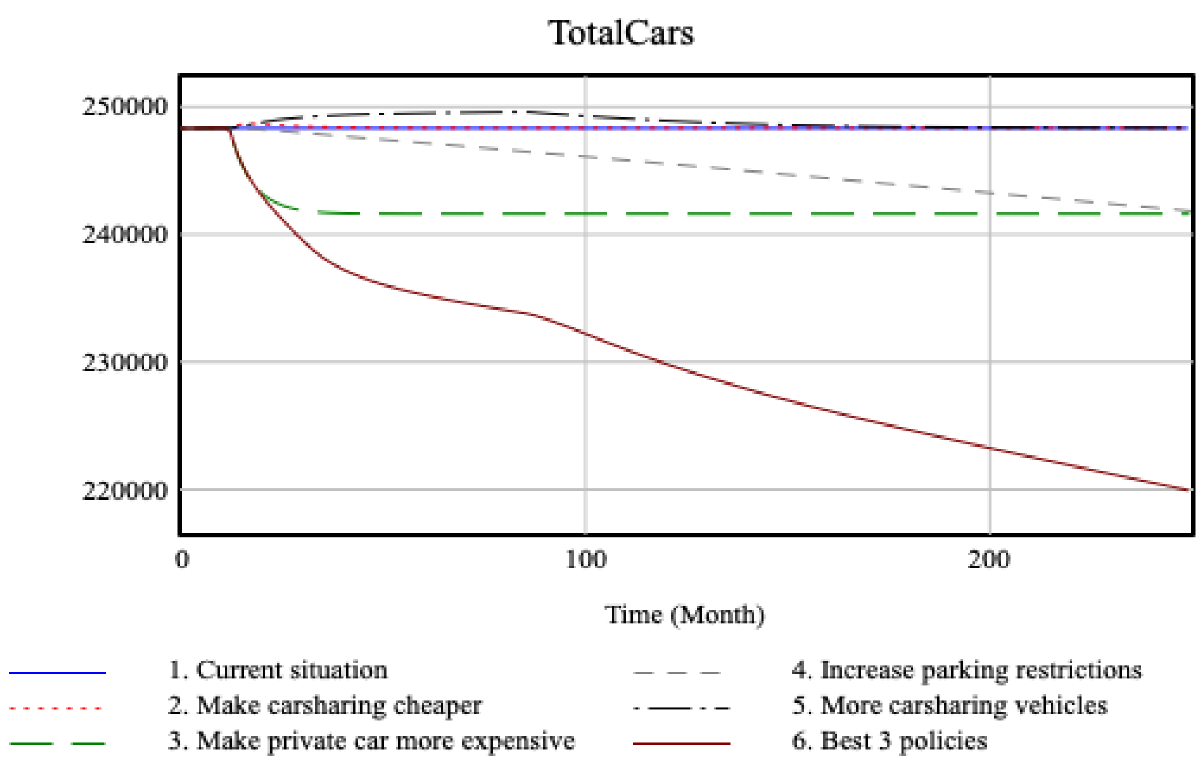

Figure 13: Policy effects on the number of cars for case 2

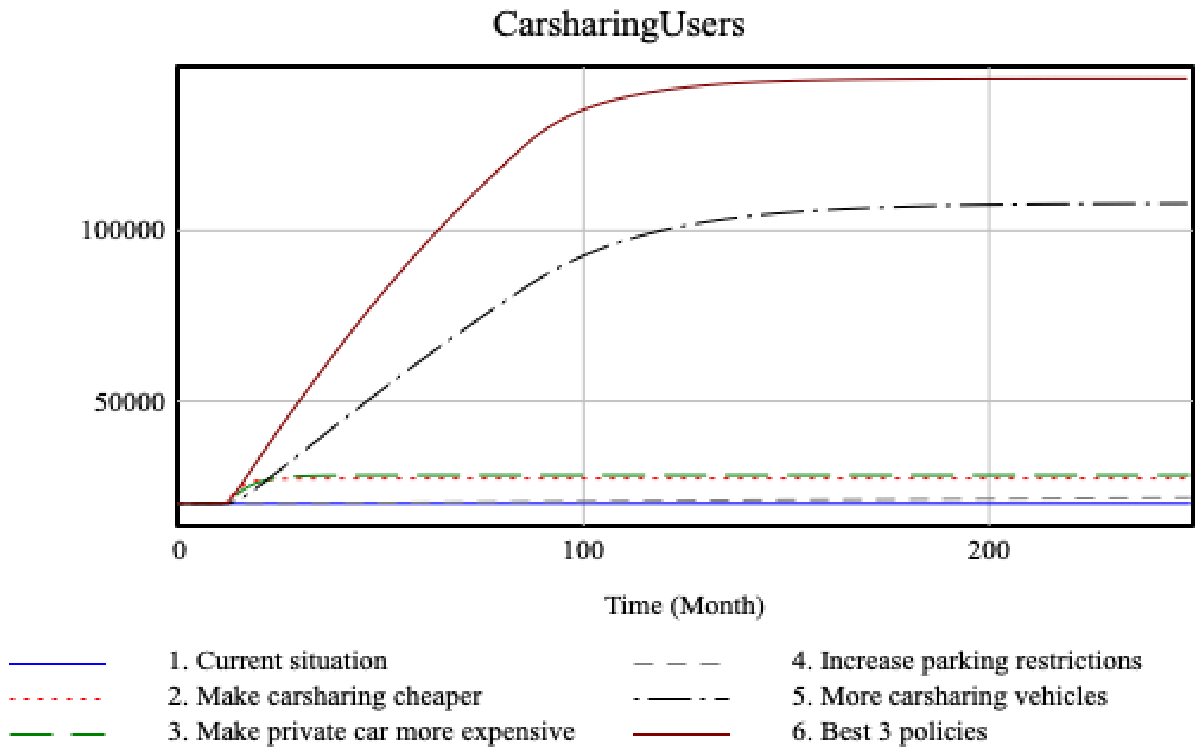

Figure 14: Policy effects on the number people using carsharing for case 2

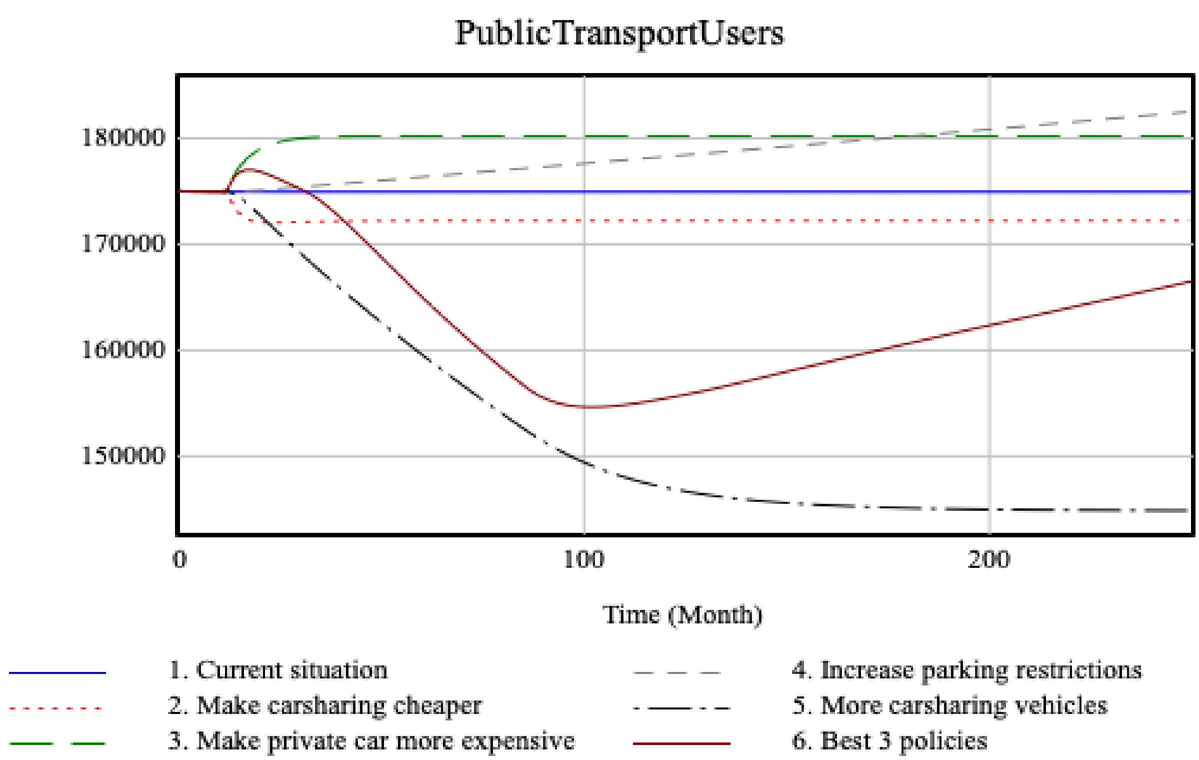

Figure 15: Policy effects on the number of people using public transport for case 2

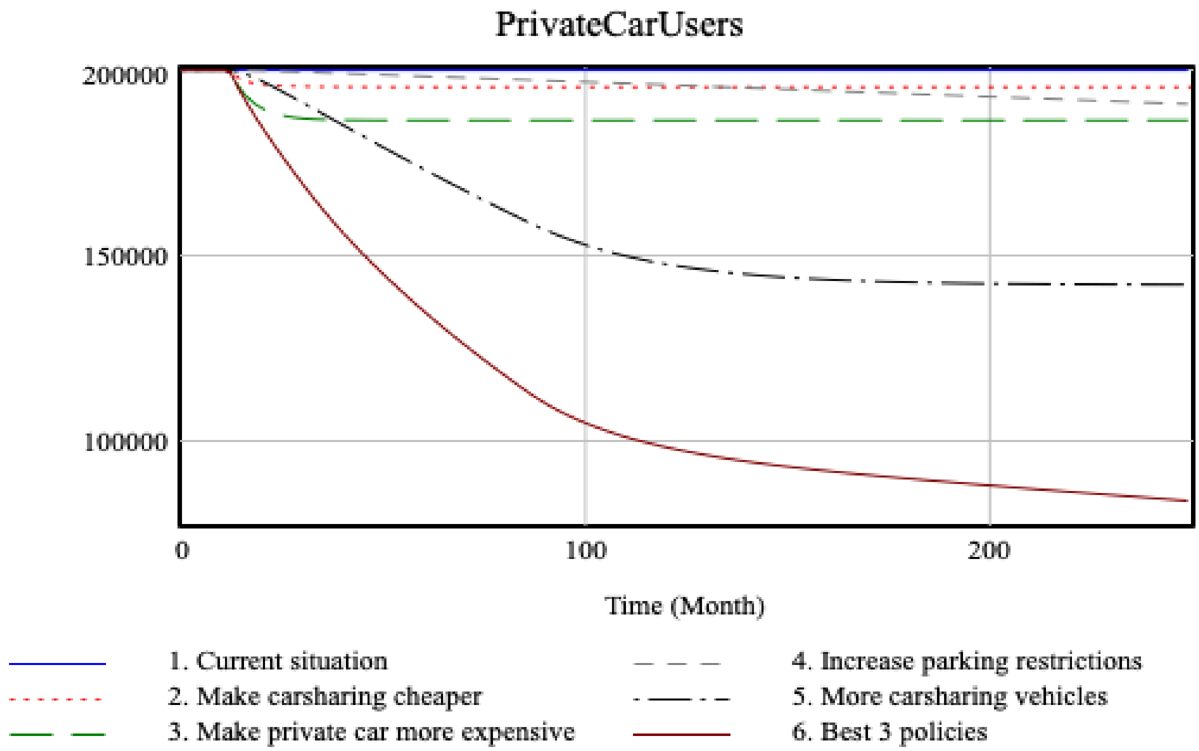

Figure 16: Policy effects on the number of people using private car for case 2

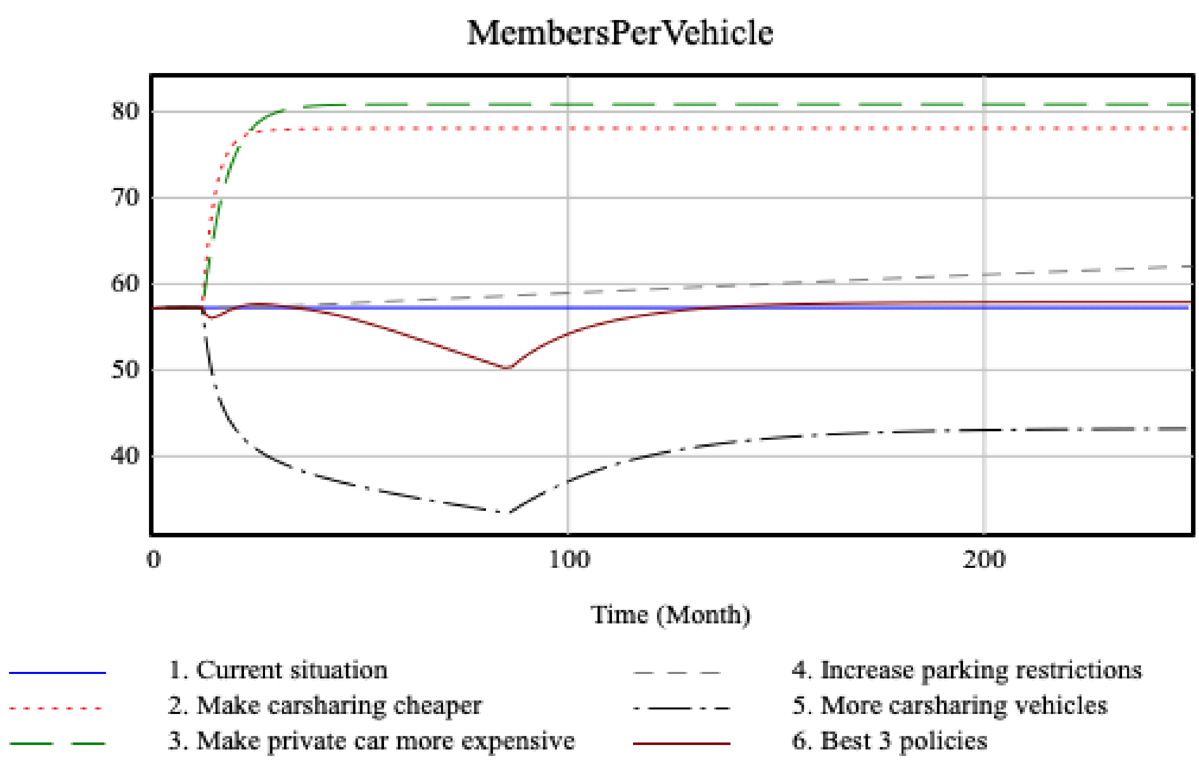

Figure 17: Policy effects on user-vehicle ratio for case 2

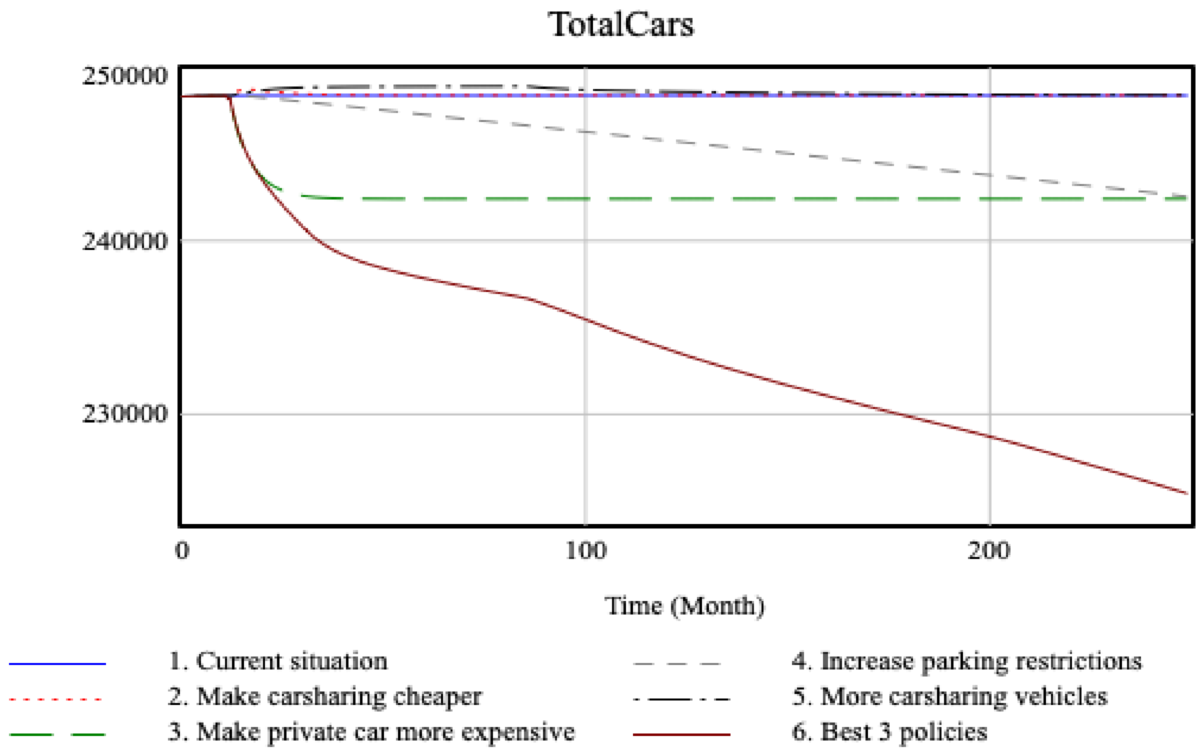

Figure 18: Policy effects on the number of cars for case 3

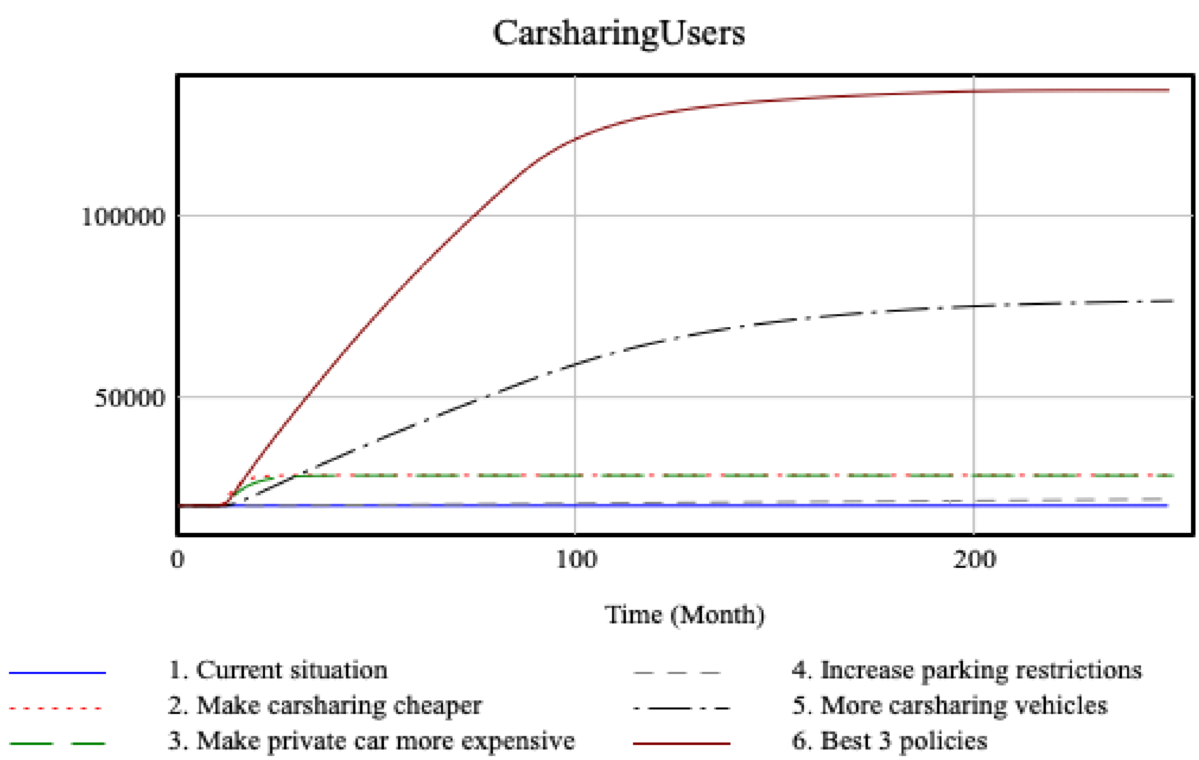

Figure 19: Policy effects on the number people using carsharing for case 3

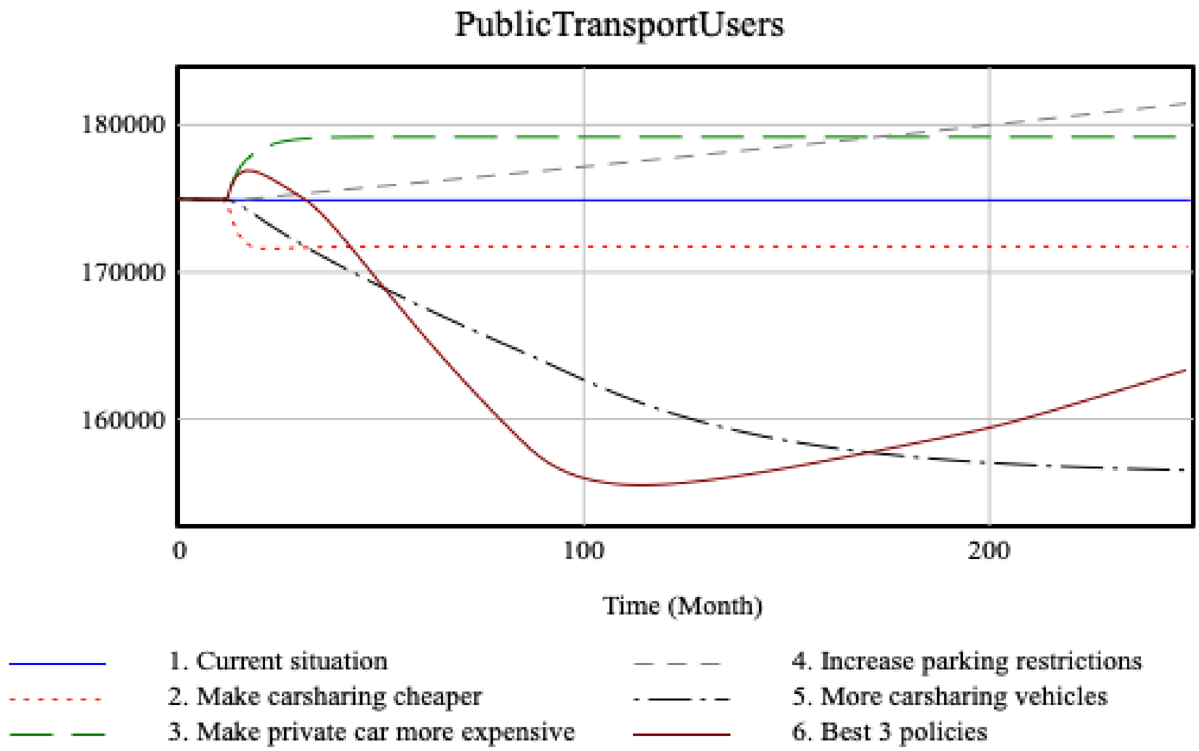

Figure 20: Policy effects on the number of people using public transport for case 3

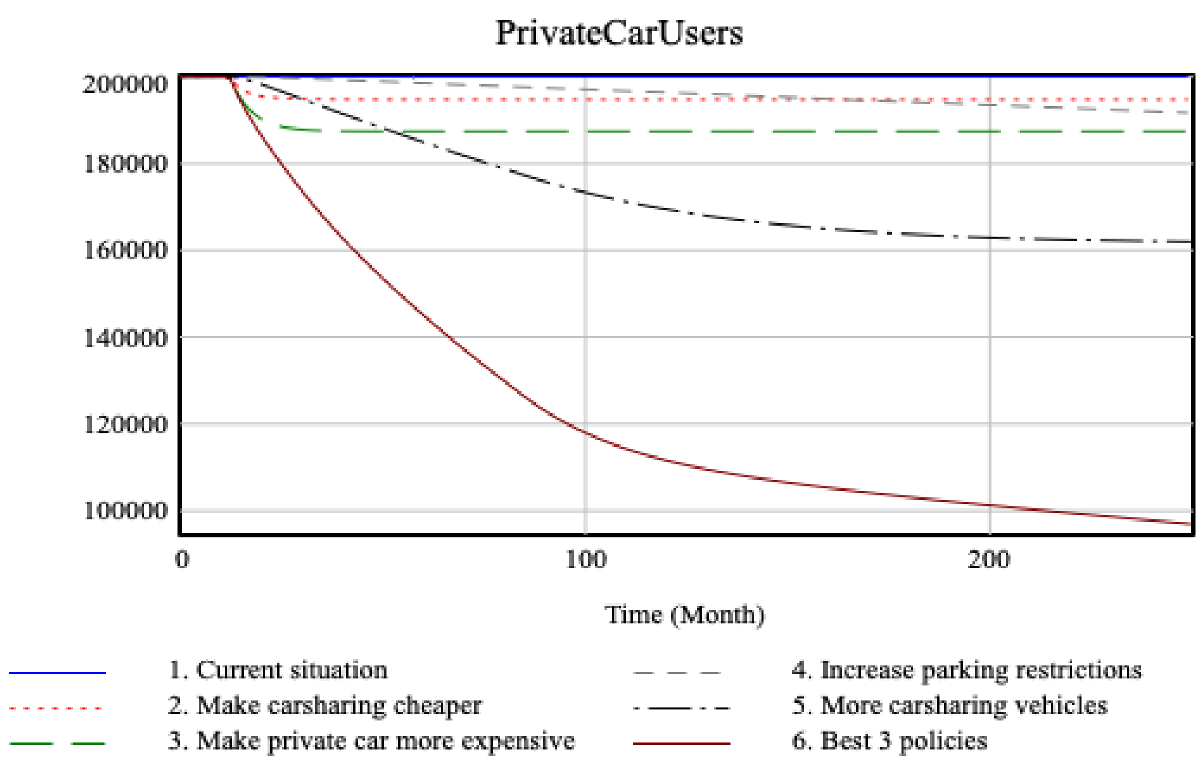

Figure 21: Policy effects on the number of people using private car for case 3

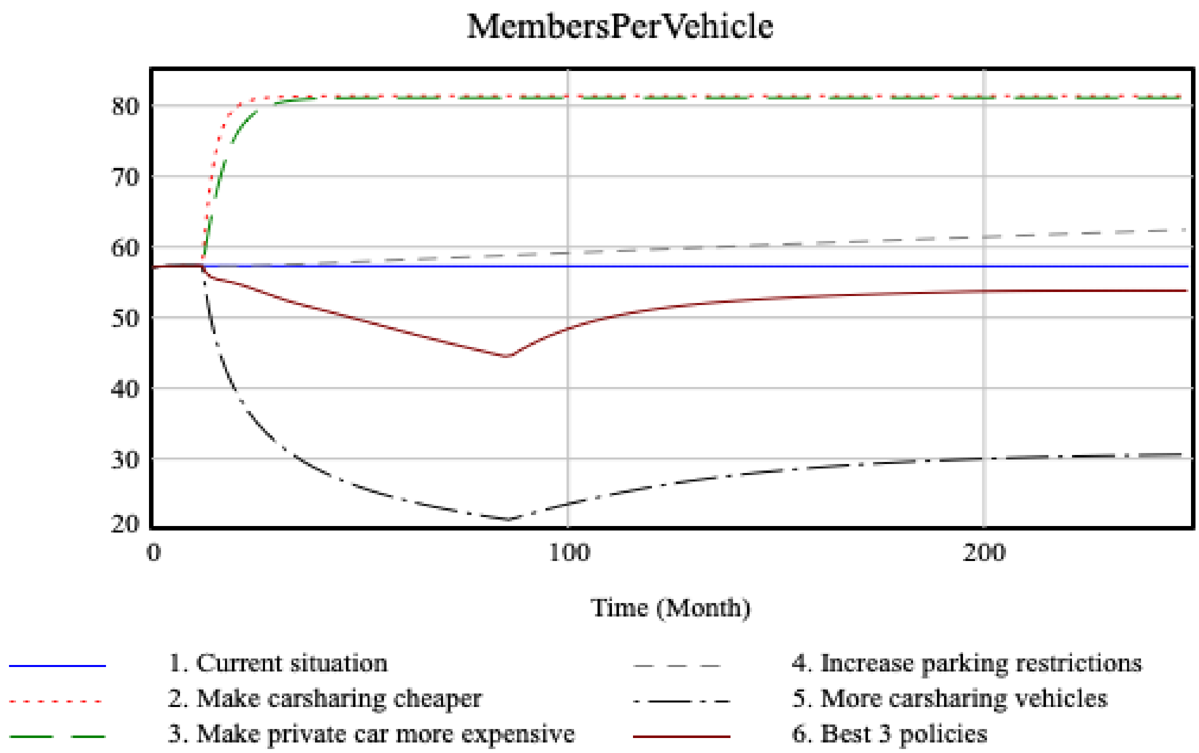

Figure 22: Policy effects on user-vehicle ratio for case 3