Bachelor in Mathematics Student Task 2024

Relationship between the Mobility in Geneva, Carbon Emissions and a New Tax

Author
Štěpán Ondřej

Supervisors
prof. Giovanna Di Marzo Serugendo
Flann Chambers

April 24, 2024

Acknowledgements

I would like to express my deepest appreciation to prof. Giovanna Di Marzo Serugendo and Flann Chambers for their guidance, feedback and help. This unforgettable experience would be impossible without them. Additionally, I am extremely grateful to Charles University for funding my trip to Geneva.

I am also thankful to prof. Fabien Pazuki for organising the BMST project. Many thanks to doc. RNDr. Zbyněk Pawlas, Ph.D. for guiding me through the formal necessities concerning this project.

Abstract

In response to the climate change, the city of Geneva has imposed a new tax on the owners of passenger cars. Therefore the aim of this project is to develop an agent-based model that follows the DPSIR framework about the relationship between the mobility in Geneva, CO_2 emissions and a new tax system. The model will be programmed in GAMA platform, an environment for agent-based simulations. The project will be not only about the implementation of such simulation, but also about the analysis of its output data.

The tax system implemented in the model will differ from the one that was passed, however it will still lead to some interesting results. For example, we will see that the emissions produced in 2035 decrease when we increase the tax or if we let more people switch to electric cars. On the other hand, we will see that the amount of the CO_2 emissions produced in 2035 is *not* monotonously dependent on the annual tax growth rate. And even though the tax implemented in the model differs from the one that was passed in reality, this model might serve as an interesting comparison of those two tax systems.

Contents

Introduction

With two major agreements signed in the last decade (the Paris Agreement and the Green Deal), it is safe to say that climate change has become a major topic not only in Europe, but also in the western society. Therefore there is no wonder that "the City of Geneva declared a climate emergency in February 2020. It intends to reduce greenhouse gas (GHG) emissions by 60% by 2030 and to achieve carbon neutrality by 2050, in order to limit climate change and comply with the Paris Agreement" [1]. One of the key parts of Geneva's climate strategy is to reduce the carbon emissions produced by transportation [2] [3] (even though less than 1% of the global greenhouse gas emissions is produced by passenger cars and vans in the whole Europe [4] [5]). One of the ways to reduce the emissions is the new tax from the 3rd March 2024 imposed on the owners of passenger cars [6] [7].

That is why, in this project, we try to model the relationship between the car usage in Geneva, carbon emissions produced by cars and a tax imposed on car users. We focus solely on the canton of Geneva and on the commuting to and from work in peak hours (6:30-9:00 and 16:00-19:00 [8]).

We will develop a model for the mobility in Geneva during peak hours using the ABM methodology (ABM stands for agent-based modeling). In this methodology, each unit of the studied real-world system is represented by an agent. For instance, in our case, the system consists of people, tramways, buildings, roads... in Geneva, therefore we will have agents representing people, tramways, buildings, roads... in Geneva (more about these agents can be found in the Agent-based model section). Each agent has its own attributes and reflexes (reflexes represent the agent's behaviour). The agents interact with each other as well as with the environment they are in. The rule of ABM is that each agent makes its own autonomous decisions [9][10][11].

In this project, we want to study the car usage as a mean of transport to work. We also want to implement a tax system and study its impact on car usage. In this model, we have implemented a different tax system from the one that was actually passed. The main difference between the two is as follows: in the system that was passed, people pay an amount of money based on the mass of their vehicles. Furthermore, they pay an extra amount of money based on how much grams of CO_2 their car produces per kilometer. More details about the system can be found in the article "Le 3 mars, Genève vote sa prochaine imposition des véhicules" by Patrick Schneuwly, 2024 [7] (section contreprojet). On the other hand, in our model, under the default parameter settings, each person pays a fixed amount of money per kilometer according to car type the person uses (diesel, petrol or electric). The final sum the person pays is calculated at the end of the year as $traveled\_kilometers \cdot price\_per\_kilometer$. Note that the *traveled_kilometers* term stands for the amount of kilometers the person traveled *this year*, not in their entire existence. Furthermore, we have implemented that the *price_per_kilometer* starts at 0 CHF for people owning an electric vehicle. Then, the user has an option to set how the tax will increase annually for people with electric cars. By default, this is set to 0 CHF. That means that under the default settings, people owning an electric vehicle will pay 0 CHF on taxes *during the whole simulation* *run.* For the sake of completeness, let us mention that the user has an option to turn the whole tax system off (in which case, everybody pays 0 CHF on taxes) or they can set that only the type of vehicle is considered to calculate the tax - i.e. the tax will not depend on the driven kilometers.

Finally, we will analyse the output data from our simulation. More specifically, we will explore how the change of the tax, amount of people who switch to electric vehicles and the impact of the tax on relocation decisions affect the emissions.

1 Contextualisation

In this chapter we will provide basic information about our model.

1.1 Use Case

As mentioned above, we want to study the relationship between the car usage, carbon emissions produced by car users and the tax imposed on car users. First, we assume that the number of car users grows in time because of the population growth in Geneva. On the other hand, there will be two ways to decrease the number of car users. The first one will be that people will decide to stop using cars by themselves (we wanted to reflect the phenomenon described, for example, in the article “Young Europeans more likely to quit driving and have fewer children to save planet” in The Guardian [12]). The other will be the tax.

In this project, the user will be able to set parameters to model the desired situations. Moreover, if the user is only interested in the impact of the tax growth rate on the amount of the CO_2 emissions in 2035, they can use the batch experiment.

1.2 Model overview

The model is built in the GAMA platform, which is a “modeling and simulation environment for creating spatially explicit agent-based simulations” [13]. The source code for the model can be found here: `https://github.com/Stepki6/BMST24/tree/master`. Also, a short video showcasing the model can be found here: `https://youtu.be/G9k8tXgL7Ak?si=T5XBDk72we_Y9MXf`.

In the user interface, the user can set parameters and they can see the monitors, simulation and graphs. Figure 1.1 captures a screenshot of the interface.

One parameter is worth a further explanation: it is the *small_model* parameter. When disabled, each agent represents one of the Geneva’s residents (for more information about agents see the “Agent-based model” section in the next chapter). When enabled, 12 residents are represented by 1 agent (this granulation can be changed by the user). This way, we can launch the simulation for a smaller amount of agents and, as a result, it runs much faster. The road network the user sees and the buildings loaded in the simulation were obtained from the SITG website [14].

What is also worth mentioning is that only 5 (working) days each month are calculated, for the other days we assume a similar behavior. This has an important impact on the tax system: the displayed values in the “Average tax” graph are calculated based on those 60 days each year, i.e. they are *not* calculated based on the whole year. It is important to keep this in mind because the tax depends on the traveled kilometers (unless the user turns this feature off), and in 60 days people travel less than in a whole year, hence the tax outputted by the model is significantly lower than it should be.

At the end of each year, if emissions are higher than a given threshold, the government will increase taxes for the car usage. This should discourage people from using cars and thus decrease the emissions.

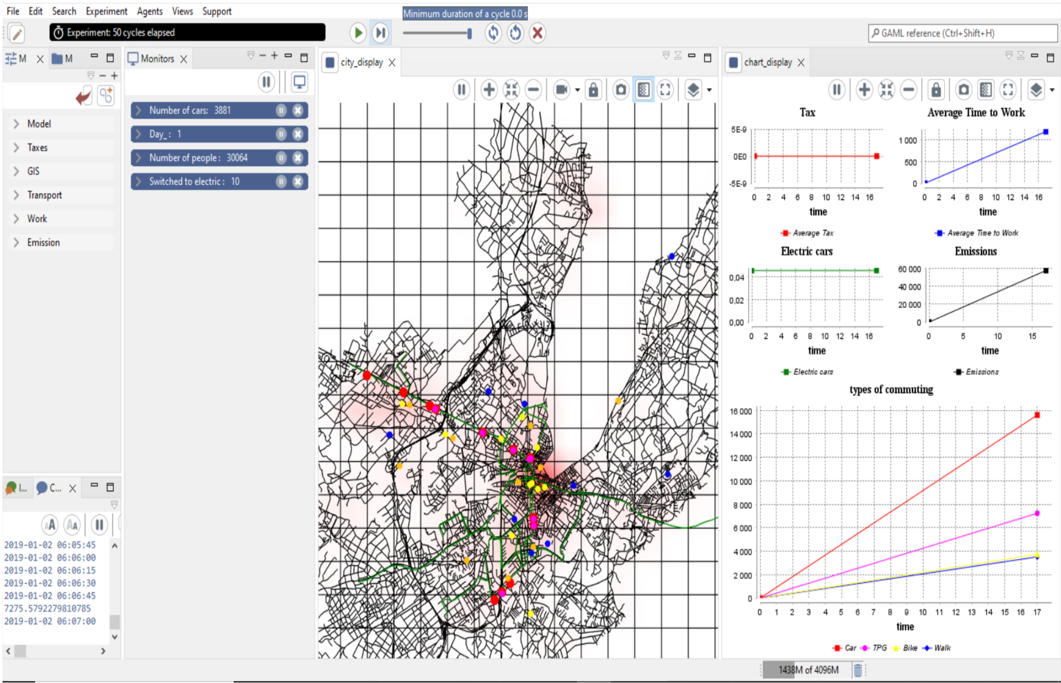

Figure 1.1 Overview of the interface

2 Method

In this chapter, we will describe the methodologies used to create the model.

2.1 DPSIR

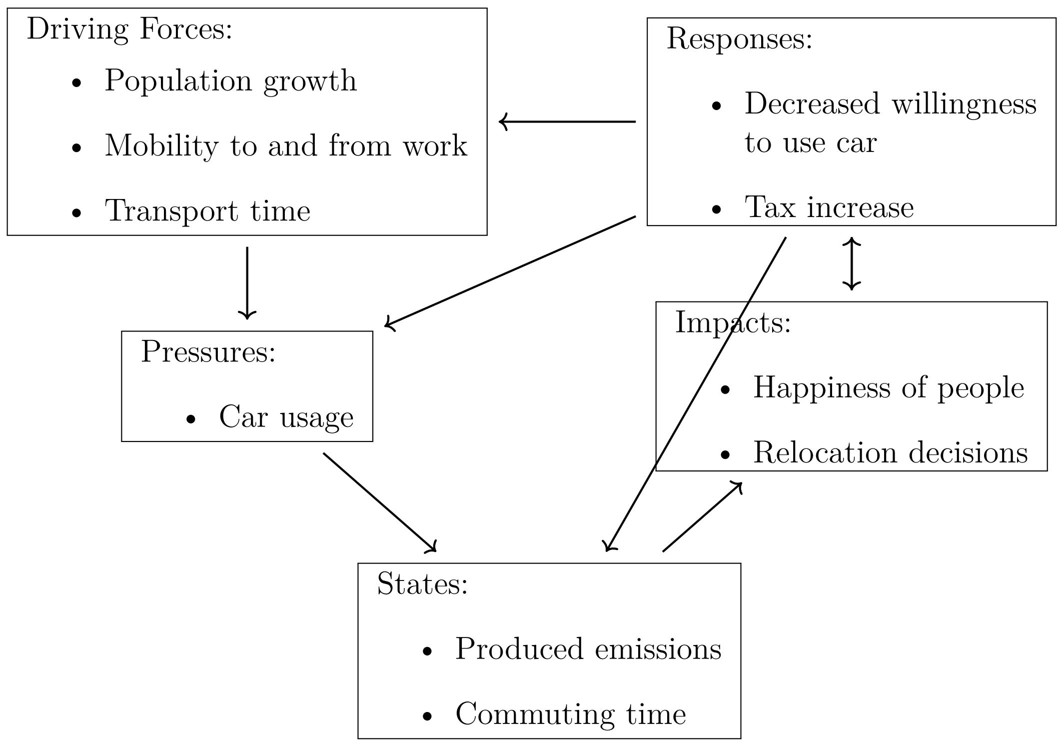

Figure 2.1 DPSIR graph of our model

In the model, we will use the DPSIR framework, which is a "causal framework for describing the interactions between society and the environment. In this framework, the Driving Forces (D) exert Pressures (P) on the environment and, as a consequence, the State (S) of the environment changes. This leads to Impacts (I) on the society, which may elicit a societal Response (R) that feeds back on Driving Forces, on State or on Impacts via various mitigation, adaptation or curative actions" [15].

Now we would like to present what the DPSIR framework will look like in our situation. Our major driving forces will be two: population growth and mobility to and from work. We assume that every Geneva's citizen has a job in Geneva. We also assume that each person goes to work between 6AM and 9AM and returns home between 4PM and 7PM. We assume that if a person lives close to their working place, they will either walk to work or go by bike. However, with increasing distance we suppose that more people will start using the TPG and cars. In this case we assume that the person chooses the mean of transport that takes the least amount of time - which is almost always the car (there is one exception to this rule: if commuting by the TPG takes only a "slightly" more time than commuting by car, there is a probability that the person chooses the TPG. Precise probabilities can be found in Table 2.1). This explains our last driving force - the transport time. After each day, we will expand the population in Geneva - i.e. we will add more people that will need to commute to work.

Every day commuting will really force people to use cars (especially if they live far from work or if there is not a good connection by the TPG) and thus pressure the car usage.

With more cars in the city, the amount of produced emissions will increase. This state of our system will influence the happiness of Geneva's residents (more emissions will lead to the decrease of happiness). Happiness of the residents will also decrease if they need a lot of time to commute. As a result, if the happiness is too low, people will try to relocate to a different place (usually closer to their working place). More precisely, happiness is a float number between 0 and 1 (including both 0 and 1). If people take more than 30 minutes to commute or if they are using cars and the tax is greater than the threshold set by the user (the "tax impact on relocations" parameter), the happiness will be automatically decreased by 0.5. Then, it will be further decreased based on the tax. Finally, if the happiness of a person is less than 0.5, that person will try to relocate. Note that in this model, we assume that only cars produce emissions - i.e. the TPG's vehicles do not produce emissions at all. That corresponds to the statement on the TPG's website that they operate roughly 450 vehicles, half of which use 100% renewable energy [16].

Finally, to the high amount of emissions, the government may respond by increasing the tax for the car usage. This should discourage people from using cars and as a consequence, the emissions should drop. However, by switching to a different mean of transport, it will take more time to get to work and as a result, people might become unhappy and relocate. Note that, by the above, increasing the tax itself will have a negative impact on the happiness of people regardless of whether they will need more time to commute.

Also, as a minor response, a few people will also stop using their cars by themselves. However, as we will see, it will not be enough to cause the emissions to drop significantly.

The Figure 2.1 summarizes the DPSIR framework used in our model.

2.2 Agent-based model

In this section we would like to describe the agents in the simulation and their mutual interaction.

2.2.1 The global agent

Let us start with the global agent. This agent represents the world (environment). Apart from attributes (which often represent some "global parameters", such as how many people will be created at the initiation of the simulation), it contains several major reflexes.

The first important reflex expands the Geneva's population. At the end of each day, this reflex adds new people to the simulation in such a way that the population in Geneva grows by roughly 1% each year, which corresponds to the official statistics [17]. Each of these newly created people is assigned a new living place, which is chosen from four particular buildings, located in the PAV area (more about the PAV project can be found online in the article "PAV Geneva Master Plan" [18]) - i.e. no new buildings are created. The idea behind this is that we are interested in CO_2 emissions, hence we do not need to know where exactly the person lives - a rough estimate is sufficient.

The second important reflex is the relocation reflex. It relocates up to a certain amount of people from their living place to a new available place. As we need to do it quickly, we can not make each person check for the available locations. Instead, we find the available places only at the beginning of the relocation process, save them into a list and then work with this list, which is usually much shorter than the list of all buildings. The relocation reflex looks like this (note that we make the people move to the location closest to their working place, which is definitely not the case in reality).

```
list to_relocate <- people who want to relocate
list available_locations <- buildings that are not full

loop person over to_relocate
{
    tmp <- building from available_locations closest to working place
    available_locations >> tmp
    available_locations << person.living_place
    decrease the number of people in person.living_place by 1
    increase the number of people in tmp by 1
    person.living_place <- tmp
    update some attributes of person
}
```

Finally, after each year, we want to impose the new tax on people. The reflex doing this works as follows: if there were more emissions than a given threshold, the price per kilometer is increased. Then the distance the person has traveled with their car is reset.

2.2.2 The grid

An unusual thing that really catches the user's eye is the grid. The motivation behind using it is as follows: we need to display the emissions. One way to do it is to create a special emission agent and place it in the world where emissions were produced. However, this creates a lot of agents and thus slows down the simulation. This is fixed by the grid. Each cell has the *emissions* attribute. Whenever a car produces emissions in a cell, that cell's emissions attribute is updated (this only works if people are displayed. Otherwise, since the simulation step is 1 hour anyways, we just update the emissions in a cell where a person arrives). Then the cells change color according to the emissions. The more red a cell is, the more emissions were produced in that cell. If we look at Figure 2.2 and Figure 2.3, we can see a clear difference in produced emissions.

The interesting part about it is that the most red area in Figure 2.2 (in the centre) corresponds to the city centre. In reality, many people work in this area, which causes a high traffic there - and as a result, the production of emissions there is really high. This corresponds with the output of the simulation.

Furthermore, we can see many pink cells in the top right part of the map. In reality, there is a residential area in this location. Consequently, when people go home from work, many of them end up in this location. As a result, the production of emissions in this area is not as high as in the city centre, but it is not low either. This again corresponds with the output of the simulation shown in Figure 2.2.

2.2.3 Buildings

The building agents do not do much. They are just displayed. They are divided into three categories (string attribute *type*) according to the way of use: residential, where people live, industrial, where people work and entertainment, where people were supposed to go to have fun, however, this is not implemented. The information about the purpose of the buildings can be found in the respective shapefile as a *DESTINAT* attribute. The shapefile is available on the SITG website (file BATIMENTS HORS-SOL) [19].

Moreover, buildings have a *max_capacity* attribute, which is an integer representing how many people can fit inside that building, and a *people_inside* attribute, which represents how many people are currently in that building. Those two attributes combined are used to determine if more people can be added into the building, which is a piece of information we need during the relocation process.

Also, all the attributes are used in the initialisation process when people agents are created. More specifically, it is used when each people agent is assigned a living place and a working place. At first, this was meant to be done as follows: for a living place, a random residential building such that its *people_inside* attribute was stricly less than the *max_capacity* attribute would be chosen. However, this took a lot of time. Thus the following approach is implemented:

```
//shuffles the buildings
list<building> shuffled_buildings <- shuffle(building);
int i <- 0;

create people
{
    ...
    living_place <- shuffled_buildings[i];
    living_place.people_inside <- living_place.people_inside+1;

    if living_place.people_inside >= living_place.max_capacity
    {
        i <- i+1;
    }
    ...
}
```

In words, we first shuffle the list of buildings and then we fill them with people one by one, paying attention to not to exceed the max capacity of the buildings.

This implementation is much faster since there is no random element in the *create people* block and the shuffled list of buildings is not changed.

The working place is chosen in the same manner.

Finally, the building information (built-in attribute *location*) is used as a target point towards which the people move. More precisely, in the morning, when commuting to work, people move to the location of their working place. Similarly, in the afternoon, people move to the location of their living place.

2.2.4 Roads, tracks and bicycle paths

The information about the road network, tracks and bicycle paths comes from the corresponding shapefiles from the SITG website [14]. To be precise, we have used the GRAPHE DE LA MOBILITE - GRAPHE ROUTIER file for roads [20], RESEAU TPG - LIGNES file for tracks [21] and CARTE VELO file for bicycle paths [22].

Roads, tracks and and bicycle paths are just displayed. Internally, the program works with roads and tracks as graphs, which are used for cars, tramways or bikers as a network they can ride on.

2.2.5 TPG stops

The information about the TPG stops comes from the RESEAU TPG - SCHEMATIQUE DES ARRETS shapefile from the SITG website [23]. Note that on the SITG website there is also a RESEAU TPG - ARRETS file, however, this one is a multi-point shapefile and it was a bit more difficult to work with.

The TPG stops are just displayed and their display can be switched off. However, the location of the stops is used when the people agents commute to work. First of all, if there is no stop close enough (at most 500 m) to either the working place or a living place of a person, this person will never use TPG. On the other hand, if a person chooses to use the TPG, they first go to the stop location.

2.2.6 Tramways

The tramway agents are just displayed, unless the user turns their display off. They go on the tracks from stop to stop (the list of stops is hard-coded in the program) and after reaching the terminus, they turn around and go back. If they reach the station with waiting people, people will get on (they will just follow the tram agent) and after reaching the desired location, people will get off. This function is implemented in the person agent in a following manner.

```
//person waits for a tram
if distance between person and a suitable tram < 250 m
{
    followed_tram <- suitable tram
}

//person is in a tram
person.location <- followed_tram.location
```

```
//person gets of the tram
if distance between person.location and the desired stop < 250 m
{
    followed_tram <- nil
    person.location <- location of desired stop
}
```

Only tramway 18 is displayed because we are mostly interested in emissions and displaying more tramways or any other means of transport seems unnecessary.

2.2.7 People

Finally, let us introduce the *person* agent. As the name suggests, this is an agent representing one Geneva's resident. It contains a lot of information about the resident - for example the living place, working place, type of car they use (diesel, petrol or electric), working hours, but also, for example, the distance between their living place and working place. In general, we store a lot of information about the agent as its attributes. That is because computing all the information over and over again, when we need it, takes a lot of time. Of course, if we launch the simulation for 300 people, we cannot really see the difference. However, for $30,000$ people the simulation runs a lot faster, for the cost of memory.

Apart from all the attributes, the person agent has several reflexes. When the time matches the start of its working hours, the agent will go to work. When the time matches the end of its working hours, it will go home. This is done in a very simple manner as follows.

```
reflex go_to_work when (time matches the start of working hours)
{
    target <- location of working place;
}
```

The *target* variable represents the place where the agent wants to go.

Now the more interesting part is the *move* reflex, that will move the agent to the *target*. Since we are mainly interested in the emissions, we do not need to display every single agent (in fact, user may choose if they want to see people agents at all). Therefore if the agent is not displayed, we just move it simply by setting its *location* to the *target*. Otherwise, the person moves to the *target* on roads or on tracks if they are in a tramway.

Probably the most important part of the whole program is the function that lets people choose the mean of transport they use. The rest of this subsection will be devoted to its description.

The rough idea is as follows. First, the person checks if the distance to work is less than 1 km. If yes, they will walk. If not, we let people choose the mean of transport more or less randomly - the only exception is that if a person does not have a car (under the default settings, every person has a car. This can be changed by the user though), they will never use a car as a mean of transport. Similarly, if there is not a good connection by the TPG (i.e. the closest stop to the living place or to the working place is more than 500 m away or the commuting by car saves at least 15 minutes of time), the person will not choose the TPG.

Apart from these rules, people choose each mean of transport randomly with different probabilities. These probabilities depend on the distance that the people need to travel and they come from the document Stratégie Climat de la ville de Genève [24]. However, we were a bit skeptical to these data since they are not only about commuting to work, but about commuting in general. As a result, according to the data, there are people walking more than 20 kilometers, but that does not seem realistic in our context. On the other hand, we have let people walk up to 6 kilometers (with a small probability), because we want to consider for example roller-skates or electric scooters as walking. Table 2.1 shows the default probabilities for each mean of transport. With respect to the current situation in the environment (the tax and the willingness of people to use cars), these probabilities might vary. To be precise, with an increasing tax, the probability of using the car decreases. With a decreasing willingness to use cars, the probability of using cars also decreases. The pseudocode capturing all this can be found at the end of this subsection. Before showing it, we will need to explain one function used in it. It is the tax function, which loosely speaking calculates how much a person will pay if they use their car to get to work.

As described in the introduction, our tax system depends on the amount of driven kilometers. When choosing the mean of transport, we want the people to take into account how much they will pay on taxes if they decide to use the car. However, this depends on how much they used the car *this* year - which is incomplete during the decision-making process - not the *previous* year. This is a problem because if each person calculated the tax they will pay after using the car in a naive way, which is shown in the following pseudocode, we would obtain that many more people use the car at the beginning of the year than at the end of the year. This is a simple consequence of the fact that at the beginning of the year the driven distance is much smaller than at the end of the year. This is illustrated by the noticeable "jumps" in Figure 2.4.

```
tax_paid <- (driven_distance + 2*distance_to_work)*
            (current_tax+tax_increase_rate);
```

We fix this problem by letting people make a plan for using the car. It works in a following way. Each year, after the taxes are calculated and the driven distances are reset, each person will reserve x days for using the car, where x is the number of times the person used the car the previous year. This is done by choosing x random integers from $0, 1, \ldots, 59$ which we will store in the *days_for_car_usage* attribute (let us remind that each year in our simulation has 60 days). We store the indices into the list *days_for_car_usage* in an increasing manner. That is because we will frequently want to know if a given element is in that list. Now each person will calculate how much they will pay on taxes this year in a following way: if they planned to use the car this day (i.e. current day is in *days_for_car_usage*), they will do it as above in the naive approach. Otherwise, they will take into account all the remaining days they have reserved for the car usage. The pseudocode for this procedure is as follows.

```
float tax_function()
{
    int nb_days <- number of remaining days in the year
                   reserved for car usage
    float tax_paid;

    if person planned to use the car today
    {
        tax_paid <- (driven_distance + 2*distance_to_work)*
                    (current_tax+tax_increase_rate);
    }
    else
    {
        tax_paid <- (driven_distance + (nb_days+1)*2*distance_to_work)*
                    (current_tax+tax_increase_rate);
    }

    return tax_paid;
}
```

As a result, if a person did not plan to use a car, they will be less likely to use it since they will think that they will pay a much higher tax (for more detail, see the following pseudocode). In other words, the car usage will be distributed more evenly throughout the year and will not be that high at the beginning and that low at the end. For comparison, you can see the red points representing the amount of car users in Figure 2.4, which shows what happens if the naive approach is implemented, and Figure 2.5, which shows what happens if the second approach is implemented.

Now, when we know what the tax function does, we can provide a pseudo code of the decision-making algorithm.

```
string choose_transport
{
    //to return home, people will
    //take the same transport as in the morning
    if morning_choice != nil
    {
        return morning_choice;
    }

    //distance to work
    float dist <- distance to work;

    //tax that the person thinks they would pay after using the car
    float tax <- tax_function();

    //willingness not to use the car
    float willingness <-
    total_nb_car_used*willingness_reduction_per_car_use+tax/800;

```

```
 //if the distance is less than 1 km, people walk
if dist < 1000#m
{
    morning_choice <- "WALK";
    return "WALK";
}


//random factor
float f <- rnd(1.0);


//distance is less than 2 km + some distortion
if dist < 2000#m + 2*(willingness-tax/800)#km
{
    //with the probability 72-75 percent, the person walks
    if f<0.72+min(0.03, tax/10000)
    {
        morning_choice <- "WALK";
        return "WALK";
    }
    //with the probability 12-20 percent, the person rides a bike
    else if f <0.87+min(0.08, tax/5000)
    {
        morning_choice <- "BIKE";
        return "BIKE";
    }
    //if the person does not have a car, and they have not decided
    //yet, they will choose the TPG. They will also choose the TPG
    //if it is reasonable to do so with 0-10 percent chance
    else if !has_car or
    ((f<(0.87+min(0.1, (willingness/3)))) and
    it takes at most 15~minutes longer to use TPG than car and
    the closest stop to the living place is at most 500~m away and
    the closest stop to the working place is at most 500~m away
    )
    {
        morning_choice <- "PUBLIC_TRANSPORT";
        return "PUBLIC_TRANSPORT";
    }
    else //update some values and use a car
    {
        nb_car_used<-nb_car_used+1;
        total_nb_car_used<-total_nb_car_used+1;
        cars <- cars+1;
        morning_choice <- "CAR";
        return "CAR";
    }
}
```

```
    //distance is less than 3 km + some distortion
    if dist < 3000#m +2*(willingness-tax/800)#km
    {
        //with the probability 42-45.5 percent, the person walks
        if f<0.42+min(0.035, tax/10000)
        {
            morning_choice <- "WALK";
            return "WALK";
        }
        //with the probability 24-31 percent, the person rides a bike.
        else if f <0.66+min(0.07, tax/5000)
        {
            morning_choice <- "BIKE";
            return "BIKE";
        }
        //if the person does not have a car, and they have not decided
        //yet, they will choose the TPG. They will also choose the TPG
        //if it is reasonable to do so with 19-29 percent chance
        else if !has_car or
        ((f<(0.85+min(0.1, (willingness/3)))) and
        it takes at most 15~minutes longer to use TPG than car and
        the closest stop to the living place is at most 500~m away and
        the closest stop to the working place is at most 500~m away
        )
        {
            morning_choice <- "PUBLIC_TRANSPORT";
            return "PUBLIC_TRANSPORT";
        }
        else //update some values and use a car
        {
            nb_car_used<-nb_car_used+1;
            total_nb_car_used<-total_nb_car_used+1;
            cars <- cars+1;
            morning_choice <- "CAR";
            return "CAR";
        }
    }

    //for the other distance categories, we proceed
    //in a similar manner
    ...
}
```

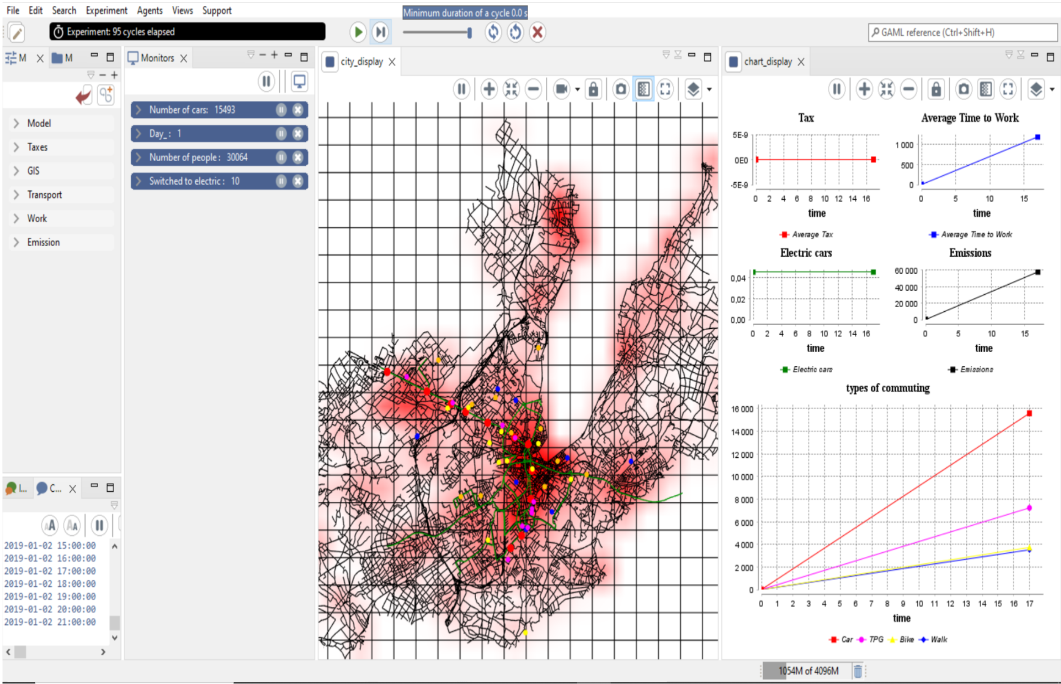

Figure 2.2 Big amount of emissions is produced - the cells turn red

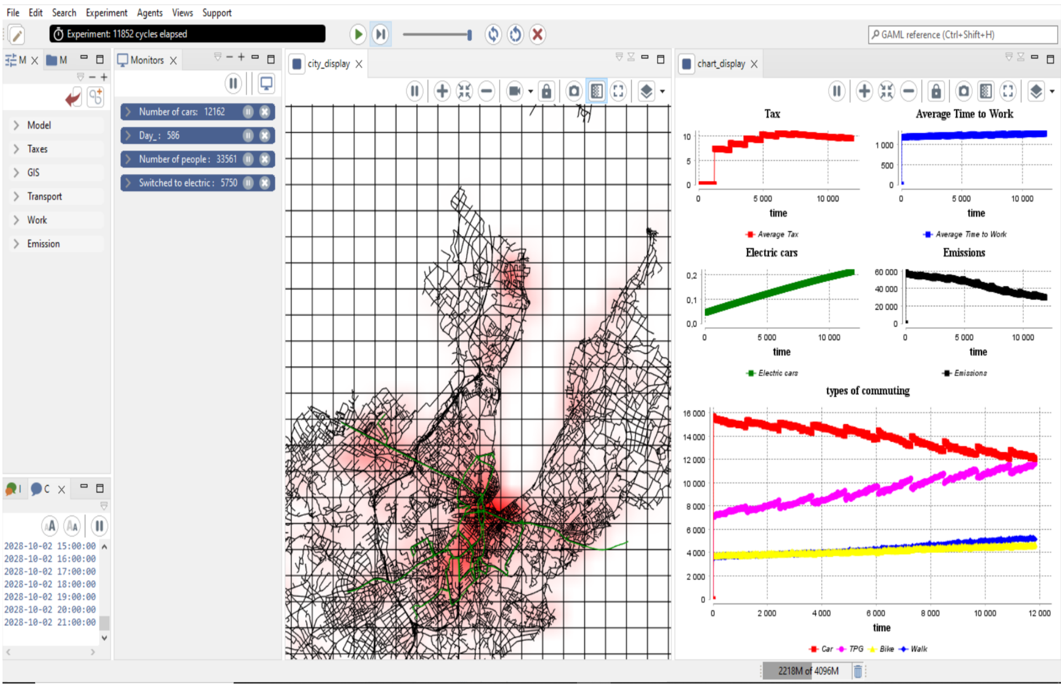

Figure 2.3 Smaller amount of emissions is produced - the cells stay lighter

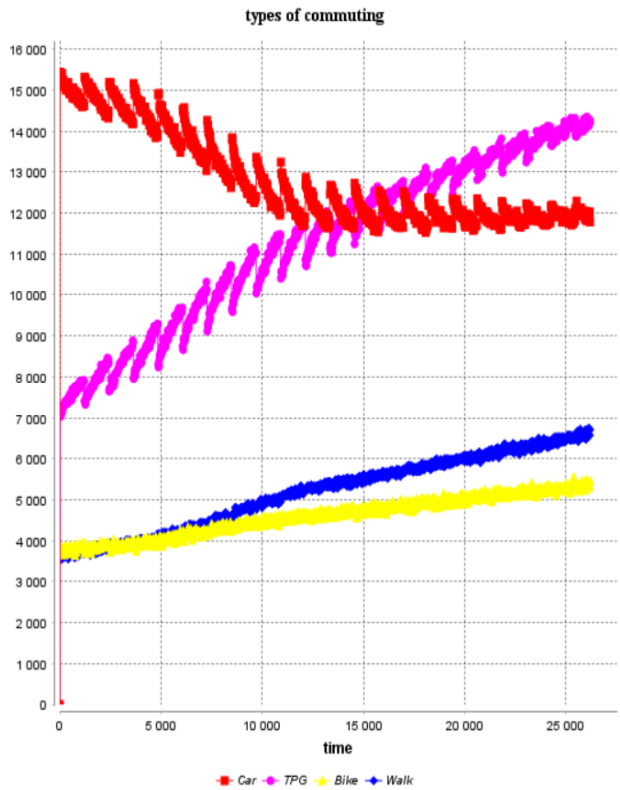

Figure 2.4 Naive implementation leads to bigger "jumps"

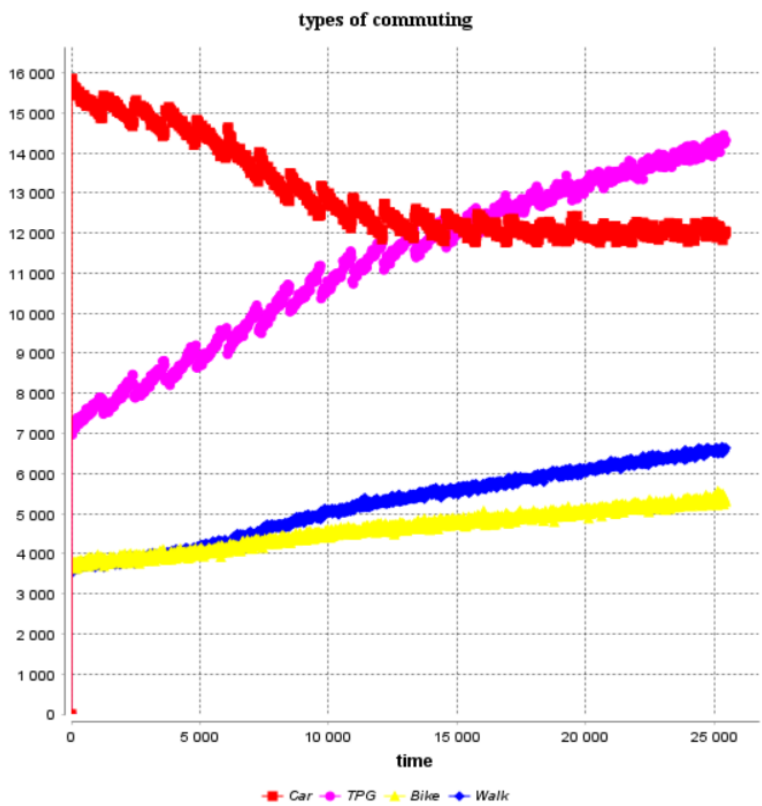

Figure 2.5 The second implementation has smaller "jumps"

Probabilities				
Distance	Walk	Bike	TPG	Car
< 1 km	100%	0%	0%	0%
1-2 km	72%	15%	0%	13%
2-3 km	42%	24%	19%	15%
3-4 km	20%	15%	35%	30%
4-5 km	19%	16%	35%	30%
5-6 km	14%	14%	32%	40%
6-8 km	0%	20%	55%	25%
8-10 km	0%	10%	60%	30%
10-15 km	0%	7%	43%	50%
15-20 km	0%	1%	49%	50%
> 20 km	0%	1%	49%	50%

Table 2.1 Probabilities for each transport choice according the document Stratégie Climat de la ville de Genève [24]

3 Results

In this chapter, we will talk about the validation. Then we will move to the data analysis, where we compare the results for different parameter values.

3.1 Validation

In the validation process, we will be interested in the amount of TPG passengers. We will try to measure if the amount of people agents entering the TPG vehicles corresponds to the real world data from the official TPG websites [25]. Of course, we will have to deal with the fact that in reality, people use the TPG not only to commute to work, but also to travel to other places. Another problem is that in our model, we only consider the Geneva's residents, although the TPG is also used by, for instance, tourists. Therefore we will only measure the amount of boarding passengers on some particular stops far away from the city centre. That is because these stops should not be used by tourists as much as the stops in the city centre are. In other words, in reality, these stops should be used only by Geneva's residents, which is exactly the case in our model.

Hence, as a validation dataset, we have chosen the number of boarding passengers in Cartigny, Village. As described above, the idea behind choosing this particular stop is that it is far from the city centre, thus the data should not be distorted by tourists. Moreover, there is only 1 line operating on that stop, which makes the comparison of the output data and the real-world data easier.

So, for the validation, we measure how many people agents have boarded the TPG in Cartigny, Village. Then we compare the measured data with the data on the TPG website [26]. We compare how many people boarded the TPG on this stop in 2021, 2022 and 2023.

Let us note that for validation we have disabled the tax system since in reality the tax did not exist in 2021, 2022 nor 2023. We have also set that 1 people agent represents 6 real people.

3.1.1 Results

In Cartigny, Village, According to the TPG website from above, $17,578$ people boarded on the TPG vehicles in 2021, 18.469 people in 2022 and it 2023, it was $19,262$ people. Our model gives that in 2021, 799 people agents have boarded on the TPG vehicles in Cartigny, Village, in 2022 it was 913 people agents and finally, in 2023, it was 979 people agents.

Now, because 1 person agent represents 6 people and because each year has roughly 250 workdays and our model works with only 60 of them, we should multiply or data by 24 in order to reasonably compare them with the data from the TPG website. We then obtain that $19,176$ people boarded on TPG in 2021, $21,912$ in 2022 and $23,496$ in 2023, which is 109%, 118% and 121% of the real-world data.

3.1.2 Discussion

Even though the outputs from the simulation seem to be close to the real world data, we still need to be a little careful. First of all, we do not take into account that in July and August, there is a significant decrease in the TPG usage in real world.

Moreover, during the initialization of the simulation, there is a process that might take away some buildings at random (that is because otherwise there are many empty buildings, so people relocate into them and after 2 simulation years, 50% of people walk to work). So, it might happen that a lot of buildings from that area are taken away, or conversely, almost none of them is taken away.

Furthermore, we were working with one particular stop. The fact that for this one we are close to the real-world data is awesome, however, we might have been lucky. In fact, for stops in the Chêne-Bougeries locality, the simulation outputs (after the multiplication by 24 as above) that the TPG usage is 10 times higher than in reality. This might be caused by multiple factors, such as the oversimplified reality encoded to the model. In fact, in our model, people prefer the TPG if they live and work close to a TPG stop and if the travel by car is at most 15 minutes shorter then the travel by the TPG. Furthermore, in this model, people are far more likely to work in the centre of Geneva (simply because there are more job offers). Thus the combination of relative proximity of Chêne-Bougeries to the centre and the preference of people to use the TPG in the above described situation might be the cause of such a discrepancy.

So, in the following section, instead of "predicting the future", we will focus on exploring certain parameters of the model - mostly the tax.

3.2 Simulation data results

In all of the simulation runs we will represent 12 people by 1 agent. We assume that there are roughly $360,000$ Geneva's residents that commute to work or to university in Geneva (we consider all Geneva's residents that are 20-64 years old. According to official statistics [17], there are $360,000$ such residents), hence we start with roughly $30,000$ people agents.

We will be mostly interested in the following data: the means of transport, the average commuting time, the average tax and, of course, emissions. We will explore its dependence on the following parameters: "Environment without tax" (turns the tax system on and off), "Tax impact on relocation" (the higher the number, the lower the impact of the tax on the relocation decision is) and "Daily switch to electric" (which tells us how many people switch to electric cars each day if we consider all $360,000$ 20-64 years old Geneva's residents). Then, we will try to see what happens if the people pay absurdly high taxes and finally, we will run a batch experiment to explore the dependence of the amount of emissions in 2035 on the tax growth rate. The Table 3.1 shows the carried experiments and contains the references to their corresponding graphs.

In all of the "Means of transport" graphs, the data represent the daily average of the usage of the given mean of transport that year. For example, the point "Bikers-$4,000$-2019" means that on average, each day in 2019 $4,000$ people agents have used a bike to commute to work or university, which would correspond to $48,000$

real Geneva's residents. Next, the "average commuting time" graphs represent the average commuting time to work/university in minutes. The "Average tax" graphs represent the average tax in CHF and finally, the "Emissions" graphs represent the average amount of emissions in kg produced each day.

In all of the simulations, we have used the same shapefiles to obtain the information about buildings, roads, TPG lines, bicycle paths and TPG stops. These files were the same as in the description of the agents in the "Agent-based model" section.

We assume that each petrol-powered car produces 192 g of CO_2 per km, each diesel-powered car produces 171 g of CO_2 per km and each electric vehicle produces 53 g of CO_2 per km. These numbers come from the article "How Much CO_2 Does a Car Emit per Mile: List by Type, Size, Energy Source" by Sheryll Gonzales, 2024 [27].

Under the default settings, at most 10% of people will relocate each year. This data comes from the article "Relocation behavior of the Swiss population in 2021", 2023 [28]. Also, 4% of population will change their car for an electric one, which corresponds to the article "Electric car sales are booming in Switzerland" by Stéphane Herzog, 2023 [29].

3.2.1 Results

Figure 3.1 presents the results when the tax system is disabled. Then, in every other experiment, the tax system is enabled. Notably, Figure 3.7 shows the dependence of emissions on the tax growth rate and Figure 3.6 shows what happens if the tax starts absurdly high and grows really fast (the parameters for that experiment were as follows: everything was on default, beginning tax was 10 CHF/km, petrol tax increment was 10 CHF/km and diesel tax increment was 12 CHF/km). Even though this does not represent an imaginary situation that could have something in common with reality, it is interesting to see how the system behaves under these extreme conditions.

Let us point out that the tax is not the only way to decrease the emissions. For example, Figure 3.5 shows what happens if we let more people switch to electric vehicles. It is also interesting to see how the system behaves if we let the tax influence people's relocation decisions. This is captured in Figure 3.2, Figure 3.3 and Figure 3.4.

Finally, Figure 3.7 shows the dependence of emissions in 2035 on the "tax increment for petrol cars" parameter (i.e. all parameters are set to default, except for the "tax increment for petrol cars" and "tax increment for gas cars", which is 20% higher). The other graphs, such as "average time to work" and "means of transport" are omitted, since we are mainly interested in the impact of the tax on the carbon emissions. However, they can be found in the "TaxAndEmissions.xlsx" file in my repository `https://github.com/Stepki6/BMST24/tree/main`.

3.2.2 Discussion

When the tax system is disabled, there are only 2 factors that decrease emissions in the system: switching to electric cars (which by the online article "How Much CO_2 Does a Car Emit per Mile: List by Type, Size, Energy Source" by

Sheryll Gonzales, 2024 [27] produce 1/4-1/3 of carbon emissions with comparison to cars with combustion engines) and willingness of people to stop using the cars. Figure 3.1 shows that in this case, the emissions decrease very slowly (in fact, it is the only simulation where in the end the emissions are produced at a rate greater than $30,000\ kg/day$).

However, Figure 3.2 shows that even turning the tax system on (with default values) and decreasing its impact on people's relocation decisions suffices to decrease the emissions production rate below $30,000\ kg/day$. In this scenario, we can also observe that at the end of the simulation, there are more people using the TPG than cars.

Now, let us compare Figure 3.2, Figure 3.3 and Figure 3.4. The respective simulations differ only in the "tax impact on relocations" parameter: to obtain Figure 3.2, it was set to 400, for Figure 3.3 it was set to 50 (default) and for Figure 3.4 it was set to 8 (the lower the number, the higher the relocation frequency). We can see that with a higher relocation frequency, more people start to commute on foot. That might be caused by the fact that more people are forced to move out even from the premium locations in the city centre so that they get closer to their working place. This way, people who need to get to the centre get the opportunity. This dramatically shortens the travelled distance, giving people the opportunity to commute on foot. As a results, emissions dramatically decrease and, since people relocate closer to their working places, the tax they pay (which is linearly dependent on the travelled distance) decreases as well (although this is also a consequence of the decreased car usage - people who do not use the car contribute 0 CHF to the sum of the paid taxes). What is unexpected though is that in the last scenario, even if there is a massive increase in walkers, the average time to work at the end is the lowest of the three scenarios. This only shows that people relocate really close to their working place and as a result, they spend less time walking then going by car from a further location.

Now we would like to compare Figure 3.3 and Figure 3.5, which differ only in the "daily switch to electric" parameter (in the former, all parameters are set to default. In the latter, everything except "daily switch to electric" is set to default. The "daily switch to electric" parameter is set to 500 (max)). At the end of the simulation captured in Figure 3.5, almost everyone had an electric car. Since there is no tax on people owning such car, it is not necessairly surprising that at the end of the simulation the average tax is almost 0 CHF. We can also see that the means of transport graph in Figure 3.5 is very similar to that in Figure 3.1. That makes sense, because as was stated above, people with electric cars are not subjects to the tax system, and thus the situation from the simulation with disabled tax system applies. Now when I think about it, if a person owns an electric car, their willingness to use the car should not decrease. In other words, when more people own an electric car, one would expect that at the end of the simulation there should be more car users. This idea is not implemented, but it may be in the future.

Finally, let us comment Figure 3.7. In this figure we can see an interesting phenomenon. One would guess that the higher the tax increase, the lower the emissions will be. However, that is not the case. We can see that the emissions plotted against the tax increment rate (it says how the tax increases each year for petrol vehicles. For diesel vehicles, the increase is 20% higher. For electric vehicles, it is 0 CHF) do not decrease. The only explanation I have for this phenomenon is that the tax is so high that it forces the people who already relocated to relocate again. And since there is a given cap, these people block those who have not relocated yet from doing so. Therefore they are stuck in their living place and there is nothing they can do about it. However, this claim needs a further analysis.

3.2.3 Contextualisation

In this subsection, we would like to put into context the measured average time to work and measured emissions.

In the above figures we can see that a person spends, on average, 20-23 minutes commuting. That is less than the real world data (29.6 minutes, according to the official statistics [30]). That is likely caused by traffic jams, that are not implemented in the model. Also, when a person uses the TPG in the model, there is a 0 minutes waiting time (except when the person is displayed) - for simplicity. Also, for simplicity, transfers are not implemented in the model. In other words, the TPG network is assumed to be 1 network instead of connected lines. That is also a cause of the shorter commuting time.

Now the emissions. According to the document Bilan des émissions de gaz à effet de serre de la ville de Genève [31], roughly $171,000,000$ kg of emissions were produced in 2019 by Geneva residents' mobility, which works out to be, if we represent 12 people by 1 agent, roughly $40,000$ kg a day. Results from our simulation were about $55,000$ kg a day, which is by 37.5% more. On one hand, there are reasons why our model outputs more emissions then it should. For example, in the model, car sharing is not implemented. Moreover, it is assumed that each person, 20-64 years old, has their own car, which is also not the case (in 2019, there were 439 cars on $1,000$ inhabitants according to the official statistics [17]). On the other hand, there are arguments for why our model outputs should be less than a real number is: for instance, our model assumes only the mobility to and from work. Also, we do not consider traffic jams. So, there are many unknowns and even formulating a hypothesis, why our model outputs a bigger number, is very difficult.

3.3 Limitations and possible improvements

In this simulation, we assume that people only commute to work and back home. In other words, they do not commute to shops, they do not have any hobbies, they do not visit each other and so on. Therefore, one of the interesting improvements could be to implement more sophisticated behaviour of the people. Moreover, inspired by the previous paragraph, we could implement the option of car sharing.

Another limitation is that we only work with people 20-64 years old. Therefore, we could add kids and seniors. Kids would go to schools in the morning, on their spare time activities in the afternoon and home in the evening. Seniors could go for example shopping. In the current implementation of the model, we only considered people that are 20-64 years old.

Then, we assume that no tourists visit Geneva throughout the whole year. Therefore the TPG is not pressured as much as in reality.

Moreover, we assume that the TPG has unlimited capacity, people wait 0 minutes at the stop and they never need to change lines. Furthermore, we assume that there are no traffic jams. As a result, the “average time to work” given by the simulation is less then the one in reality.

Next, in the model, relocation is implemented. In a similar manner, we could implement the change of jobs. It would be another pressure on the mobility - especially if people find a new job that is further from their living place than their current one is.

Next improvement would be about the code itself. There are a lot of random decisions. One problem caused by this is that there is very little control over the model. Another problem with random decisions is that they take a lot of time. So, the improvement would be to make the model more deterministic.

And finally, another improvement would be to implement the tax system in a form in which it was actually passed on the 3rd March 2024. If we would manage to validate the model, it could give us a lot of interesting results and interesting information.

Table of experiments							
Environment without tax	Tax impact on relocation	Daily switch to electric cars	Starting tax (CHF/km)	Tax increment for petrol cars (CHF/km)	Tax increment for diesel cars (CHF/km)	Other parameters	Corresponding graphs
True	50	130	0.01	0.0025	0.0030	Default	Figure 3.1
False	400	130	0.01	0.0025	0.0030	Default	Figure 3.2
False	50	130	0.01	0.0025	0.0030	Default	Figure 3.3
False	8	130	0.01	0.0025	0.0030	Default	Figure 3.4
False	50	500	0.01	0.0025	0.0030	Default	Figure 3.5
False	50	130	10	10	12	Default	Figure 3.6
False	50	130	0.01	0.001 0.002 0.003 0.004 0.005 0.006 0.007 0.008 0.009 0.010	0.0012 0.0024 0.0036 0.0048 0.0060 0.0072 0.0084 0.0096 0.0108 0.0120	Default	Figure 3.7

Table 3.1 Table of carried experiments and references to their corresponding graphs

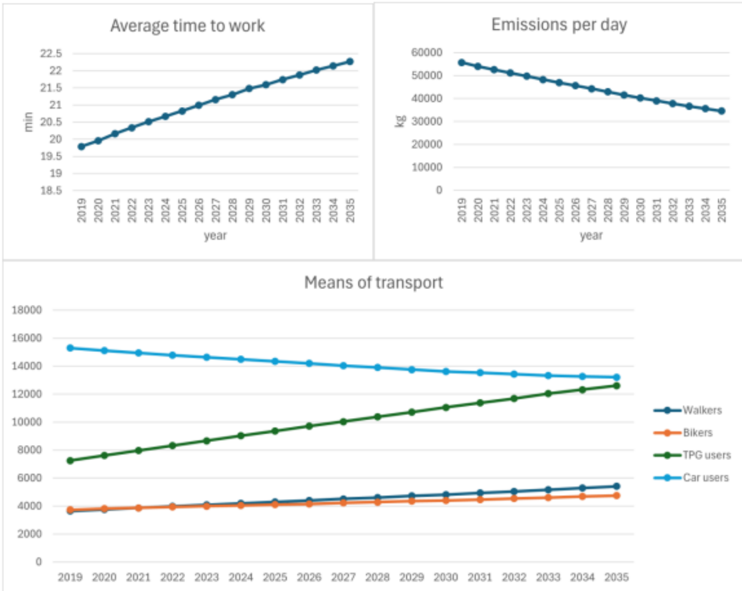

Figure 3.1 The tax system is turned off

Figure 3.2 Tax has a very low impact on relocation decisions

Figure 3.3 Tax has a standard impact on relocation decisions

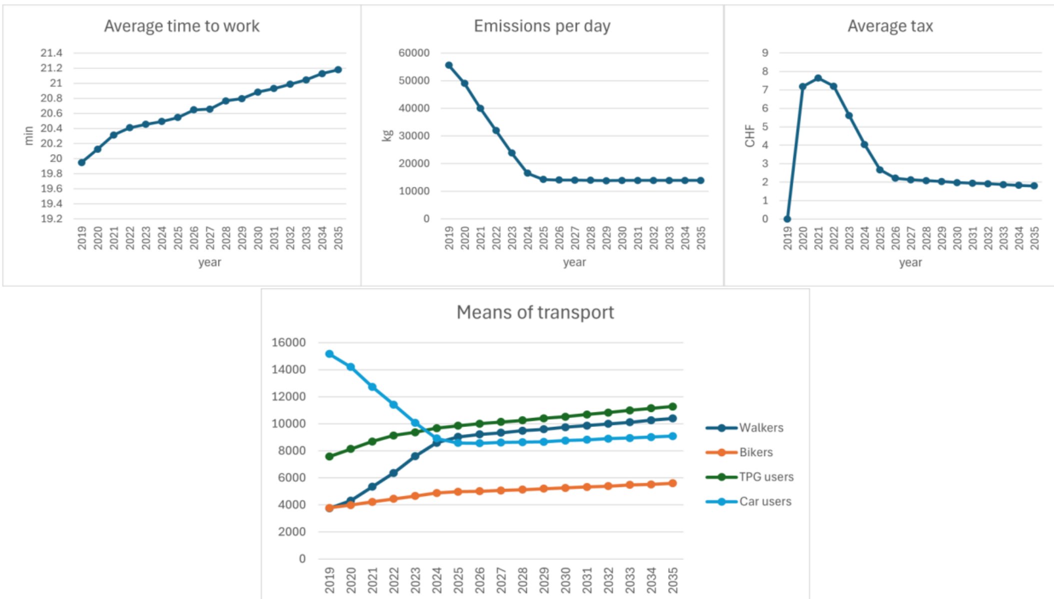

Figure 3.4 Tax has a huge impact on relocation decisions

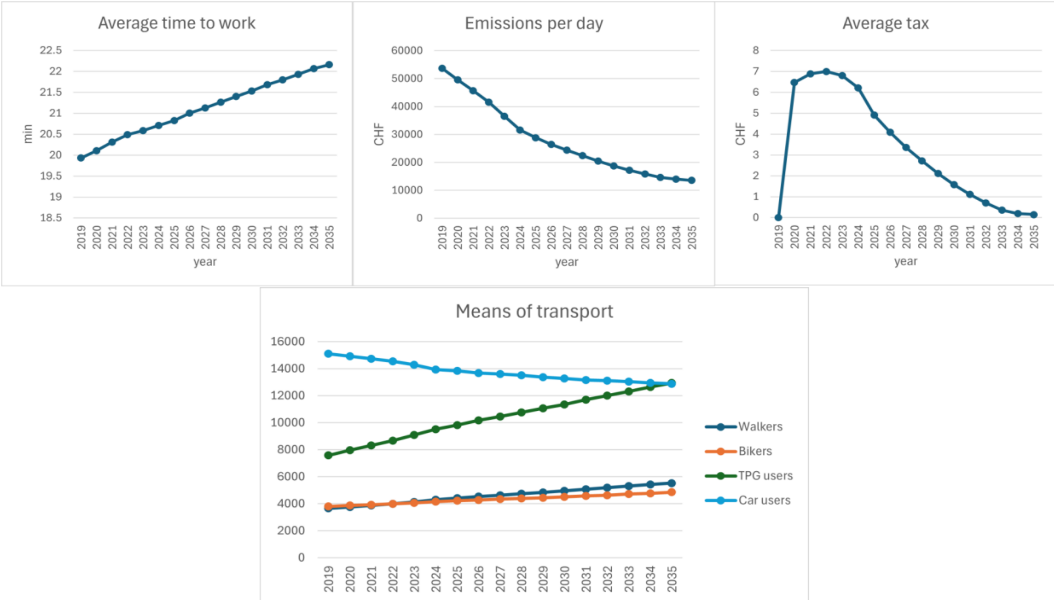

Figure 3.5 People switch to electric cars often, tax has a standard impact on relocation decisions

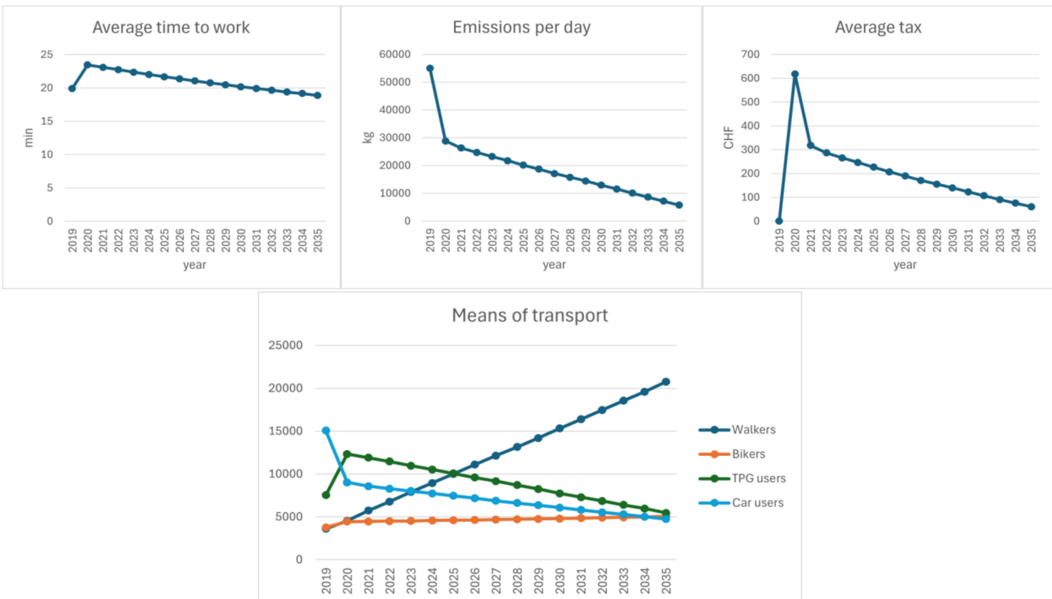

Figure 3.6 People pay really high taxes

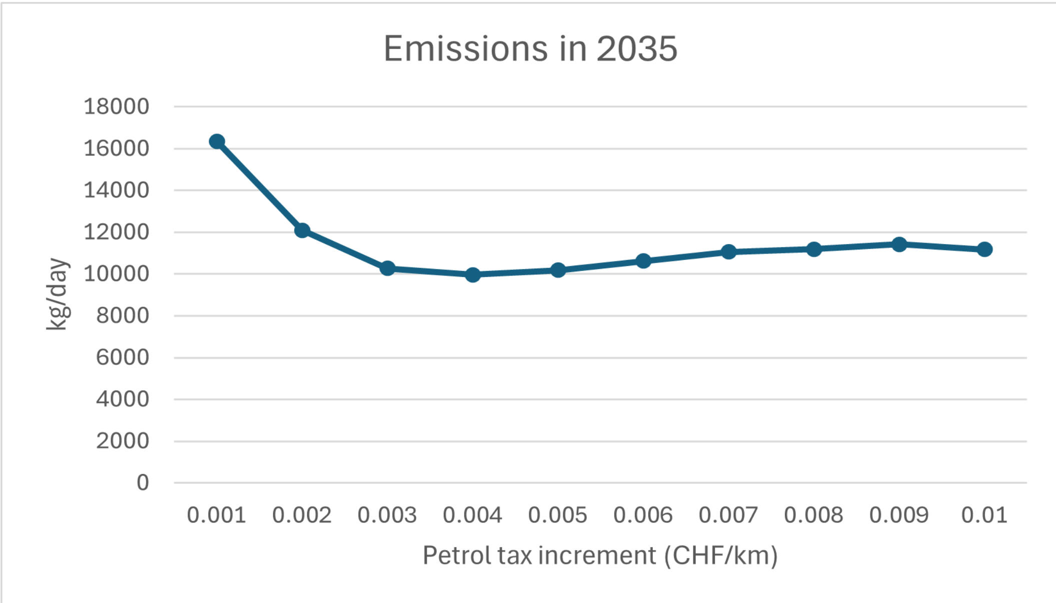

Figure 3.7 Emissions in 2035 plotted against the tax growth rate

Conclusion

3.4 Summary

In this project, we have developed an agent-based model that follows the DPSIR framework of the relationship between the mobility in Geneva, carbon emissions and a tax system. Even though we were not particularly successful in the validation of the model, we have still explored some of the parameters and their impact on the system. Notably, we have shown that by a rapid conversion to electromobility, the emissions decrease - and the tax at the end reaches 0 CHF. However, this should *not* be projected into the real world, because in our model, we did not have to solve the issue with recharging points, the electrical network in general, nor the inability of electric cars to travel long distances with such convenience and in such short time as cars with combustion engines.

Bibliography

1. *City of Geneva Climate strategy*. 2022. Available also from: https://www.geneve.ch/en/document/climate-change-strategy-brochure-english-ville-geneve. Available online.
2. *City of Geneva's Climate Change Strategy*. 2022. Available also from: https://www.geneve.ch/en/news/information-packs/climate-change-geneva/climate-change-strategy. Available online.
3. *Stratégie climat: mobilité*. 2022. Available also from: https://www.geneve.ch/actualites/dossiers-information/changement-climatique-geneve/strategie-climat/mobilite. Available online.
4. Hannah Ritchie, Pablo Rosado; Roser, Max. *Our World in Data-CO2 and Greenhouse Gas Emissions*. 2023. Available also from: https://ourworldindata.org/co2-and-greenhouse-gas-emissions. Available online.
5. Buysse, Claire; Miller, Josh. *Transport Could Burn Up the EU's Entire Carbon Budget*. 2021. Available also from: https://theicct.org/transport-could-burn-up-the-eus-entire-carbon-budget/. Available online.
6. *Votation populaire du 3 mars 2024*. 2024. Available also from: https://www.ge.ch/votations/20240303/cantonal/7/. Available online.
7. Schneuwly, Patrick. *City of Geneva Climate strategy*. 2024. Available also from: https://acidmoto.ch/site/le-3-mars-geneve-vote-sa-prochaine-imposition-des-vehicules/#1707725769714-7e1c1ea3-01d2. Available online.
8. *Se Déplacer dans les Monts de Genève*. 2016. Available also from: https://www.montsdegeneve.com/pratique/se-deplacer/. Available online.
9. Bonabeau, Eric. Agent-based modeling: Methods and techniques for simulating human systems. *Proceedings of the National Academy of Sciences*. 2002, vol. 99, no. suppl_3, pp. 7280–7287. Available from DOI: 10.1073/pnas.082080899.
10. Macal, C.; North, Michael. Agent-based modeling and simulation. In: 2009. Available from DOI: 10.1109/WSC.2009.5429318.
11. Macal, C.; North, Michael. Tutorial on agent-based modelling and simulation. *J. Simulation*. 2010, vol. 4, pp. 151–162. Available from DOI: 10.1057/jos.2010.3.
12. *The Guardian: Young Europeans more likely to quit driving and have fewer children to save planet*. 2023. Available also from: https://www.theguardian.com/world/2023/oct/25/young-europeans-quit-driving-fewer-children-save-planet-climate-crisis. Available online.
13. *GAMA*. 2014. Available also from: https://gama-platform.org/wiki/Home. Available online.
14. *SITG*. [N.d.]. Available also from: https://ge.ch/sitg/. Available online.

15. Maxim, Laura; Spangenberg, Joachim H.; O'Connor, Martin. An analysis of risks for biodiversity under the DPSIR framework. *Ecological Economics*. 2009, vol. 69, no. 1, pp. 12–23. ISSN 0921-8009. Available from DOI: https://doi.org/10.1016/j.ecolecon.2009.03.017. The DPSIR framework for Biodiversity Assessment.

16. *tpg's contribution to sustainable development*. [N.d.]. Available also from: https://www.tpg.ch/en/sustainable-development. Available online.

17. *Geneva statistics*. 2021. Available also from: https://www.bfs.admin.ch/bfs/en/home/statistics/regional-statistics/regional-portraits-key-figures/cantons/geneva.html. Available online.

18. *PAV Geneva Master Plan*. [N.d.]. Available also from: https://www.awp-architecture.com/projects/pav-geneva. Available online.

19. *Batiments hors-sol*. [N.d.]. Available also from: https://ge.ch/sitg/sitg_catalog/sitg_donnees?keyword=batiments+hors-sol&topic=tous&datatype=tous&service=tous&distribution=tous&sort=auto. Available online.

20. *Graphe de la mobilite - graphe routier*. [N.d.]. Available also from: https://ge.ch/sitg/sitg_catalog/sitg_donnees?keyword=GRAPHE%20DE%20LA%20MOBILITE%20-%20GRAPHE%20ROUTIER&topic=tous&service=tous&datatype=tous&distribution=tous&sort=auto. Available online.

21. *Reseau TPG - lignes*. [N.d.]. Available also from: https://ge.ch/sitg/sitg_catalog/sitg_donnees?keyword=RESEAU%20TPG%20-%20LIGNES&topic=tous&service=tous&datatype=tous&distribution=tous&sort=auto. Available online.

22. *Carte velo*. [N.d.]. Available also from: https://ge.ch/sitg/sitg_catalog/sitg_donnees?keyword=CARTE%20VELO&topic=tous&service=tous&datatype=tous&distribution=tous&sort=auto. Available online.

23. *TPG stops*. [N.d.]. Available also from: https://ge.ch/sitg/sitg_catalog/sitg_donnees?keyword=TPG%20arret&topic=tous&service=tous&datatype=tous&distribution=tous&sort=auto. Available online.

24. *Stratégie Climat de la Ville de Genève*. [N.d.]. Available also from: https://www.geneve.ch/document/strategie-climat-document-technique-ville-geneve. Available online.

25. *TPG home page*. [N.d.]. Available also from: https://opendata.tpg.ch/pages/accueil/. Available online.

26. *Ridership per month per line*. 2024. Available also from: https://opendata.tpg.ch/explore/dataset/montees-mensuelles-par-arret-par-ligne/analyze/?disjunctive.ligne&disjunctive.ligne_type_act&disjunctive.arret&disjunctive.arret_code_long&q=cartigny,+village&q.timerange.mois=mois:%5B2023-01-01+TO+2023-12-31%5D&dataChart=eyJxdWVyaWVzIjpbeyJjaGFydHMiOlt7InR5cGUiOiJhcmVhIiwiZnVuYyI6IlNV
3D. Available online.

27. Gonzales, Sheryll. How Much CO2 Does a Car Emit per Mile: List by Type, Size, Energy Source. 2024. Available also from: https://8billiontrees.com/carbon-offsets-credits/how-much-co2-does-a-car-emit-per-mile/.

28. News, MOVU. Relocation behavior of the Swiss population in 2021. 2023. Available also from: https://www.movu.ch/ratgeber/en/relocation-behavior-2021/.

29. Herzog, Stéphane. Electric car sales are booming in Switzerland. 2023. Available also from: https://www.swisscommunity.org/en/news-media/swiss-review/article/electric-car-sales-are-booming-in-switzerland.

30. *Commuting*. 2022. Available also from: https://www.bfs.admin.ch/bfs/en/home/statistics/mobility-transport/passenger-transport/commuting.html. Available online.

31. *Bilan des émissions de gaz à effet de serre de la ville de Genève*. 2022. Available also from: https://www.geneve.ch/document/bilan-emissions-effet-serre. Available online.

List of Figures

List of Tables

List of Abbreviations

- ABM - Agent-based modeling
- SITG - Système d'Information du Territorie Genevois (Information system of the Geneva's territory)
- TPG - Transports Publics Genevois (public transport in Geneva)
- CO_2 - Carbon dioxide
- PAV - Praille-Acacias-Vernets
- CHF - Swiss franc

A Attachments

A.1 Code

The code and all used shapefiles can be found here:
`https://github.com/Stepki6/BMST24/tree/master`.
To obtain the output data, the “Refined Geneva” model was used.

A.2 Measured data

The measured data can be found here:
`https://github.com/Stepki6/BMST24/tree/main`.
The most important ones are the excel files named “FinalAnalyses”, which contain the data that were used to create Figure 3.1, Figure 3.2, Figure 3.3, Figure 3.4, Figure 3.5 and Figure 3.6. The data that were used to create Figure 3.7 are contained in the “TaxAndEmissions.xlsx” file.