

MEMOIRE

Présenté en vue de l'obtention du Master en **Ingénieur de Gestion**, finalité **spécialisée**

Shared electric autonomous vehicles’ profitability in Brussels based on the simulation of the average daily trips

Par Jennifer Leclipteur

Directeur: Professeur Bram De Rock

Assesseur: Professeur Thomas Demuynck

Année académique 2020 - 20*21*

J’autorise la consultation de ce mémoire

# Acknowledgements

I would like to thank my promoter Pr. Bram De Rock for his advice and availability.

I wish also to thank Mrs. Van Laethem, Mr. Hermia, Mr. Hamesse from IBSA and Mr. De Paepe from StatBel for their valuable help in finding the specific data I needed.

How not to thank my friends and family for their support. I would particularly like to thank my father for the stimulating discussions we had about this thesis. It helped me to see things differently and find new ideas. I would also thank Marc for his reading of my thesis and feedback on the English and scientific writing.

Finally, I would like to thank the ULB and the Solvay Brussels School on the one hand for the qualitative education I have received during those six years and on the other hand for giving me the occasion of investigating a topic which fascinates me and tasting what research looks like.

# Executive summary

The goal of this thesis is to assess the profitability of a service provider managing a fleet of shared electric autonomous vehicles with ride sharing (SAEVs) fulfilling all motorized travel needs in the region of Brussels, Belgium. In the scenario depicted in this paper, autonomous taxis (aTaxis) are the only motorized means of transport: no more private cars and no more public transports.

The methodology used has been motivated by a deep literature review. This literature review also allowed to set the state of the researches and highlight advantages (such as less accidents, less pollution, time gain, space gain in the city, …) brought by autonomous vehicles.

The methodology applied in this work is an agent-based simulation of the autonomous taxis’ (aTaxis) fleet. For this purpose, the 1,224,645 residents, 428,486 commuters and 10,069 tourists travelling in Brussels have been simulated based on specific data. Each person got personal attributes such as an age, a gender, a place of residence, a household type, a worker type, a place of work and a daily trips pattern.

The average 3,411,960 daily trips have then been created based on this population and their habits. Each trip possesses an origin, a destination and a timing.

Those trips were used for the simulation of the aTaxis fleet with different scenarios. A full (one simulated day) simulation on the territory of the municipality Ganshoren has been realized in order to assess the impact of the authorization of empty rides. Results for a shorter period of time (423 simulated minutes) have been studied for the whole territory of Brussels. Using results from the Ganshoren’s simulations, the values of pertinent variables (number of aTaxis, number of charging stations, the number of kilometers traveled, …) have been extrapolated to get values for a whole day in the whole territory of Brussels.

These values were then used for the costs analysis of the service. The literature review provided a used framework. However, new costs have been considered in this thesis: cleaning costs and costs linked to the management of the company.

After all those simulations, the pricing strategy and a profitability analysis have been investigated.

The results of this thesis are a population file gathering all 1,663,200 simulated residents, commuters or tourists of Brussels with their personal attributes and a trips file assembling all average daily trips happening in Brussels. An error of 7.7% on the total number of commuters has been observed while the average number of trips per person per day (2.1) is slightly inferior to the observed value from the literature. Nevertheless, the average trip length of 6 km corresponds to what is observed in reality.

The conclusions on the aTaxis fleet simulation are aligned with the literature. A total number of 358,412 aTaxis is needed to fulfill the needs of the people traveling in Brussels in the scenario forbidding empty rides. This represents a decrease of 1.8% of the current vehicle fleet size. Furthermore, only 92,751 aTaxis are needed if empty rides are allowed reaching a fleet size reduction of 74.59%. This reduction is similar to the observations from the literature.

Besides reducing the number of aTaxis by 74.12%, allowing empty rides also decreases the number of charging stations by 19.68% while increasing the total travelled kilometer by 40.34%. This demonstrates the inefficiency of forbidding empty rides.

The service simulated in this thesis proposes a high level of comfort since a user only has to wait 6 to 9 seconds in average before living with his aTaxi to his destination. Moreover, users have seldom to share their trips with strangers since the average number of passengers per trip is 1.08 in both cases.

It is demonstrated in the work that an aTaxi in Brussels costs in average 1.262 € / km in the scenario forbidding empty rides and 0.339 € in the scenario allowing them. Those results are higher than the literature’s results due to the new costs considered and the incertitude on the insurance costs.

Finally, to be breakeven, the company is forced to request a price (0.269 € / km) increasing the annual travel spending per person by 8.42%. Even if SAEVs bring other non-monetary advantages, this model is not yet profitable in Brussels. Further researches are needed in order to improve the model.

# Content

[I. Acknowledgements 2](#_Toc80021478)

[II. Executive summary 3](#_Toc80021479)

[III. Content 5](#_Toc80021480)

[IV. List of abbreviations 7](#_Toc80021481)

[V. List of figures 8](#_Toc80021482)

[VI. List of tables 9](#_Toc80021483)

[VII. List of equations 10](#_Toc80021484)

[VIII. Introduction 11](#_Toc80021485)

[IX. Literature review 13](#_Toc80021486)

[A. Impacts of autonomous vehicles 13](#_Toc80021487)

[B. Six levels of automation 15](#_Toc80021488)

[C. State of the art 16](#_Toc80021489)

[X. Thesis goal 22](#_Toc80021490)

[A. Scenario analyzed 22](#_Toc80021491)

[B. Methodology 23](#_Toc80021492)

[C. Tools used 25](#_Toc80021493)

[D. Contributions 26](#_Toc80021494)

[XI. aTaxis’ fleet simulation 27](#_Toc80021495)

[A. Data 27](#_Toc80021496)

[1. 2019 as a reference year 27](#_Toc80021497)

[2. Statistics Sectors as a geographic level 27](#_Toc80021498)

[B. Methodology 28](#_Toc80021499)

[1. Overview 28](#_Toc80021500)

[2. Allocate a trip chain type 30](#_Toc80021501)

[3. Create trips 32](#_Toc80021502)

[4. aTaxis’ fleet simulation 34](#_Toc80021503)

[C. Results 39](#_Toc80021504)

[1. Population simulated 39](#_Toc80021505)

[2. Trips simulated 40](#_Toc80021506)

[3. aTaxis’ fleet simulation 41](#_Toc80021507)

[XII. Costs analysis 46](#_Toc80021508)

[XIII. Pricing and profitability analysis 50](#_Toc80021509)

[XIV. Discussion and limitations 51](#_Toc80021510)

[A. Possible improvements 51](#_Toc80021511)

[B. Future researches 54](#_Toc80021512)

[XV. Conclusion 59](#_Toc80021513)

[XVI. Bibliography 61](#_Toc80021514)

[XVII. Appendix 83](#_Toc80021515)

[A. Figures 83](#_Toc80021516)

[1. Appendix 1: Distribution of trips through time per category of destination 83](#_Toc80021517)

[2. Appendix 2: Modal share according to the trip length 85](#_Toc80021518)

[B. Tables 86](#_Toc80021519)

[1. Appendix 3: Literature review comparison table 86](#_Toc80021520)

[2. Appendix 4: Possible combinations of age category, status in the household, household type and work id 92](#_Toc80021521)

[3. Appendix 5: Trip Chain Types probability distribution 96](#_Toc80021522)

[C. Complementary folders 97](#_Toc80021523)

[1. Appendix 6: Details on the methodology of the create of the residents and their household 97](#_Toc80021524)

[2. Appendix 7: Details on the methodology of the allocation of a work ID and a workplace to the simulated people 101](#_Toc80021525)

# List of abbreviations

aTaxi = autonomous Taxi

SAEV = Shared Autonomous Electric Vehicle

resp. = respectively

V2V = Vehicle-to-Vehicle

V2I = Vehicle-to-Infrastructure

AV = Autonomous Vehicle

SAV = Shared Autonomous Vehicle

TCO = Total Cost of Ownership

AEV = Autonomous Electric Vehicle

# List of figures

[Figure 1 (on the left) New autonomous car design for a meeting (Volvo 360c) (© Volvo Car Group, Affaires publiques, SE-405 31 Göteborg, 2021) Figure 2 (on the right) New autonomous car design for resting (Volvo 360c) (© Volvo Car Group, Affaires publiques, SE-405 31 Göteborg, 2018) 13](#_Toc80021526)

[Figure 3 Autonomous vehicles: Automation levels (SAE International, 2018) 16](#_Toc80021527)

[Figure 4. Levels of geographic subdivision of Brussels (Monitoring des quartiers, 2019c) 28](#_Toc80021528)

[Figure 5 Trip chain types including a workplace. H stands for Home, W for Workplace and L for Leisure. The small numbers indicate the order in which the trips are done arrow represents the direction of the trip. The bold numbers are the reference of trip chain types. The red lines are the trips not done in Brussels when the trip chain type is assigned to a commuter. Trip chain types with an asterisk are the trip chain types not considered for commuters. 31](#_Toc80021529)

[Figure 6 Trip chain types without workplace. H stands for Home, L for Leisure and GL for General Leisure. The small numbers indicate the order in which the trips are done arrow represents the direction of the trip. The bold numbers are the reference of trip chain types. 32](#_Toc80021530)

[Figure 7 Possible charging stations' statuses and transitions.The arrows depict the possible transitions from one status to another one. 36](#_Toc80021531)

[Figure 8 Possible cleaning stations' statuses and transitions. The arrows depict the possible transitions from one status to another one. 36](#_Toc80021532)

[Figure 9 aTaxis' possible statuses and transitions in the scenario without empty ride. A red traffic light means that the aTaxi is not moving and staying at the station when in that status. While a green traffic light means the aTaxi is moving from one station to another one when in this status. The arrows depict the possible transitions from one status to another one. 37](file:///D:\Thesis\Bon\Writting\MemSol_v5.docx#_Toc80021533)

[Figure 10 aTaxis' possible statuses and transitions in the scenario with empty rides. A red traffic light means that the aTaxi is not moving and staying at the station when in that status. While a green traffic light means the aTaxi is moving from one station to another one when in this status. The arrows depict the possible transitions from one status to another one. 38](file:///D:\Thesis\Bon\Writting\MemSol_v5.docx#_Toc80021534)

[Figure 11 Comparison of the trip lengths distribution in the simulated Trips File and Monitor 2019 (Derauw et al., 2019) 41](#_Toc80021535)

[Figure 12 aTaxis’ status through time of the day in the Ganshoren simulation without empty rides whole day 43](#_Toc80021536)

[Figure 13 aTaxis’ status through time of the day in the Ganshoren simulation with empty rides whole day 43](#_Toc80021537)

[Figure 15 Charging stations' status through time of the day in the Ganshoren simulation without empty rides whole day 44](#_Toc80021538)

[Figure 14 Charging stations' status through time of the day in the Ganshoren simulation with empty rides whole day 44](#_Toc80021539)

[Figure 16 Distribution of the trips to a leisure place through time 83](#_Toc80021540)

[Figure 17 Distribution of the trips to home through time (Cornelis et al., 2012) 83](#_Toc80021541)

[Figure 18 Distribution of the trips to a study place through time (Cornelis et al., 2012) 84](#_Toc80021542)

[Figure 19 Distribution of the trips to a workplace through time (Cornelis et al., 2012) 84](#_Toc80021543)

[Figure 20 Modal share according to the trip length (Derauw et al., 2019) 85](#_Toc80021544)

[Figure 21 Classical study / work path in Belgium. The numbers above the timeline represent the ages while the word inside the arrow the study / work status corresponding to the given age class. 101](#_Toc80021545)

# List of tables

[Table 1 Ganshoren Simulations Results whole day 42](#_Toc80021546)

[Table 2 Simulation results until 7.03 a.m. (423 minutes from midnight) Brussels and Ganshoren without empty rides 45](#_Toc80021547)

[Table 3 Computation table from 423 minutes to the whole day for the whole territory of Brussels (Bxl) based on Ganshoren (Gans.) results. The blue columns are the results used in the costs computation and profitability analysis. 45](#_Toc80021548)

[Table 4 aTaxis Company Costs per kilometer 47](#_Toc80021549)

[Table 5 Profitability analysis 50](#_Toc80021550)

[Table 6 Literature review comparison table 86](#_Toc80021551)

[Table 6 Literature review comparison table 87](#_Toc80021552)

[Table 6 Literature review comparison table 88](#_Toc80021553)

[Table 6 Literature review comparison table 90](#_Toc80021554)

[Table 6 Literature review comparison table 90](#_Toc80021555)

[Table 6 Literature review comparison table 91](#_Toc80021556)

[Table 7 Possible combinations of age category, status in the household, household type and work id 92](#_Toc80021557)

[Table 7 Possible combinations of age category, status in the household, household type and work id 93](#_Toc80021558)

[Table 7 Possible combinations of age category, status in the household, household type and work id 94](#_Toc80021559)

[Table 7 Possible combinations of age category, status in the household, household type and work id 95](#_Toc80021560)

[Table 8 Trip Chain Types probability distribution 96](#_Toc80021561)

# List of equations

[Equations 1-3 Haversine's formula for the computation of the distance (d) between two points on earth of latitude and longitude respectively and where is the Earth’s radius (6,373 km) (Environnement, durabilité et bien-être, 2021). 34](#_Toc80021562)

# Introduction

Some weeks ago, the Brussels’ government has decided to ban diesel vehicles from Brussels from 2030 and gasoline vehicles from 2035 (RTBF, 2021). The goal is to force the use of electric vehicles. However, Belgium is one of the European countries with the lowest density of charging stations (Gaudy, 2021). The charging constraints linked to electric cars is an important cause of stress for users (Bartlett, 2012). Chen et al. (2016) think that electric autonomous vehicles are the solution to get rid of these constraints. That is why shared electric autonomous vehicles (SAEVs) are investigated in this thesis.

The transition phase to switch from a state without any autonomous vehicle (AV) to a fully automated fleet is interesting but already very often studied (Kornhauser et al., 2016 & Kornhauser et al., 2013 Zachariah, 2013 Zhu, 2016 Bösch, 2018 D. Fagnant & Kockelman, 2015 D. Fagnant & Kockelman, 2016 Litman, 2021 Wadud, 2017 Loeb & Kockelman, 2019 Burghout & Andréasson, 2015 Leurent, 2019 Poulhès & Berrada, 2019 Vosooghi et al., 2019 ITF, 2015 D. J. Fagnant & Kockelman, 2014 Hörl, 2018 Hyland & Mahmassani, 2018 Chen et al., 2016 Babicheva et al., 2019). This thesis thus focuses on a scenario where AVs replace all motorized vehicles currently in Brussels and fulfill one hundred percent of the residents, commuters and tourists’ daily travel needs. More particularly, this work assesses the profitability of a company providing such a service.

For this purpose, an agent-based simulation is used following the methodology of Kornhauser et al. (2012). The first step consists thus in reproducing the population of Brussels based on specific data. This results in the population file: a file gathering all simulated personal attributes of residents, commuters and tourists travelling in Brussels.

Their actual trips are then simulated resulting in the trips file. Those trips are used for the fleet sizing. The aTaxis and charging stations are simulated according to the demand represented by the trips file. The number of aTaxis and charging stations as well as the total travelled kilometers are extracted from this simulation in order to compute costs and revenues of this service.

The costs are evaluated following the methodology proposed by Chen et al. (2016). Nevertheless, cleaning costs and costs due to the management of the company are added to this process. Finally, the pricing strategy and profitability are analyzed.

This thesis starts with a literature review (section IX.) presenting the advantages of SAEVs (section IX.A.), giving some specification on the vocabulary used in this paper (section IX.B.) and summarizing the current state of the art in the research field of AVs (section IX.C.). Then, the thesis goal is described in detail (section X.). It depicts the scenario analyzed (section X.A.), the methodology followed (section X.B.), the tools used in that purpose (section X.C.) and the contributions of this work (section X.D.). The volume captured by this service is evaluated in section XI. This section starts by presenting the data used (section XI.A.). Then it contains a more specific methodology on the aTaxis’ fleet simulation (section XI.B.) and finally shows the volume results (section XI.C.). Afterwards, the costs are tackled (section XII.) in order to finally assess the pricing strategy and the profitability of this service (section XIII.). Section XIV.A. lists the possible improvements of this work while section XIV.B. proposes some ideas of future studies. In the end, the final conclusions are summarized in section XV.

# Literature review

## Impacts of autonomous vehicles

By many people, autonomous vehicles are seen as the future of transportation. They indeed think that AVs will be safer, more convenient and cleaner. This section of the thesis gives the literature opinion on the impacts of AVs.

In 2019, there has been 3,928 accidents in Brussels including 19 fatalities (IBSA, 2019g). In the literature ((Zachariah, 2013), (Zhu, 2016), (Bösch, 2018), (Wadud, 2017), (Burghout & Andréasson, 2015), (Spieser et al., 2014), (Kockelman et al., 2017), (Kok et al., 2017)), it is common to assume that this number of accidents will plummet because 95% of the accidents are caused by human error (Parlement européen, 2019). Thus, by removing the human dimension from the driving activity, the number of accidents decreases.

With autonomous cars, passengers will not only be safer, but they will also win time since they do not need to be focus on the road during their trips. A Belgian spends in average ten hours per week in transport (Fédération Belge et Luxembourgeoise de l’Automobile et du Cycle, 2020). They can now use this time to work, rest or do any activity feasible in a car. Nevertheless, the car design will probably be adapted to these new possibilities like shown on Figures 1 and 2.

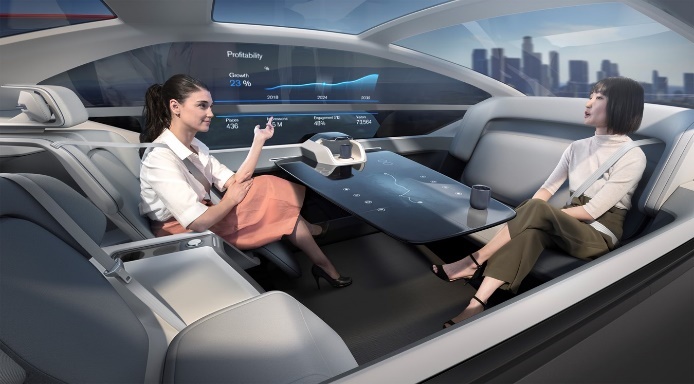


Figure 1 (on the left) New autonomous car design for a meeting (Volvo 360c) (© Volvo Car Group, Affaires publiques, SE-405 31 Göteborg, 2021)  
Figure 2 (on the right) New autonomous car design for resting (Volvo 360c) (© Volvo Car Group, Affaires publiques, SE-405 31 Göteborg, 2018)

Thanks to autonomous vehicles (AV), time spent in travel will be more efficient. However, it will also be shorter. Indeed, scientists predict a decrease of congestion thanks to AVs (Anderson et al., 2016). As seen in section XI.C.3.b, the number of cars required to fulfill all users need is inferior to the current number of cars on roads. Many searchers (Spieser et al., 2014), (ITF, 2015), (D. J. Fagnant & Kockelman, 2014), (Chen et al., 2016), (Zhang et al., 2014), (Ma et al., 2017)) see the reduction of traffic jams as a consequence of less cars on the roads.

Moreover, Treiber (2007) has demonstrated that congestions increase fuel consumption by 80%. Therefore, less congestion thanks to AVs means reduction of fuel consumption and pollution. Several aspects of AVs participate in the pollution reduction. Firstly, with a centralized dispatcher, the resources are optimized. Cars are allocated to the people needing it, reducing the number of vehicles (Brimont et al., 2017). On top of that, ride sharing allows decrease of the energy consumption per passenger (Brimont et al., 2017) to 4.7% (Zhang et al., 2014). Vehicles are also more intensely used, leading to shorter lifespan ((Zhang et al., 2014), (Spieser et al., 2014)). Therefore, old vehicles are substituted by new vehicles with improved technologies reducing the pollution. Automobile indeed evolves towards more sustainable vehicles (Jursch, 2021). Secondly, emissions induced by cold starts can be reduced by 85% (D. Fagnant & Kockelman, 2016) to 95% (Zhang et al., 2014). Furthermore, by anticipating accelerations and decelerations, AV can reduce the energy consumed in acceleration and braking by 4 to 10% ((Anderson et al., 2016), (D. Fagnant & Kockelman, 2015)). As a consequence, there is fuel saving and less brake wear (D. Fagnant & Kockelman, 2015). Shared electric autonomous vehicles (SAEV) reduce even more the environmental cots especially if renewables energies are used to produce the power grid. ((Loeb et al., 2018), (Reiter & Kockelman, 2017)). Finally, smart parking decisions could also increase fuel savings by avoiding “cruising for parking” ((D. Fagnant & Kockelman, 2015), (Bullis, 2011)).

AVs will indeed have an impact on urban parking. According to Fagnant & Kockelman (2016), eights parking spots per vehicles can be saved. It is 96% of the current parking places according to Burghout & Andréasson (2015). While IFT (2015) analyses different market penetration levels. With 50% of the vehicles fleet being autonomous, the parking space saved is insignificant while with a full market penetration, we can get rid of 85% of the parking spot.

Nevertheless, other authors are more skeptical on autonomous cars advantages. By reducing the driver burden allowing him to have efficient time while traveling, Auld et al. (2017) think that traveling behavior will change, increasing the number of trip. This would have, according to him, all opposite effects to what is stated here above. Litman (2021) is also afraid that transforming vehicles’ designs such as depicted on Figures 1 and 2, will increase vehicles’ weight and thus their energy consumption.

## Six levels of automation

You are probably already driving an autonomous car. There exists indeed several levels of automation as defined by the very cited SAE International (2018) and summarized on Figure 3. The levels are organized from the less automated vehicle (level zero) to the fully automated car (level six).

The two main categories are the vehicles still driven by the human and the one driven by the system. A level zero car has no automation at all. The driver is responsible for doing everything.

A level one car starts to have some automation such has your car probably possess. It includes cruise control and lane centering. While a level one can not both provide steering and brake / acceleration support at the same time, a level two car can.

Level three corresponds to the “real autonomous” level. The system can drive the vehicle under limited conditions such as in traffic jam. At level four, the pedals and steering may not be install letting the whole control to the system. Finally, level five vehicles can drive in all conditions and the system has whole control.

This thesis considers level five vehicles only.

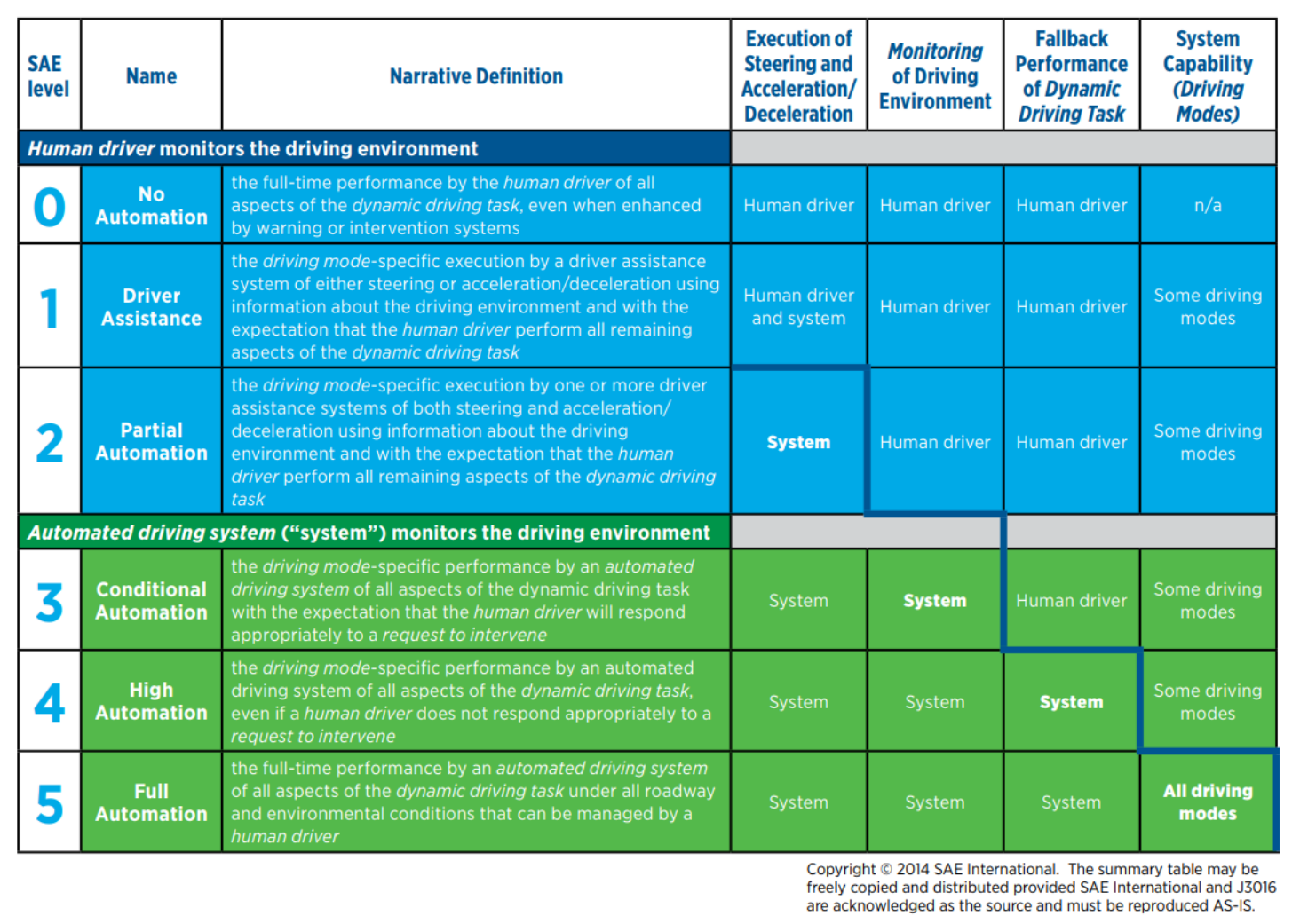


Figure 3 Autonomous vehicles: Automation levels (SAE International, 2018)

## State of the art

Several searchers have already tackled the topic of autonomous cars. Most of them focuses on the simulation of the autonomous vehicles’ fleet. However, the characteristics of their scenarios vary. Table 6 in Appendix 3 summarizes parameters of the major papers in the field.

The first parameter is the geographic region for the AVs implementation. Since a study require heavy region simulation, a few places are represented and studied by different searchers. In this way, the state of New Jersey (USA) has been simulated by Kornhauser et al. (Kornhauser et al., 2012) based on census data and then Kornhauser et al. (2013), Kornhauser et al. (2016), Zachariah (2013) and Zhu (2016) went deeper on the analysis as explained below. This is called an agent-based simulation. Other agent-base simulations exist in the literature such as POLARIS used by Auld et al. (2017) to model trips happening in Chicago (USA) or Stockholm (Sweden) simulated thanks to similar data ((Taylor, 2003), (Almroth et al., 2014)) by Burghout & Andréasson (2015). Martinez & Viegas (2017, 2016) and ITF (2015) also simulated the traveling demand based on a survey, but the area studies is Lisbon (Portugal). While Spieser et al. (2014) and Azevedo et al. (2016) analyze AVs in Singapore thanks to data from surveys and taxis’ GPS data. Spieser et al. (2014) also used a Poisson process in order to model the demand. Babicheva et al. (2019) also use a spatio-temporal Poisson distribution. However, Babicheva et al. work with a fixed fleet size and simulates a (dis)utility function for the waiting time (Babicheva et al., 2019). Next to that, Gurumurthy & Kockelman (2018) use cellphones data in order to simulate the trips happening in Orlando, Florida (USA).

Bösch (2018) was the first to introduce the use of MatSim, a “dynamic traffic simulation software” as described by Hyland & Mahmassani (2018), for AVs simulations. Bösch (2018) recreated the region of Zurich (Switzerland) on MatSim. While for their simulations, Fagnant and Kockelman (2016, 2014), Loeb & Kockelman (2019), Chen et al. (2016), Levin et al. (2017) and Loeb et al. (2018) used the representation of Austin, Texas (USA) on MatSim created by Liu et al. (2017). Berlin (Germany) (Bischoff et al., 2017) and Rouen, Normandie (France) (Vosooghi et al., 2019) are also studied using MatSim.

Less realistically, Burns (2013) models the attraction to the centrum of the city and simulated the trips in three different areas: Ann Arbor, Michigan (USA) to represent a small to medium town, Babcock Ranch, Florida (USA) representing a suburban region and Manhattan, New York (USA) as urban. Leurent (2019) created a synthetic ring-shape city with homogeneous population density along the periphery called Orbicity and studies divers AVs scenarios happening in Orbicity. Orbicity is then used by Berrada to investigate different Business Models for AVs (Berrada, 2019).

The smaller region of Palaiseau, Saclay (France) is studied by Babicheva et al. (2019) and Poulhès & Berrada (2019). Those analyses investigate the possibility of replacing a bus with a specific itinerary by an autonomous one. This region is also used by Berrada (2019).

The roads are generally not represented apart in Babicheva et al. (2019), Poulhès & Berrada (2019) and Berrada (2019) where a specific itinerary is studied or in Orbicity ((Leurent, 2019), (Berrada, 2019)). When using SimMobility or MatSim the actual roads are not represented but their characteristics of speed and congestion are used ((Spieser et al., 2014) and (Bösch, 2018), (D. Fagnant & Kockelman, 2016), (Loeb & Kockelman, 2019), (Liu et al., 2017), (Vosooghi et al., 2019), (D. J. Fagnant & Kockelman, 2014), (Hörl, 2018), (Chen et al., 2016), (Levin et al., 2017), (Bischoff et al., 2017), (Loeb et al., 2018), (D. Fagnant et al., 2015), (Azevedo et al., 2016)). The road characteristics come from OpenStreetMap (OpenStreetMap, n.d.) which is an open-source world map editable by everyone. It is a veritable database with all road and buildings characteristics. Only those papers use real position of the origins and destinations. Other studies ((Kornhauser et al., 2012), (Kornhauser et al., 2013), (Kornhauser et al., 2016) (Zachariah, 2013), (Zhu, 2016) (Poulhès & Berrada, 2019), (ITF, 2015), (D. J. Fagnant & Kockelman, 2014), (Hyland & Mahmassani, 2018), (Chen et al., 2016), (Babicheva et al., 2019), (Loeb et al., 2018), (Berrada, 2019)) aggregate the demand at a station level. The whole territory studied is divided into squares with a grid and a station is in the center of each square. The square size can vary from 0.25 miles (402 m) x 0.25 miles (D. J. Fagnant & Kockelman, 2014) to 16 miles (25.75 km) x 16 miles (Hyland & Mahmassani, 2018).

The third parameter is the market penetration. Only few scientists tackle the full penetration ((Burns, 2013), (ITF, 2015)). Others study penetration rates from 0.1% ((Chen et al., 2016), (Loeb et al., 2018)) to 90% ((ITF, 2015), (D. Fagnant & Kockelman, 2015)). When only a percentage of the demand is simulated, it is considered as a partial market penetration with the other trips being fulfilled by non-autonomous vehicles. It is then also considered as multimodal since a commuter could take different modes to go from his origin to his desired destination given that other non-autonomous vehicles are available. This has an impact on the AVs’ fleet size needed (ITF, 2015).

Fourthly, several implementations exist. AVs can be owned as a private ((Bösch, 2018), (D. Fagnant & Kockelman, 2015), (Wadud, 2017)) car or shared and manage by a centralized dispatcher. Among shared autonomous cars, it can include ride sharing ((Kornhauser et al., 2013), (Kornhauser et al., 2016), (Zachariah, 2013), (Zhu, 2016), (Bösch, 2018), (D. Fagnant & Kockelman, 2015), (D. Fagnant & Kockelman, 2016), (Litman, 2021), (Loeb & Kockelman, 2019), (Poulhès & Berrada, 2019), (Vosooghi et al., 2019), (Burghout & Andréasson, 2015), (ITF, 2015), (Hörl, 2018), (Martinez & Viegas, 2017), (Babicheva et al., 2019), (Heilig et al., 2017), (Wen et al., 2018), (Berrada, 2019)) or not ((Bösch, 2018), (Burns, 2013), (D. Fagnant & Kockelman, 2015), (Litman, 2021), (Liu et al., 2017), (Leurent, 2019), (Spieser et al., 2014), (ITF, 2015), (D. J. Fagnant & Kockelman, 2014), (Hörl, 2018), (Hyland & Mahmassani, 2018), (Chen et al., 2016), (Martinez & Viegas, 2017), (Zhang et al., 2014), (Loeb et al., 2018), (D. Fagnant et al., 2015), (Azevedo et al., 2016), (Wen et al., 2018), (Berrada, 2019)). With ride sharing, two strangers can share a SAV for a trip having closed origins and destinations. Auld et al. (2017) tackles autonomous cars but with lowest automation level than the driverless vehicles.

The fifth classification parameter is the fuel. Some papers consider electric vehicles and the charging problems it implies. If Bösch (2018) and Burns (2013) do not simulate electric vehicles, they analyze its advantages and challenges. For the simulation of AEVs, Burns (2013), (D. Fagnant & Kockelman, 2015), (D. Fagnant & Kockelman, 2016), (Litman, 2021), (Loeb & Kockelman, 2019), (Leurent, 2019), (Vosooghi et al., 2019), (ITF, 2015), (D. J. Fagnant & Kockelman, 2014), (Chen et al., 2016), (Loeb et al., 2018) and (Berrada, 2019) are more interesting.

After the interesting characteristics of the existing analyses, this thesis summarizes some methodologies and conclusions. Kornhauser et al. (2012) have synthetized the 9 million residents of New Jersey (USA) and their 32 million of daily trips with their origin, destination and starting time. Based on that, Zachariah (2013) has pixelized the region with squares of size 0.5 miles (805 m) x 0.5 miles. A taxi station is reachable in each square by walking less than five minutes. Using the Manhattan distance and a fixed travel speed, Zachariah (2013) simulated the taxis fleet. In his scenario, ride sharing was allowed provided that the resulting detour is inferior to 20% of the initial itinerary. He demonstrated that less vehicles are needed, and the number of kilometers traveled per day decrease thanks to SAVs. Kornhauser et al. (2013) then analyzed the impact of the number of common destinations and of the departure delays implied by the ride sharing demonstrating that the marginal benefits in vehicle occupancy decreases while the depart delay or the number of common destinations increases. Kornhauser et al. (2013) analyze the interest of an aTaxis fleet in the whole state of New Jersey (USA) while Kornhauser et al. (2016) analyses the specificities of each county. Zhu (2016) finally tried and compared different relocation strategies and showed that the total vehicle kilometer traveled is reduced by 43% thanks to SAVs with ride sharing.

Bösch (2018) follows a similar agent-based methodology using activity-based tour patterns. Nevertheless, the path and mode choices are also included in the trip simulation. When driving passengers, the aTaxi uses real roads with their characteristics such as the speed but when the AV is empty, the travel time is computed using the beeline Euclidean distance with a trip-specific correction factor multiplied by the average speed (Loeb & Kockelman, 2019). The ride sharing applies the first-in-last-out (FILO) rules and like Kornhauser et al. (2013, 2016), the simulation does not allow detours extending the trip duration by more than 20%. Ten percent of the total travel demand of Zurich (Switzerland) is simulated and the results show that one SAV does in average 10 trips per day with an average users’ waiting time of 3.11 minutes with a rejection rate of 3.8% because of waiting time higher than 10 minutes (Bösch, 2018).

Burghout & Andréasson (2015) propose a ride sharing model with a maximum allowed detour of 30% of the travel time, a maximum waiting time of 10 minutes and a first-in-first-out (FIFO) rules. His analysis is based on 498 732 trips simulated based on the home-work and work-home commuting data of Stockholm (Sweden) coming from the REGENT (Almroth et al., 2014). Those data are then fitted to the morning and afternoon peaks assuming Gaussian distribution (Almroth et al., 2014). Only 51% of those data are kept for the simulation by removing trips coming or going outside the studied area. Conclusions of this paper demonstrate that without ride sharing the total number of kilometers traveled increased by 24%.

Chen et al. (2016) focuses on the implementation of SAEVs and the strategic question of charging infrastructure position. Her simulation is in three times: first she creates charging stations when an aTaxi needs to be charged and can not find a free charging station, then she does the simulation again knowing the position of the charging stations in order to determine the fleet size and finally she run the simulation on several days to get the final results. The simulation uses 5% of the daily 8.8 million trips happening in Austin, Texas (USA) simulated thanks to the data of Austin’s 2010 Capital Area Metropolitan Planning Organization (CAMPO, 2021) and of the U.S. National Household Travel Survey (NHTS) of 2009 (U.S. Department of Transportation Federal Highway Administration, 2017). Since it has been assumed that only 2% of the inhabitants use the SAEVs, the final sample used is only 0.1% of all daily trips. Chen et al. (2016) has been able to show that the fleet size is sensitive to the charge time and the vehicle range (meaning the total distance an electric vehicle can travel before its battery to be empty) and that the number of charging stations is dependent on this vehicle range as well.

Loeb et al. (2018) have then improved Chen et al.’s analyses (2016). Unlike Chen et al. (2016), Loeb et al. (Loeb et al., 2018) allows charging vehicles to accept a trip request. They assumed that all users pre-order their trip five minutes in advance. They showed that the modification of this order time does not have a significant impact on the results. Their simulation demonstrates that 19.8 % of the kilometers traveled are empty rides (meaning the aTaxi drive without any passenger) while 23% of those empty kilometers are to reach a charging station. The vehicle range affects the number of charging stations but does not improve the response time once having reached 175 km. However, reducing the charging time and mainly, as already stated by Loeb et al. (2018), increasing the fleet size improve the response time.

Vosooghi et al. (2019), Hörl (2018), Hyland & Mahmassani (2018) and Seow et al. (2010) examine several relocation strategies. Vosooghi et al. (2019) get to the conclusion that SAVs reach a 20% economy compared to privately owned AVs. Seow et al. (2010) demonstrate that the assignment of the nearest taxi using the First-come-first-served (FCFS) rule is inefficient. Finally, Hyland & Mahmassani (2018) states that the best assignment strategy allows aTaxis to be diverted to a new request while booked and consider en route drop off. His scenario uses a fixed feet size, forbids rejecting requests and ignores refueling.

Next to those simulations, Bösch (2018) studied different economic (monopoly of aTaxis, monopoly of SAVs with ride sharing and oligopoly of SAVs with and without ride sharing) and regulations (pricing of private AVs, subsidizing public transport and restriction on private empty rides) scenarios in order to give recommendations for policies. Berrada (2019) also investigated several Business Models of AVs with a microeconomic model including three levels (operational, tactical, and strategic), and three pressure forces (regulation, unit costs, and demand preferences). Leurent (2019) analyzed the medium-term supply demand equilibrium of AVs while Fagnant & Kockelman (2015) uses external costs (crash or congestion) of today private cars to assess AVs advantages.

Wadud (2017) inspects who will be the first adopters of AVs using a total cost of ownership (TCO) analysis in the UK. His analyses included not only private users but also taxis and freight companies. He concludes that commercial operations will be the early adopters. Concerning the private users, the households with the highest income will be the first adopters.

Finally, all researchers ((Spieser et al., 2014), (ITF, 2015), (D. J. Fagnant & Kockelman, 2014), (Chen et al., 2016), (Zhang et al., 2014), (Ma et al., 2017)) agree that SAVs will reduce the number of vehicles needed to fulfill travelers’ demand with a reduction of number of vehicles needed between 43% (Zhu, 2016) and 95% (Burghout & Andréasson, 2015). According to Ma et al. (Ma et al., 2017) SAVs do not increase the number of vehicle kilometers traveled. However, the majority of scientists ((ITF, 2015), (D. J. Fagnant & Kockelman, 2014), (Chen et al., 2016)) have demonstrated that the number of vehicle kilometers traveled will increase with SAVs.

# Thesis goal

This thesis studies the profitability of electric autonomous Taxis in Brussels through the simulation of the average daily trips in Brussels. The first section of this chapter depicts the major hypotheses of the scenario considered while the second section describes the methodology followed.

## Scenario analyzed

This work focuses on the Belgian region of Brussels. In Belgium, Brussels is both a region, a city and a municipality. If the region and the city refer to the same territory, the municipality is much smaller. In this paper, unless otherwise noted, the word Brussels refers to the whole region including the municipality of Brussels but also the eighteens other municipalities.

Brussels has been chosen because, until now, according to the author of this thesis, no paper in the literature focuses on the case study of Brussels. (Furthermore, Brussels is a central city in Europe, being the capital of Europe, hosting the European Institutions (CIRB-CIBG, 2021) and is part of a big metropolitan area being between Paris and Amsterdam (Cambier, 2018). Brussels is a capital and presents thus a dense urban population and trips habits. Nevertheless, the city is a small city compared to other European capitals. Moreover, Toyota (Hope, 2019) (T, 2019) and Aon (De Bleser, 2016) have already conducted some tests with an AV in the streets of Brussels showing car manufacturers are willing to implement autonomous cars in this city. In addition, the author living and studying in Brussels has easier access to data about Brussels than another city.

The scenario studied in this thesis assumes a full penetration of the transportation market while only focusing on people transport (excluding thus freight transport). This scenario has been chosen to avoid the complexity created by multimodal trips and to focus on the “long term” analysis of a stable market instead of the development of this one. Moreover, this assumption is sparsely investigated in the literature. The author is indeed only aware of two papers using this hypothesis ((Burns, 2013), (ITF, 2015)).

Like many others ((Kornhauser et al., 2013), (Kornhauser et al., 2016), (Zachariah, 2013), (Zhu, 2016), (Bösch, 2018), (D. Fagnant & Kockelman, 2015), (D. Fagnant & Kockelman, 2016), (Litman, 2021), (Loeb & Kockelman, 2019), (Poulhès & Berrada, 2019), (Vosooghi et al., 2019), (Burghout & Andréasson, 2015), (ITF, 2015), (Hörl, 2018), (Martinez & Viegas, 2017), (Babicheva et al., 2019), (Heilig et al., 2017), (Wen et al., 2018), (Berrada, 2019)), this paper focuses on the shared autonomous vehicles with ride sharing. Ride sharing allows two strangers to share a SAV for a trip having closed origins and destinations. It has been shown to be cheaper, more efficient and cleaner ((Poulhès & Berrada, 2019) & (Vosooghi et al., 2019)). Nevertheless, unlike Burghout & Andréasson (2015) (resp. (Kornhauser et al., 2013), (Kornhauser et al., 2016), (Zachariah, 2013), (Zhu, 2016)) which allows detour as long as the traveling time is not impacted by more than 30% (resp. 20%), this work forbids detour like Poulhès & Berrada (2019). This simplification reduces the computation time of the simulation. As from this point in this paper, shared autonomous vehicles have to be understood as shared autonomous vehicles with ride sharing.

Even if it makes the simulation more complex, this simulation was not imaginable with gasoline vehicles. Brussels has indeed decided to forbid diesel cars in 2030 and gasoline cars in 2035 (RTBF, 2021). This work is looking to be the more realistic possible. This assumption was thus compulsory. Furthermore, it is cleaner (Touzot, 2021) and follows similar investigations ((Bösch, 2018), (Burns, 2013), (D. Fagnant & Kockelman, 2015), (D. Fagnant & Kockelman, 2016), (Litman, 2021), (Loeb & Kockelman, 2019), (Leurent, 2019), (Vosooghi et al., 2019), (ITF, 2015), (D. J. Fagnant & Kockelman, 2014), (Chen et al., 2016), (Loeb et al., 2018)).

## Methodology

In order to assess the profitability of the scenario describe in the above section, this thesis first determines the volume, meaning the aTaxis’ fleet size. Then, the costs are summarized. To finally, assess the feasibility of the price needed for the project to be at least break even.

The methodology used for the fleet sizing in this thesis is an agent-based simulation similar to 1, (Zachariah, 2013), (Zhu, 2016), (D. Fagnant & Kockelman, 2016), (Loeb & Kockelman, 2019), (Liu et al., 2017), (Burghout & Andréasson, 2015), (Spieser et al., 2014), (Auld et al., 2017), (ITF, 2015), (Chen et al., 2016), (Martinez & Viegas, 2017), (Zhang et al., 2014), (Loeb et al., 2018), (D. Fagnant et al., 2015), (Azevedo et al., 2016)). This work indeed first synthetizes the population of Brussels based on very specific statistics. In this way, each resident is created with some personal attributes: an age, a gender, a place of residence, a household type, a worker type, a place of work and a daily trips pattern. Commuters and tourists are also reproduced with fewer attributes.

Based on the population simulated and thanks to statistics on the timing and length of the trips happening in Brussels, daily trips are simulated.

The aTaxis’ fleet can then be simulated. Three scenarios are investigated:

* A simulation during the equivalent of one day (1440 minutes) considering only the trips with an origin and / or a destination in the municipality of Ganshoren forbidding empty rides;
* A simulation during the equivalent of one day (1440 minutes) considering only the trips with an origin and / or a destination in the municipality of Ganshoren allowing empty rides;
* A simulation considering all trips from the simulated Trips File (so the whole region of Brussels is considered) starting before 7.03 a.m. (423 minutes) forbidding empty rides.

The ideal would have been to do two full simulations during the equivalent of one day (or even more) considering all trips from the Trips File one forbidding empty rides and the other one allowing them. Unfortunately, it would have taken more than one year to run because of the complexity of the script. That is why Ganshoren has been chosen. Ganshoren is the municipality with the fewest number of daily trips with an origin and / or a destination in its territory. It was thus possible to run the code on those trips in a realistic amount of time.

The results obtained for both simulations on Ganshoren territory are compared in order to assess the impact of allowing empty rides. Then the results at 7h03 in Ganshoren are used to define a ratio with results at 7h03 on the whole territory of Brussels. The fleet simulation indeed provides useful variables values (traveled kilometers, number of trips, number of aTaxis needed, number of charging stations, total charging time) which are scaled to Brussels thanks to this ratio before to be used in the cost, pricing and profitability analysis.

More details on the population, trips and aTaxis’ fleet simulations are specified in section XI.B. and all Excel Files (also including costs and profitability analysis) and Python scripts are accessible on the git: XXX.

The costs analysis corresponds to a literature review of the costs involved in the SAEVs’ fleet management. However, the cleaning costs and the administrative costs due to the management of the company as such are added compared to what exists in the literature.

Finally, the pricing and profitability assessment compares the price needed for the company to be breakeven with results stated in the literature and current travel costs in Brussels.

## Tools used

Spyder: Spyder (Spyder, 2020) is a free scientific development environment included in the Anaconda platform. It allows the programming of the coding language Python. All codes made and used in the simulations for this thesis were developed using Python. Several libraries have been used but most notably Pandas which permits to import data tables from csv (Comma Separated Values) files, manage and modify the data, and save them to new csv files. The random library has also been used for all random assignments.

Microsoft Excel: Excel (Microsoft, 2021d) is a spreadsheet software developed by Microsoft. It has been used for simple computations and data cleaning as well as for graphs making.

Microsoft Access: Access (Microsoft, 2021b) is database management software developed by Microsoft. It was used to handle big databases such as the matrix of workflows (Service Public Fédéral Belge, 2017a).

Microsoft PowerPoint: PowerPoint (Microsoft, 2021c) is a presentation software developed by Microsoft. The majority of the figures in this thesis have been created with PowerPoint because it is easy to insert geometric shapes, align them and adapt their visual aspect.

Microsoft Word: Word (Microsoft, 2021a) is a text editor software developed by Microsoft. This paper has been written and formatted using Word. This software provides useful tools to create automated content table, list of figures, list of tables, list of equation and bibliography which have been used for this thesis.

GitHub: GitHub (GitHub Inc., n.d.) is a repository hosting service and development platform. It helps for the collaboration and updating of development projects. It has been used in this thesis in order to share the scripts and computations realized. The 7,600 lines of script and 77 Excel sheets are indeed shared on the repository XXX.

## Contributions

The major contribution of this thesis is the conclusion and analysis of the profitability of a company managing a centralized fleet of electric shared autonomous taxis fulfilling all trips happening in Brussels. This demonstrates a necessary increase of 8.42 % of the average travel budget per person for this system to be breakeven with the most realistic scenario possible given the available data. Of course, it needed some simplifying hypotheses described in section X.A.. Nevertheless, it provides a first simulation for more sophisticated ones. It also provides a worst-case scenario on the profitability.

For the analysis of the profitability, the simulation of the daily average trips was needed. Therefore, this thesis offers a Trip File for analyses or simulations other than autonomous cars.

In order to create this Trip File, it first needed to simulate the entire population living in Brussels. This simulation includes specific attributes assignments such as the work id, the workplace, the household type, the sector of residency, age and gender of individuals, … This simulation can also be used for other purposes in the future.

Finally, the cost analysis brings new specifications on the cleaning costs compared to what already exists in the literature. This work also includes administrative costs due to the management of the company. Those new costs increase the realism of autonomous vehicles profitability analyses.

# aTaxis’ fleet simulation

## Data

Most of the data is coming from the neighborhoods’ monitoring (“monitoring des quartiers” in French) (Monitoring des quartiers, 2019c). It provides detailed statistics at the statistics sector level (for more information see below X.A.2.) for different years. IBSA (IBSA, n.d.) has helped fulfill the missing data. However, IBSA’s data are only available at a municipal level. Besides mentioned otherwise, the data from the neighborhood’s monitoring is always per sectors while the data from the IBSA is always per municipality. Other sources that have been used such as ARES (Académie de recherche et d’enseignement supérieur, n.d.-c) and Onderwijs Vlanderen Dataloep (Vlaanderen is onderwijs & vorming, 2018) for the higher education’s data. The origin of each piece of information will be specified in the methodology.

### 2019 as a reference year

2019 has been chosen as reference year and besides it is specified all data used are 2019’s data. Even if 2019 does not represent the latest data. 2020’s data are the latest available data at the time this thesis is written. However, 2020 has be hammered by the COVID-19 pandemic, enforcing multiple lockdowns, homeworking, closing schools, universities, … (Sudinfo, 2020) The travel data of 2020 have been highly affected in that regard. Therefore, 2019’s data are more representative of a normal behavior of the population of Brussels.

Since autonomous cars will not penetrate Brussels market before at least 2030 ((Kok et al., 2017), (Litman, 2021)), the population could have been predicted. However, it introduces additional hypotheses and inaccuracies. It has been chosen to use 2019’s data as if it was the population at the time of full penetration of the market by autonomous taxis. The reader is free to work on the prediction of 2030’s population of Brussels and repeat the process in order to compare the results. The methodology is voluntarily detailed to allow it.

### Statistics Sectors as a geographic level

Brussels is geographically divided in three different levels of details: municipalities, neighborhoods, and statistics sectors (Monitoring des quartiers, 2019c) (Service Public Fédéral Belge, 2017b). Figure 4 compares the three levels. For this work, the highest detailed level has been chosen namely the statistics sectors level. It allows the depiction of the most accurately possible detail of origin and destination for each trip. Moreover, in this simulation, there will be only one aTaxis’ station per statistics sector. It has to be small enough for users to walk to it wherever they are in the statistics sector. The average walking distance is 237 m corresponding to 3.23 minutes by walk (Julien, 2021) which is reasonable and corresponds to the pixelization used in similar studies (D. J. Fagnant & Kockelman, 2014). Note that for simplicity, statistics sectors will be referenced to as sectors in this paper.

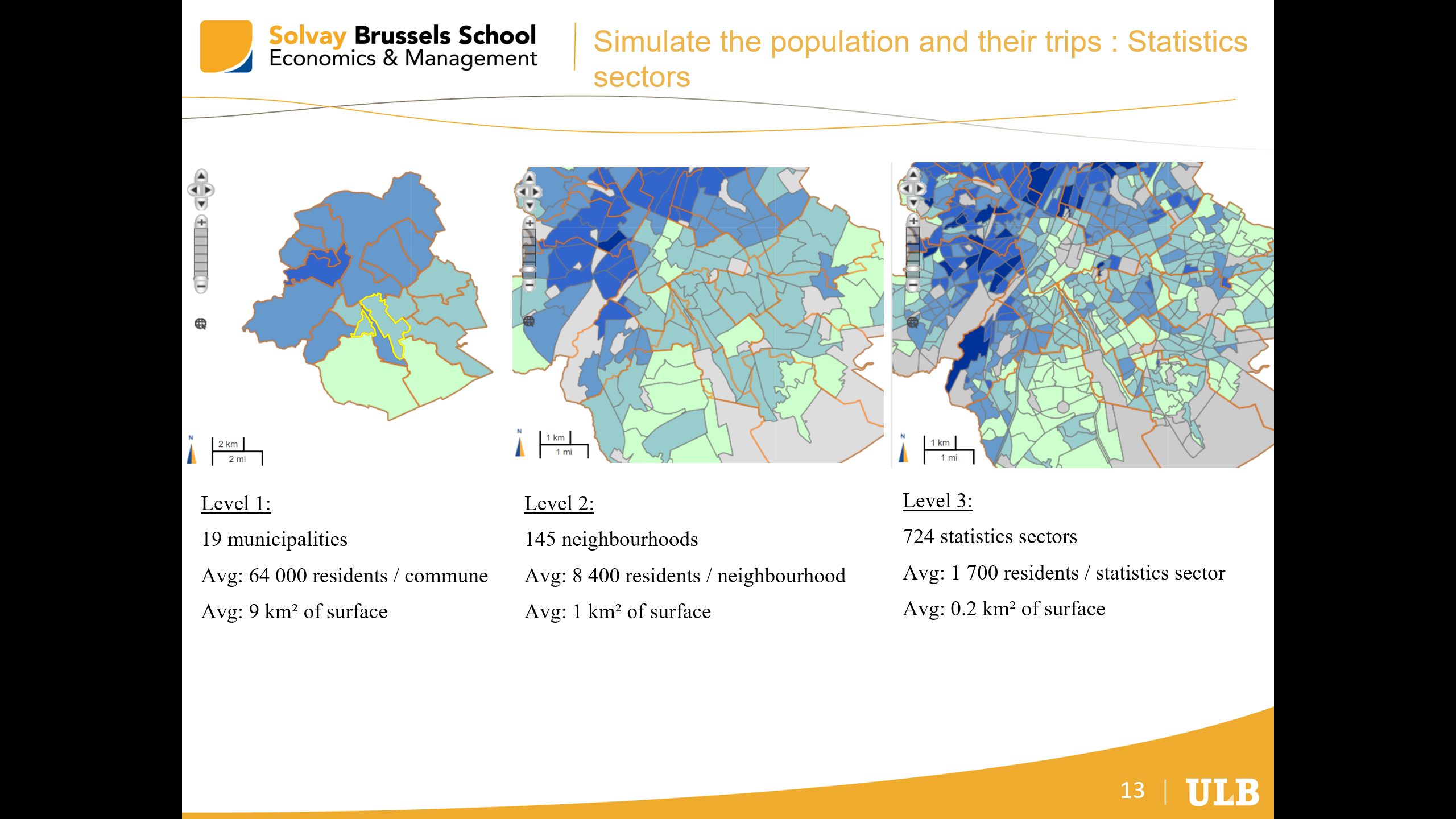


Figure 4. Levels of geographic subdivision of Brussels (Monitoring des quartiers, 2019c)

## Methodology

### Overview

The methodology applied for this thesis follows the process proposed by Kornhauser et al. (2012). However, Kornhauser et al.’s work was based on really detailed data from the U.S. Census data (United States Census Bureau, n.d.) not available for Brussels (the last Belgian census dates of 2011 and is not as specific as the US one). This work follows the same methodology but is based on slightly higher-level statistics (at the sectors level as explained in IX.A.2.).

The first step is to create people (in our case living in Brussels) with their attributes: the sector where they are living, their id, their age, their gender, an attribute telling if they are considered as children in their household, their household type and their household id. Those attributes are allocated according to statistics about the population of Brussels (Monitoring des quartiers, 2019bf), (Monitoring des quartiers, 2019bg), (Monitoring des quartiers, 2019d), (Monitoring des quartiers, 2019e), (Monitoring des quartiers, 2019f), (Monitoring des quartiers, 2019g), (Monitoring des quartiers, 2019h), (Monitoring des quartiers, 2019i), (Monitoring des quartiers, 2019j), (Monitoring des quartiers, 2019k), (Monitoring des quartiers, 2019l), (Monitoring des quartiers, 2019m), (Monitoring des quartiers, 2019n), (Monitoring des quartiers, 2019o), (Monitoring des quartiers, 2019p), (Monitoring des quartiers, 2019q), (Monitoring des quartiers, 2019r), (Monitoring des quartiers, 2019s), (Monitoring des quartiers, 2019t), (Monitoring des quartiers, 2019u), (Monitoring des quartiers, 2019v), (Monitoring des quartiers, 2019w), (Monitoring des quartiers, 2019x), (Monitoring des quartiers, 2019y), (Monitoring des quartiers, 2019z), (Monitoring des quartiers, 2019aa), (Monitoring des quartiers, 2019ab), (Monitoring des quartiers, 2019ac),(Monitoring des quartiers, 2019ad), (Monitoring des quartiers, 2019ae), (Monitoring des quartiers, 2019af), (Monitoring des quartiers, 2019ag), (Monitoring des quartiers, 2019ah), (Monitoring des quartiers, 2019ai), (Monitoring des quartiers, 2019aj), (Monitoring des quartiers, 2019ak), (Monitoring des quartiers, 2019al), (Monitoring des quartiers, 2019am), (Monitoring des quartiers, 2019an), (Monitoring des quartiers, 2019ao), (Monitoring des quartiers, 2019bh) (IBSA, 2019h) (Monitoring des quartiers, 2019ap) (IBSA, 2019b) (Monitoring des quartiers, 2019ax) (Monitoring des quartiers, 2019az) (Monitoring des quartiers, 2019aq) (Monitoring des quartiers, 2019be) (Monitoring des quartiers, 2019bd) (Monitoring des quartiers, 2019bc), (Monitoring des quartiers, 2019ba), (Monitoring des quartiers, 2019bb) (IBSA, 2019b) (Service Public Fédéral Belge, 2019a) Famifed (2019) (Van Leeuw & Leroy, 2020) (Service Public Fédéral Belge, 2019b) (IBSA, 2018). Details on the methodology used can be found in the complementary folder in Appendix 6 (section XVII.C.1.).

Secondly, their work id is then added also according to statistics (Monitoring des quartiers, 2018) (IBSA, 2019f), (Fédération Wallonie-Bruxelles, n.d.) (IBSA, 2019e) (IBSA, 2019e) (Académie de recherche et d’enseignement supérieur, n.d.-c) (Académie de recherche et d’enseignement supérieur, n.d.-b) (Académie de recherche et d’enseignement supérieur, n.d.-a). (Université Catholique de Louvain, 2021), (ADT ATO.brussels, 2015), (Wikipedia, 2021), (Fédération Wallonie-Bruxelles, 2018) (Vlaanderen is onderwijs & vorming, 2018) (Du Brulle, 2014) (BCSS, 2019) (INASTI, 2021), (INASTI - Service Statistiques, 2019) (INASTI, 2021), (INASTI - Service Statistiques, 2019). All age - household type - work id combinations are not possible. A child of 5 years will indeed not live as a single mother and study at the university. Possible combinations are presented in the Table 7 in Appendix 4 (section XVII.B.2). Details on the methodology used can be found in the complementary folder in Appendix 7 (section XVII.C.2.a).

The third step is to determine the sector where each person works. Note that in this thesis, the word “work” has to be understood at its broad sense including the place of study. Details on the methodology used can be found in the complementary folder in Appendix 7 (section XVII.C.2.b).

The last element allocated to each person is their trip chain type (section XI.B.2.). According to Lebrun et al. (2014) , there exists 31 patterns of travels during a day in Belgium represented on Figures 5 and 6. Based on the probability for each of them (Table 8 in Appendix 5), one specific pattern is allocated to each person.

Commuters living outside Brussels and tourists are also created with slightly less attributes but following the same logic and having their own patterns. Details on the methodology used can be found in the complementary folder in Appendix 7 (sections XVII.C.2.c and XVII.C.2.d).

The trips can now be created with an origin, destination and start time for each (section XI.B.3.). The aTaxis’ fleet reaction according to those trips is then simulated in order to determine the number of aTaxis needed to fulfill the whole demand with less than 5 minutes waiting time (section XI.B.4.).

The detailed computations and process for each of these steps are presented in the rest of this section while all Excel Files and Python scripts are accessible on the git: XXX.

### Allocate a trip chain type

When studying the mobility habits of a population, it is common to use trip chains (Lebrun et al., 2014), (Kornhauser et al., 2012). Trip chains are patterns representing the daily trips of a person. Those used in this thesis are the 31 ones used in Brussels in Beldam and Monitor reports (Lebrun et al., 2014). They are shown on Figures 5 and 6. Those trip chain types are grouped in two main categories: the ones including a workplace and the one without workplace (Lebrun et al., 2014). In our case, people not having a workplace are people with “stay at home” as work id or tourists. Both categories have their own probability distribution used in order to allocate a trip chain type to each person simulated previously. In “Cahiers de l’Observatoire de la mobilité de la Région de Bruxelles-Capitale » (Lebrun et al., 2014), trip chain types without workplace have a general leisure place instead. This is considered as the longest leisure activity of the day. However, in this thesis no difference is made between a “simple” leisure and a general leisure.

The probabilities distribution presented in “Cahiers de l’Observatoire de la mobilité de la Région de Bruxelles-Capitale » (Lebrun et al., 2014) date from 2014. However, in sack of more recent data, this work makes the assumption that Brussels’ residents travelling behaviors have not changed significatively between 2014 and 2019. Those probabilities distributions are percentages of the mobile population. The immobile people represent 22.5% (Monitor@Vias, 2016). The immobile people are people not doing any trip per day in average. Those include prisoners, hospitalized people and elderlies in nursing home (having a collective household type in our simulation) but not only. There also exists people free to leave their home but not doing it in average. In order to adapt the probabilities distributions, the percentage of people with a collective household type in the simulated population (6.76 %) is deduced from the 22.5% and this remaining 15.74 % then multiply the probabilities distributions adding the possibility to be immobile in the distribution.

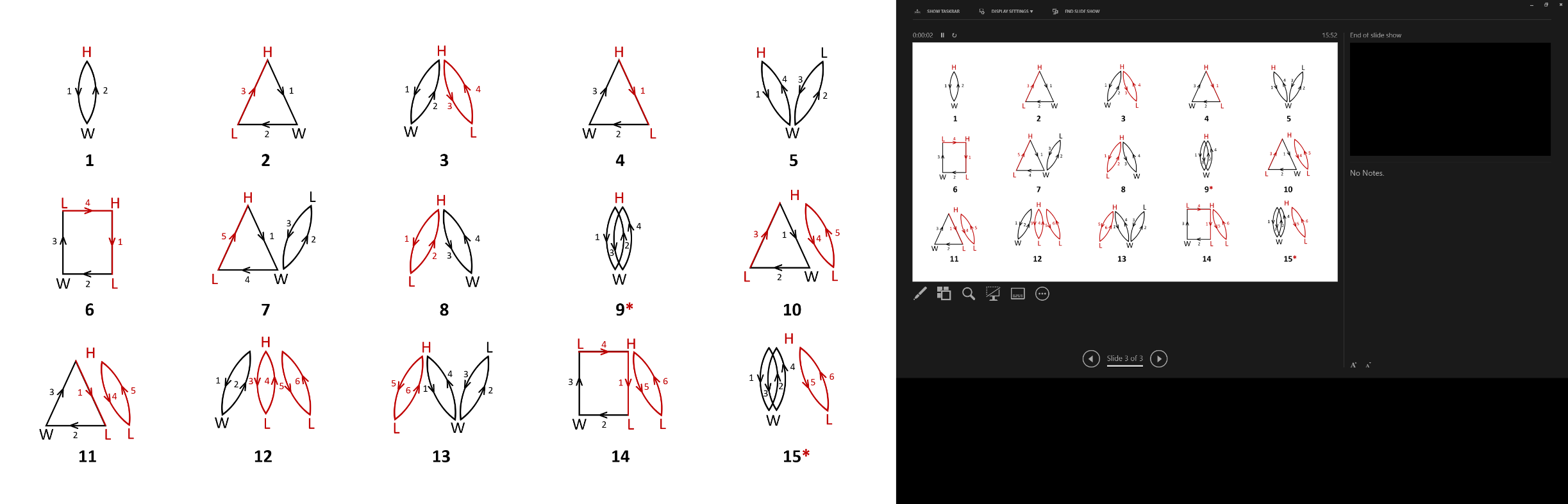


Figure 5 Trip chain types including a workplace. H stands for Home, W for Workplace and L for Leisure. The small numbers indicate the order in which the trips are done arrow represents the direction of the trip. The bold numbers are the reference of trip chain types. The red lines are the trips not done in Brussels when the trip chain type is assigned to a commuter. Trip chain types with an asterisk are the trip chain types not considered for commuters.

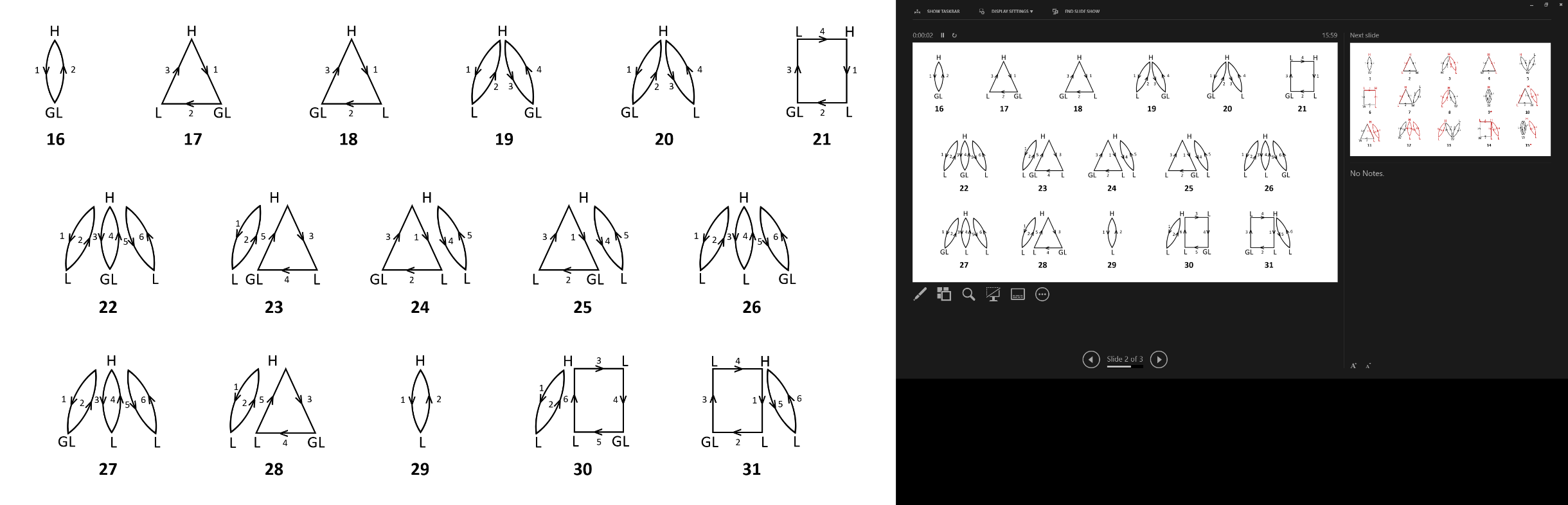


Figure 6 Trip chain types without workplace. H stands for Home, L for Leisure and GL for General Leisure. The small numbers indicate the order in which the trips are done arrow represents the direction of the trip. The bold numbers are the reference of trip chain types.

Commuters live outside Brussels. All their trips are not especially in Brussels. Monitor data (Monitor@Vias, 2016) demonstrate that only 3% of the commuters working in Brussels while living outside Brussels practice their leisure in Brussels. In sack of simplicity, for commuters, all trips from home not being to work (in red on Figure 5) are assumed as not being in Brussels and therefore not considered in this thesis. Some trip chain types including the commuter to come back at home before going back to his workplace (trip chain type 9 and 15 on Figure 5) correspond generally to people going back home to eat. Nevertheless, it seems seldom for commuters living far from their workplace to do twice the return trips on a day. Therefore, those two trip chain types are excluded for commuters. Those assumptions change the probability distribution since some complex trip chain types now become simpler ones as depicted in the correspondence Table 8 in Appendix 5.

### Create trips

Each trip possesses a sector of origin, a sector of destination, a starting time, a duration, and a length. It is also characterized by a type: home to workplace, workplace to leisure, home to leisure and all opposite possibilities. The trip chain type assigned to each person determines the order in which trips of each type have to be created. The starting time is allocated according to the probability distribution of trips in Belgium per destination type through the time in the day (Cornelis et al., 2012) at the minute precision. Here again, the hypothesis that Brussels’ residents’ travelling behaviors have not changed significatively between 2014 and 2019 is taken. The comparison between Beldam 2012’s (Cornelis et al., 2012) graphs and Mobel80 graphs (Toint, 1999) indeed show no significant change (except the morning pic happening slightly later in 2012 than in 1999) in the temporality of the trips between 1999 and 2012 which lets think that it still has not changed. The probability distribution for the trips to a leisure place is the result of the weighted sum of all possible leisure presented in Beldam 2012 ((Cornelis et al., 2012) shopping, go to a service provider, for a meals, go to his family, go for a walk or leisure). Concerning the trips to the workplace, a difference is made between a trip to an actual work and trips to a school (including nursery, kindergarten, primary school, secondary and higher education). The probability distributions can be found on Figures 16 to 19 the Appendix 1.

When a trip involves the home place or the workplace, its geographic location is already determined. Nevertheless, it is not the case for the leisure places. The methodology applied to determine the leisure place is different from Pr. Kornhauser (Kornhauser et al., 2012) because those data were not available for Brussels. He indeed used the list of leisure places and defined patrons for the ratio of customers per employee per NACEBEL code. The process applied in this thesis is more deductive. To determine the sector of the leisure, the probability distribution of the length trips (Cornelis et al., 2012) is used. Knowing the sector of the origin of the trip and a length randomly pick according to the probability distribution, a list of possible sectors is easily determined. The exact sector of the leisure destination is then randomly picked from this list. Once again, the probability distribution used here corresponds to 2012 trips. However, between 1999 and 2012, the average trip length as changed from 12 km to 12,3 km which is not a big change (Cornelis et al., 2012).

Such as in Burns’ (2013) and Loeb & Kockelman’s (2019) simulations, all distances are computed as beelines from the centroid of the sector of the origin to the sector of the destination according to Equations 1 to 3 (Lafon, 2020). While the duration of the trip results in the division of this distance by the average car speed in Brussels: 23.7 km/h (Lebrun et al., 2013).

Equations 1-3 Haversine's formula for the computation of the distance (d) between two points on earth of latitude and longitude respectively and where is the Earth’s radius (6,373 km) (Environnement, durabilité et bien-être, 2021).

Thanks to this simulation, the Trips File is now ready. However, not all of those trips have to be considered for the aTaxis’ fleet simulation. First, the trips with the same sector as origin and destination were removed. Then, according to Monitor 2019 (Derauw et al., 2019), some of the remaining trips were done by walk or by bike. As depicted on the Figure 20 in Appendix 2, depending on the length of the trip a certain part is indeed done by walk or bike. Those trips have thus been removed has well prioritizing the shortest trips in the concerned length category to be assigned to walk or bike.

### aTaxis’ fleet simulation

The aTaxis’ fleet simulation follows Chen’s methodology (Chen 2016) and uses the same logic for the cleaning stations creation as the one presented for the charging stations creation. The cleaning stations are indeed added compared to Chen’s work (Chen 2016) as well as the pickup and drop off time following Burghout & Andréasson (2015).

As explained earlier, the territory of Brussels is divided in sectors. Each sector corresponds to an aTaxis’ station. This means that a user could in average have to walk 237 m corresponding to 3.23 minutes (Julien, 2021) in order to reach the station which is totally feasible and realistic. Charging and cleaning stations are also located at some of those aTaxis’ stations.

Three different simulations have been done:

* A simulation during the equivalent of one day (1440 minutes) considering only the trips with an origin and / or a destination in the municipality of Ganshoren forbidding empty rides;
* A simulation during the equivalent of one day (1440 minutes) considering only the trips with an origin and / or a destination in the municipality of Ganshoren allowing empty rides;
* A simulation considering all trips from the simulated Trips File (so the whole region of Brussels is considered) starting before 7.03 a.m. (423 minutes) forbidding empty rides;

The ideal would have been to do two full simulations during the equivalent of one day considering all trips from the Trips File one forbidding empty rides and the other one allowing them. Unfortunately, it would have taken more than one year to run because of the complexity of the script. That is why Ganshoren has been chosen. Ganshoren is the municipality with the fewest number of daily trips with an origin and / or a destination in its territory. It was thus possible to run the code on those trips.

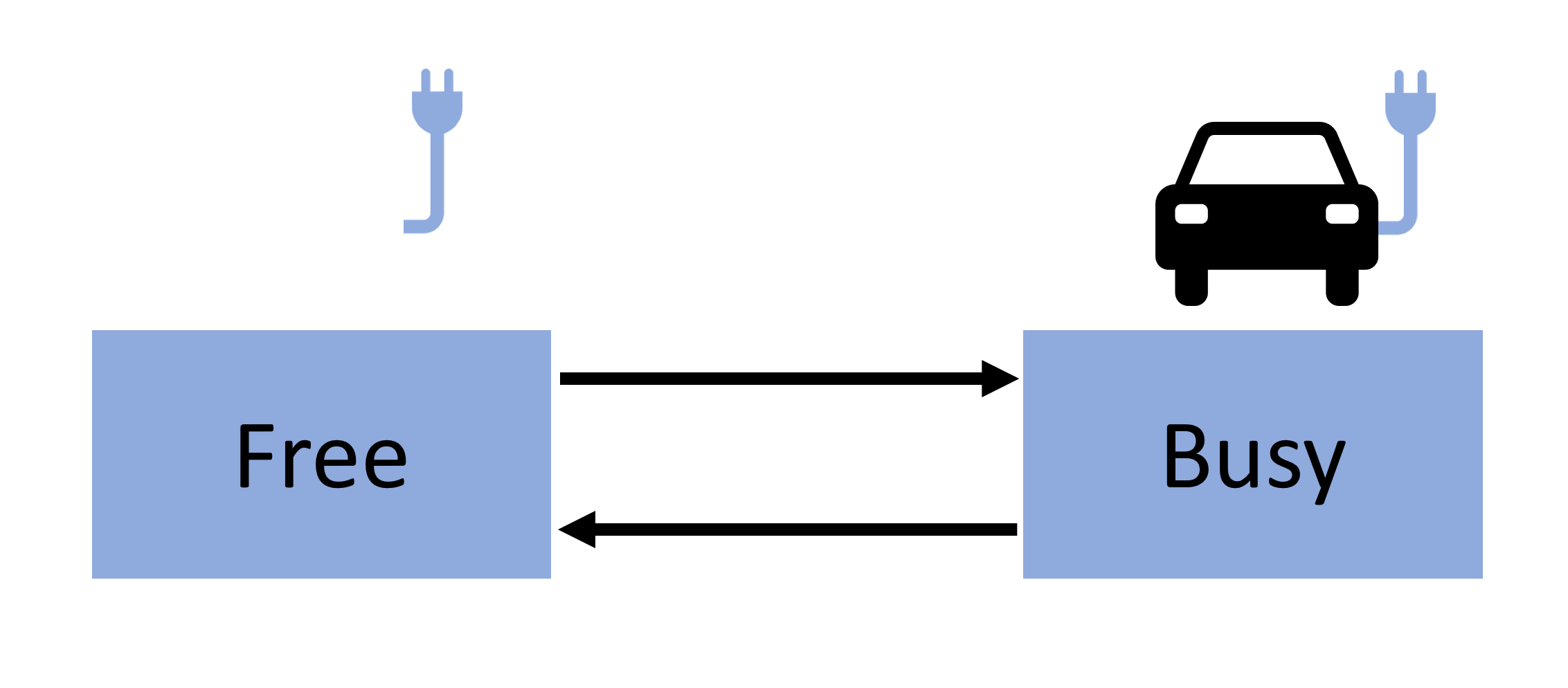
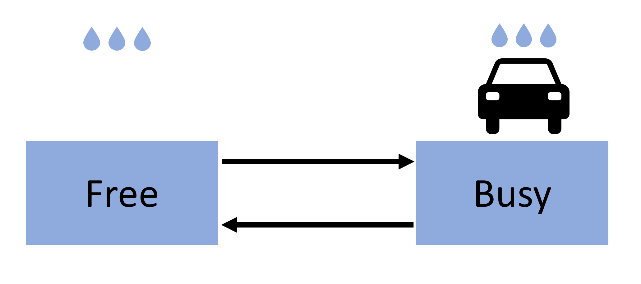


Figure 7 Possible charging stations' statuses and transitions.The arrows depict the possible transitions from one status to another one.

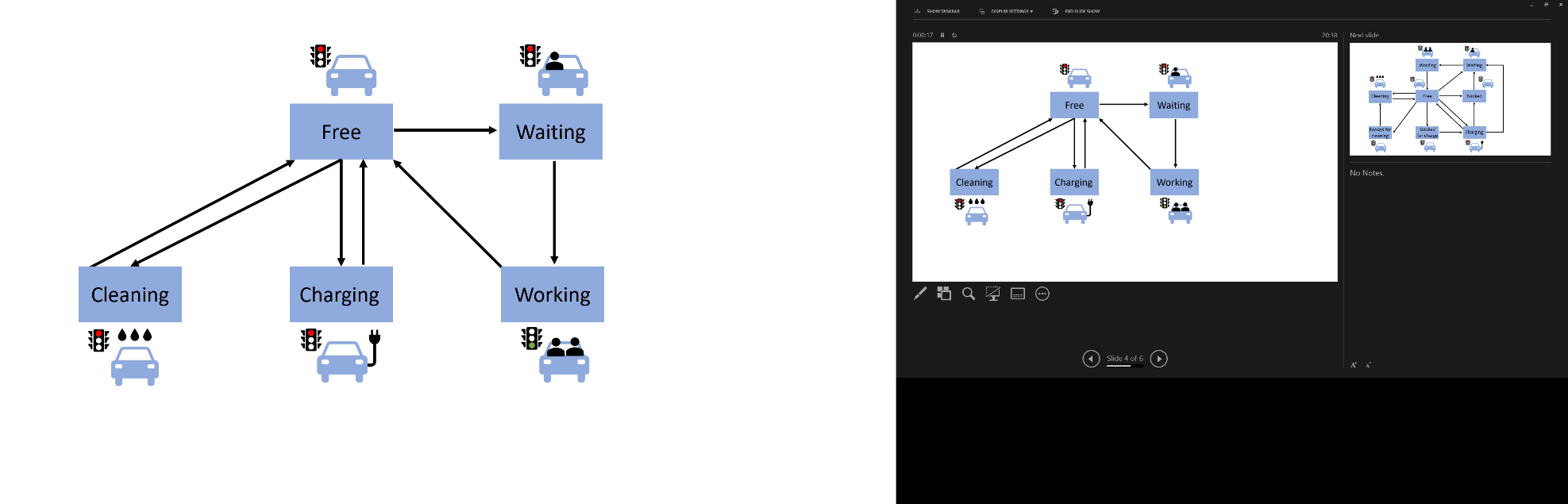
Figure 8 Possible cleaning stations' statuses and transitions. The arrows depict the possible transitions from one status to another one.

In each simulation, there are four different entities: the aTaxis, the charging stations, the cleaning stations and the requests. Each of them can have different status as shown on Figures 7 to 10. A request simply moves from unsatisfied to satisfied once its starting time arrives. On the one hand, charging and cleaning stations can either be busy – when an aTaxis is being charged or cleaned at this station - or free when there is no car at this charging or cleaning station. On the other hand, a taxi can have five different statuses when empty rides are forbidden:

* free: when empty at a station;
* waiting: when at least one passenger is onboard and waits for others to join;
* working: when travelling with its passengers to their destination;
* charging or;
* cleaning.

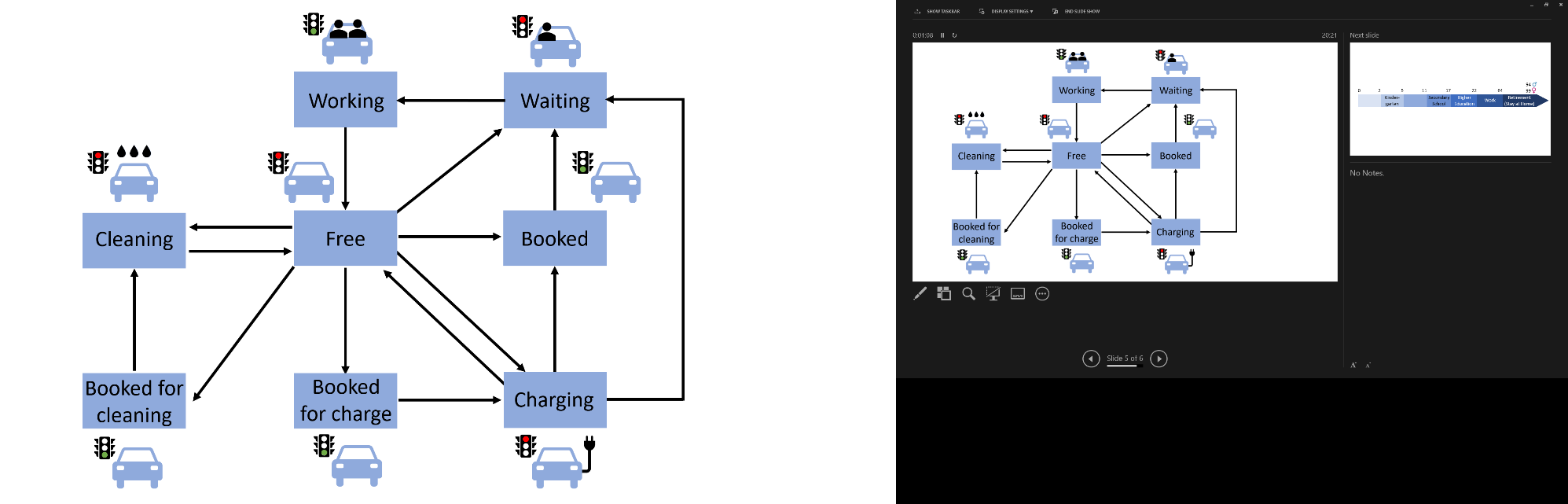
Figure 9 also depicts the possible transitions between those statuses. A free aTaxi can become waiting if he has accepted a request but it also can become charging if its battery is too low or cleaning if he already has realized forty trips since its last cleaning. While waiting, the aTaxi waits at least one minute corresponding to the pickup time and maximum five minutes and then becomes working. The pickup time allows the passenger to get into the car like proposed by Burghout & Andréasson (2015). However, the pickup time is two minutes in Burghout & Andréasson (2015). While some searchers have opted for the rejection of requests once the waiting time is above 10 minutes ((D. Fagnant et al., 2015), (Loeb et al., 2018), (Bösch, 2018)), this thesis always fulfill a request such as (Hyland & Mahmassani, 2018) within a maximum waiting time of 5 minutes. This corresponds to one of the scenarios of Burghout & Andréasson (2015). A working aTaxi only becomes free again once it reaches its destination and has allowed one minute as drop off time to its passengers. Similarly, to the pickup time, the drop off time allows the passenger to get out of the car (Burghout & Andréasson, 2015). This time, the drop off time is identical to Burghout & Andréasson (2015). A charging vehicle can stop its charge in order to fulfill a request such as proposed by Loeb et al. (Loeb et al., 2018). While a cleaning car can not because the aTaxi has to wait for the fifteen minutes of cleaning to be done. Of course, if a charging aTaxi is fully charged, it becomes free again and releases the station.

Figure 9 aTaxis' possible statuses and transitions in the scenario without empty ride. A red traffic light means that the aTaxi is not moving and staying at the station when in that status. While a green traffic light means the aTaxi is moving from one station to another one when in this status. The arrows depict the possible transitions from one status to another one.



In the simulation allowing empty rides, relocation was realized thanks to trips anticipation similarly to other researches ((Burghout & Andréasson, 2015), (Loeb et al., 2018), (Babicheva et al., 2019)). It is realistic to imagine that the aTaxis’ company would be able to perform some machine learning with the daily trips data in order to predict and anticipate the coming trips. Furthermore, the users should be able to book an aTaxi in advance, helping the dispatcher in this way. Each free or charging aTaxi checks whether there will be a request in the next forty minutes with sector of origin closed enough for the aTaxi to be there before the starting time plus the maximum waiting time. Forty minutes indeed represent longest possible trip duration in Brussels. If the SAEV can reach the origin station in time and has enough battery both in order to reach the origin and the destination, it receives a sixth status: “booked” and rides to the concerned station. Once at the station, it becomes waiting as in the simulation without empty rides. In this simulation, aTaxis can also realize empty trips in order to reach a charging or cleaning station. It then has respectively the status “booked to charging station” and “booked to cleaning station”. When a SAEV is booked – wherever he is going to – it can not abandon its original destination for another one. When a free aTaxi wants to charge (resp. clean) itself looks for the closest charging (resp. cleaning) station free. It is only if no charging (resp. cleaning) station on the entire territory is free that a new one is created. Figure 10 presents the resulting status and possible transitions for this simulation. When riding empty, the aTaxi also reaches the speed of 23.7 km / h (Lebrun et al., 2013).

Figure 10 aTaxis' possible statuses and transitions in the scenario with empty rides. A red traffic light means that the aTaxi is not moving and staying at the station when in that status. While a green traffic light means the aTaxi is moving from one station to another one when in this status. The arrows depict the possible transitions from one status to another one.



In each scenario, passengers can share ride with other users having the exact same station of origin, the exact same station of destination and a starting time difference inferior to the maximum waiting time. Those are strict rules forbidding any detour like Poulhès & Berrada (2019), Babicheva et al. (2019) and Berrada (2019). They have been chosen for sake of simplicity and running time. Up to five passengers can share a ride since the aTaxis are sedans cars such as many other studies ((Kornhauser et al., 2013), (Kornhauser et al., 2016), (Zachariah, 2013), (Bösch, 2018), (Wadud, 2017), (Loeb & Kockelman, 2019), (Poulhès & Berrada, 2019), (ITF, 2015), (Babicheva et al., 2019), (Azevedo et al., 2016)).

If no aTaxi can fulfill a request in time, a new aTaxi is created fully charged at the origin of the concerned trip. Identically, if a SAEV can not reach a charging or cleaning station among those free, a new station is created at the position of the SAEV. That is how the fleet is constituted and the stations created.

Some parameters are important in the simulation. The number of seats (5), the maximum waiting time (5 minutes) and the cleaning time (15 minutes in order to clean the inside of the car every forty trips (Bösch, 2018)) have already been aborded. However, parameters about the electric characteristics of the car are also important. The battery range in this simulation is 130 km and it takes four hours to fully charge the battery at a Level II charging station. Those hypotheses have been chosen because they allowed the achievement of the lowest costs despite increasing the total fleet and the number of charging stations required in the study of Chen (2016). Chen (2016) indeed has compared different scenarios with different battery range and charging stations’ power to come to this conclusion.

## Results

### Population simulated

The residents, commuters and tourists of Brussels have been recreated with their personal attributes (an age, a gender, a place of residence, a household type, a worker type, a place of work and a daily trips pattern, …).

The results obtained show too many (32,216) children with “collective” as household type. A child can not indeed be in prison or in nursing home. For children, a household type being collective thus means that he is at the hospital. However, only 510 beds (IBSA, 2019c) in total are available for children in the hospitals of Brussels. Therefore, the “too many” “collective” children have been reassigned to households with some children.

Furthermore, the whole population contains 1,320,941 people while in reality there should be only 1,205,395. The difference of 9.59% comes mainly from the number of youngers aged between 15 and 19 years living in couple without children. Because of the lack of specific data, the methodology resulted in a number of youngers aged between 15 and 19 years living in couple without children ten times higher than youngers aged of 20 years. Ninety percent of the youngers aged between 15 and 19 years living in couple have been removed.

The final simulated population thus corresponds to the input data used and is composed by 1,224,645 people. This represents an overpopulation of 1.57% which is negligible. Excluding the “collective” households, the residents are spread among 542,706 households compared to 548,365 households in reality. The difference of 1.03% is negligible and explained by the “collective” households. The simulation has also created 428,486 commuters living outside Brussels and working (resp. studying) in Brussels. When comparing the number of students commuting in kindergarten in the simulated population (14) to the IBSA numbers (IBSA, 2019d) (4,557), there is a big difference. The same conclusion is observable for primary school (41 V.S. 10,410) and in secondary school (265 V.S. 18,635) students (IBSA, 2019d). This represents an error of 7.7.% in the total number of commuters and could be subject of improvements.

There is not much more data which can be used as validation because all statistics available and pertinent found by the author have been used as input in order to have very detailed simulated population. Of course, at each step, it has been checked that the statistics used as input are still represented and right in the output.

### Trips simulated

In total, 3,411,960 trips have been created. This represents 2.1 trips per person per day in average. This number is inferior to the 2.4 presented in Beldam 2012 (Cornelis et al., 2012). Even when excluding the 310,933 immobile people from the computation, the results remain inferior to Beldam’s (2.5 V.S. 3.3) (Cornelis et al., 2012). This means that the total number of trips is underestimated in this simulation. It can be explained by the fact that not all trips of commuters are counted here since they do not happen in the territory of Brussels.

The Figure 11 depicts the lengths’ distribution of the simulated trips and compares them to Monitor 2019 results (Derauw et al., 2019). As a remainder, Monitor 2019 considers trips happening in the whole Belgium (Derauw et al., 2019) while this simulation only focuses on trips happening inside Brussels. Moreover, Monitor 2019’s trip length distribution (Derauw et al., 2019) has been used as input in order to determine the leisure places but is not involved in the length of trips between the home and workplace (cf. section XI.B.3.). Figure 11 shows no big difference for trip lengths inferior to 5 km. However, the trips with a distance between 5 and 10 km are much more represented in the simulation than in Monitor 2019 (Derauw et al., 2019). The opposite conclusion can be drawn on the trips longer than 10 km. It can be explained by the fact that Monitor 2019 considers the whole Belgium. There are probably more long trips happening outside Brussels than inside Brussels. Nevertheless, the average trip length for the Trip File (6.42 km) is far inferior than the average length on for trips in Brussels presented in Monitor 2019 (Derauw et al., 2019) (14 km). However, Derauw et al. (2019) do not specify whether the length considered is the length of the whole journey (including the distance travelled outside the territory of Brussels) or only the travelled distance inside Brussels. This could explain the difference. Brussels environment indeed also states an average trip length of 6 km (Odile, 2014).

Figure 11 Comparison of the trip lengths distribution in the simulated Trips File and Monitor 2019 (Derauw et al., 2019)

According to this simulation, 21,914,643.94 km are travelled every day in Brussels. It is 7.2% less than reported by (Kwanten, 2017). It confirms that the number of trips (total and average per person) is underestimated by this simulation.

### aTaxis’ fleet simulation

#### Impacts of the authorization of empty rides

The results of the simulations in the territory of Ganshoren are depicted in the Table 1. Allowing empty rides reduces the number of aTaxis by 74.12% and the number of charging stations by 19.68% while increasing the total travelled kilometer by 40.34%. Empty rides allow aTaxis to do much more trip on average (12.68 V.S. 3.29).

The charging time is reduced because taxis are more often working or doing an empty ride as seen when comparing Figures 12 and 13. In the simulation forbidden empty rides, the aTaxis charge even if it is not “really” needed simply because they can not do anything else. Therefore, they charge themselves to be sure not to have to decline a request because of a too low battery level. Figure 13 also demonstrates that the use of aTaxis a more efficient with empty rides. There are indeed far less free aTaxis through the whole day. It is worth noting that a big part of the SAEVs is booked (either to fulfill a request or to reach a charging station) confirming the high number of traveled kilometers while empty.

The quality of the service seems very good in both cases. A user indeed only has to wait 6 and 9 seconds in average before living with his aTaxi to his destination. Moreover, users have seldom to share their trips with strangers since the average number of passengers per trip is 1.08 in both cases.

As expected, Figures 14 and 15 depict the inefficiency of forbidding empty rides. In the scenario with empty rides, the charging stations are nearly always busy. On the contrary, when forbidding empty rides, more new stations are created to fulfill the need of the aTaxis unable to move, resulting in a majority of free stations through the whole day.

In both cases, no cleaning stations have been created because no aTaxi has reached forty trips during the simulation time (the equivalent of one day). Cleaning costs will nevertheless be considered as explained in section XII. Furthermore, the financial impacts of allowing empty rides will also be discussed in that section.

|  |  |  |
| --- | --- | --- |
|  | Ganshoren with empty rides | Ganshoren without empty rides |
| Number of aTaxis | 1,532 | 5,920 |
| Number of cleaning stations | 0 | 0 |
| Number of charging stations | 1,392 | 1,733 |
| Average number of travelled km per aTaxi when working | 79.15 | 20.56 |
| Average empty km per aTaxi (km) | 32.35 | 0 |
| Total empty km (km) | 49,553.68 | 0 |
| Total travelled km (km) | 170,811.48 | 121,715.20 |
| Average number of trips per aTaxi | 12.68 | 3.29 |
| Average charge time (min) | 7.01 | 38.13 |
| Total charge time (min) | 10,739 | 225,729 |
| Average waiting time per person (min) | 0.15 | 0.1 |
| Average number of people per trip | 1.08 | 1.08 |
| Average person-km per aTaxi | 90.73 | 23.48 |
| Total person-km | 138,998.20 | 138,998.20 |

Table 1 Ganshoren Simulations Results whole day

Figure 12 aTaxis’ status through time of the day in the Ganshoren simulation without empty rides whole day

Figure 13 aTaxis’ status through time of the day in the Ganshoren simulation with empty rides whole day

Figure 15 Charging stations' status through time of the day in the Ganshoren simulation without empty rides whole day

Figure 14 Charging stations' status through time of the day in the Ganshoren simulation with empty rides whole day

#### From Ganshoren to Brussels

Table 2 summarizes results obtained at 7.03 a.m. (423 minutes after midnight) for Ganshoren and the whole territory of Brussels. The ratio represents the part of the results for Ganshoren at 7.03 a.m. from the results for the whole day. Those are the ratios used to get Brussels results for the whole day in Table 3. Note that those results do not allow empty rides. The results observe in the section XI.C.3.a are thus applied to get the results for Brussels with empty rides. Using Ganshoren results as a proxy to get the results for the whole region of Brussels while it only represents 1 % of the total number of trips can seem a big simplification. However, it is common in the literature to run the simulation on a so small part of the demand Chen et al., 2016, Loeb et al., 2018.

|  |  |  |  |
| --- | --- | --- | --- |
|  | No empty ride | | |
|  | **Brussels until 423** | **Ganshoren until 423** | **Ganshoren whole day** |
| Number of aTaxis | 70,532 | 1,165 | 5,920 |
| Number of cleaning stations | 0 | 0 | 0 |
| Number of charging stations | 14,807 | 222 | 1,733 |
| Average number of travelled km per aTaxi when working | 9.85 | 5.8 | 20.56 |
| Average empty km per aTaxi (km) | 0 | 0 | 0 |
| Total empty km (km) | 0 | 0 | 0 |
| Total travelled km (km) | 694,740.2 | 6,757 | 121,715.2 |
| Average number of trips per aTaxi | 1.52 | 0.83 | 3.29 |
| Average charge time (min) | 11.05 | 10.03 | 38.13 |
| Total charge time (min) | 779,222 | 11,684 | 225,729 |
| Average waiting time per person (min) | 0.51 | 0.23 | 0.1 |
| Average number of people per trip | 2.16 | 1.31 | 1.08 |
| Average person-km per aTaxi | 23.57 | 8.96 | 23.48 |
| Total person-km | 1,662,611 | 10,444 | 138,998.2 |

Table 2 Simulation results until 7.03 a.m. (423 minutes from midnight) Brussels and Ganshoren without empty rides

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | No empty | | | | | Empty | | |
|  | **Bxl 423** | **Gans. 423** | **Gans. day** | **Ratios Gans. day / 423** | **Bxl day** | **Gans. day** | **Ratios Gans. empty / no empty** | **Bxl day** |
| Number of aTaxis | 70,532 | 1,165 | 5,920 | 5.08 | 358,412 | 1,532 | 0.26 | 92,751 |
| Number of charging stations | 14,807 | 222 | 1,733 | 7 .81 | 115,588 | 1,392 | 0.80 | 92,844 |
| Total travelled km (km) | 694,740 | 6,757 | 121,715 | 18.01 | 12,514,495 | 170,812 | 1.40 | 17,562,469 |
| Total charge time (min) | 779,222 | 11,684 | 225,729 | 19,32 | 15,054,177 | 10,739 | 0.05 | 716,199 |
| Total person-km | 1,662,611 | 10,444 | 138,999 | 13.31 | 22,127,532 | 138,998.2 | 1 | 22,127,532 |

Table 3 Computation table from 423 minutes to the whole day for the whole territory of Brussels (Bxl) based on Ganshoren (Gans.) results. The blue columns are the results used in the costs computation and profitability analysis.

As shown in Table 3, the total number of aTaxis needed is respectively 358,412 (no empty rides) and 92,751 (with empty rides). Currently 365,000 vehicles drive every day in Brussels (Odile, 2014). aTaxis would thus lead to a decrease of the number of vehicles of 1.8% only if empty rides are forbidden. However, this number rockets to 74.59% once empty rides are allowed. This last reduction falls in the range described by the literature (between (Zhu, 2016) and 95% (Burghout & Andréasson, 2015) as explained in section IX.C.). Furthermore, the total number of kilometers travelled does not increase as observed by searchers (ITF, 2015), (D. J. Fagnant & Kockelman, 2014), (Chen et al., 2016). This thesis would rather aligned with the conclusion on the total number of travelled kilometers of (Ma et al., 2017). This observation could be explained by the ride sharing.

# Costs analysis

The costs analysis follows the methodology of Chen et al. (Chen et al., 2016) while adding the cleaning costs and all “administrative” costs linked to the company management. Chen et al. (Chen et al., 2016) indeed describe vehicles’ costs and then fixed and variable costs due to the charger. All costs per km are summarized in Table 4 both for the scenario allowing the empty rides and the one forbidding them. The convention in the field is to present cost per km to facilitate comparison between studies. The shift from per kilometer values to per year values is easily achieved by a simple multiplication by the total number of kilometers traveled per year respectively 12,514,495 km (without empty rides) and 17,562,469 (with empty rides).

|  |  |  |
| --- | --- | --- |
|  | Costs (€ / km) without empty rides | Costs (€ / km) with empty rides |
| Vehicle Capital (Total) | 0.543 | 0.152 |
| Non-autonomous electric vehicle | 0.448 | 0.108 |
| Autonomous premium | 0.095 | 0.023 |
| Battery replacement | 0.000 | 0.022 |
|  |  |  |
| Vehicle operations (Total) | 0.240 | 0.068 |
| Maintenance | 0.029 | 0.029 |
| Insurance | 0.212 | 0.039 |
|  |  |  |
| Electricity (Total) | 0.025 | 0.025 |
|  |  |  |
| Charging infrastructure (Total) | 0.026 | 0.015 |
| Level II charger | 0.025 | 0.014 |
| Maintenance | 0.001 | 0.000 |
|  |  |  |
| Cleaning Costs (Total) | 0.017 | 0.003 |
| Outside cleaning material | 0.003 | 0.001 |
| Outside cleaning workforce | 0.014 | 0.003 |
| Inside cleaning material | 0.000 | 0.000 |
| Inside cleaning workforce | 0.000 | 0.000 |
|  |  |  |
| Administrative Costs (Total) | 0.410 | 0.076 |
| Workforce | 0.393 | 0.072 |
| Office | 0.013 | 0.002 |
| Office material | 0.005 | 0.001 |
| Abonnements | 0.000 | 0.000 |
|  |  |  |
| Total | **1.262** | **0.339** |

Table 4 aTaxis Company Costs per kilometer

The vehicle capital costs are computed based on an electric non-autonomous vehicle with five seats price on top of which an autonomous premium is added (Chen et al., 2016). The reference car is comparable to a Nissan LEAF or a Ford Focus Electric BEV (Chen et al., 2016) which price is about 40,000 € (Nissan, 2021), (Automobile Propre, 2021). As stated by Schultz (Schultz et al., 2014), the autonomous premium is 10,000 $ which corresponds to 8,500 € (with the change rate on the 30th July 2021 (Exchange-Rates.org, n.d.)). The aTaxi’s lifespan is approximated to 372,000 km (Chen et al., 2016) which represents 29.19 years (no empty ride) and 5.38 years (with empty rides) in our simulations. The Belgian law forbids a taxi to ride more than 7 years (29 MARS 2007. - Arrêté du Gouvernement de la Région de Bruxelles-Capitale relatif aux services de taxis et aux services de location de voitures avec chauffeur., 2007). In the case without empty ride, the life span is thus caped at 7 years. However, in the case allowing empty rides, the lifespan is inferior to seven, thus it does not matter. According to Chen et al.’s (2016) assumptions, the battery must be replaced after 185,900 km. It thus never happens in the scenario without empty rides while it happens once in the car’s life when empty rides are allowed. This replacement costs amount to 8,160 € per vehicle. In a nutshell, capital vehicle’s cost reach respectively 0.543 € / km (no empty ride) and 0.152 € / km (with empty ride).

The scenario without empty rides results in higher vehicles’ costs due to the limit of seven years in the lifespan of the aTaxi. As a consequence, the total number of kilometers travelled by the aTaxi during its life is reduced increasing the costs per kilometer.

The vehicle operations’ costs gather maintenance and insurance costs. Chen et al. (2016) affirm that maintenance costs are 0.055 $ / miles which is worth 0.028 € / km. Following Chen et al. (Chen et al., 2016) and Burns et al.’s (Burns et al., 2012) hypotheses, the insurance cost of an aTaxi is 2.5 times the normal insurance cost for a non-autonomous car travelling more than 20,000 km per year (1,079.5 € in average (assurance.be, 2021)). Brought back to a per kilometer basis, the insurance costs represent respectively 0.212 € / km and 0.039 € / km.

The aTaxis considered in this simulation consume 0.1 kWh / km (Selectra, 2019) and the electricity price is 0.25 € / kWh (Selectra, 2019). This means that the vehicle’s fuel costs 0.025 € / km.

Concerning the charging infrastructures, one Level II charger costs 10,000 € ((Chang et al., 2012), (Clean cities, 2021) and has a lifespan of 10 years (Chang et al., 2012). It also requires maintenance costs of 32 € / year (Clean cities, 2021). Given that respectively 115,588 and 92,844 chargers are required in Brussels depending on the scenario, the total costs due to the charging infrastructures amount to 0.026 € / km and 0.015 € / km.

Furthermore, the cleaning costs are considered in two different ways: the seldom outside cleaning and the recurrent inside cleaning. On the one hand, the outside cleaning only happens six times a year (Creatests.com, 2015) and lasts 1 hours per car. The costs associated to it are the water and products needed (6.3 € per cleaning in average (Creatests.com, 2015)) and the workforce. The workforce corresponds to the average gross wage in Brussels, 4,156 € / month (Service Public Fédéral Belge, 2019c) broken down to an hourly wage. On the other hand, the inside cleaning is done every forty trips (Bösch, 2018) and lasts fifteen minutes. It requires less materials than the outside cleaning explaining that the average cost per cleaning is only 2 €. The same hourly wage as for outside cleaning is used to compute the workforce costs associated to the inside cleaning. The aTaxis realize on average less than forty trips per day. Therefore, even the inside cleaning is a seldom event. It happens once every twelve days when empty rides are forbidden and every three days when they are allowed. Simply put, the whole cleaning costs represent 0.017 € / km (no empty ride) and 0.003 € / km (with empty ride).

Finally, the administrative costs linked to the company in itself are tackled. In order to determine the number of employees needed, the ratio of employees per car in the fleet of the car sharing company Cambio in Brussels has been used (0.09 employees per car) (Cambio Brussels, n.d.-a), (Cambio Brussels, n.d.-b). Keeping the same gross average wage in Brussels as for the cleaning costs (Service Public Fédéral Belge, 2019c), adding laptops, phones (with a lifespan of 3 years) and phone abonnement costs, this represents 1,300 € per year per employee. Even if there is more and more homeworking, an office is needed and costs 175 € per year per square meter (RG Invest, n.d.). According to "Direction de l’information légale et administrative (Premier ministre)" (2020), a space of 10 m² per employee is needed. This leads to office’s costs of 58,076,010 € / year (no empty ride) and 15,029,097 € / year (with empty rides). The total administrative costs thus reach 0.410 € / km (no empty rides) and 0.076 € / km (with empty rides).

In summary, all costs considered, an aTaxi in Brussels costs in average 1.262 € / km in the scenario forbidding empty rides and 0.339 € in the scenario allowing them. It is higher than the costs found by Chen et al. (2016) (0.218 € /km). It is normal since new costs have been added compared to Chen et al.’s analysis. However, even while subtracting those new costs, the costs remain higher. It is due to higher costs of insurance. As stated by Loeb & Kockelman (2019), the insurance costs remain highly uncertain explaining this difference.

# Pricing and profitability analysis

The costs are now known and can be used to determine the minimal price to ask to the users for the company to be at least break even. Table 5 gathers all pertinent variables. Without any surprise, the scenario without empty ride requires a higher price. Besides the higher number of total kilometers travelled, the scenario with empty rides remains cheaper.

|  |  |  |
| --- | --- | --- |
|  | No empty ride | With empty rides |
| Costs per km (€) | 1.262 | 0.339 |
| Total travelled km per day (km) | 12,514,495 | 17,562,469 |
| Total pers km per day (km) | 22,127,532 | 22,127,532 |
| Price per km to be breakeven (€) | 0.714 | 0.269 |

Table 5 Profitability analysis

When compared to the prices found in the literature, prices resulting from these simulations are higher (0.084 € / km (Johnson, n.d.), 0.079 € / km (Burns, 2013), 0.141 € / km (Bösch, 2018)) than the majority of then. Nevertheless, it is in the average fare raised by Berrada (2019). These differences can notably be explained by the new costs included in the analysis.

The current price for a classical taxi trip in Brussels is 1.8 € / km (Taxis Verts, 2019) while with an uber it is approximately 1.25 € / km (Ubertarif, n.d.), (Lesage, 2019). aTaxis are thus far cheaper than current taxis. However, in this scenario were aTaxis have to fulfill all travel needs in Brussels, the average cost per user per year reaches 3,511.64 € per year (no empty ride) and 1,322,51 € per year (with empty rides). Currently, the average yearly budget per person assigned to traveling expenses is 1,219.84 € (IBSA, 2019a). The scenario without empty ride thus seems unrealistic. The scenario with empty ride represents an increase of 8.42%. This could maybe be accepted by the population given all others non-monetary advantages resulting from SAEVs. It remains nevertheless to be verified.

# Discussion and limitations

## Possible improvements

The quality of this work relies mainly on the data used. The more specific are the data the more accurate is the simulation. If sometimes the data available are really specific such has the flow of workers (Service Public Fédéral Belge, 2017a), some parts of the simulation (notably data on students in the Dutch higher education) have required many hypotheses because of the lack of data. Also, all data were not available at a statistics sector level and had to be broken down using the population ratio losing some accuracy. This population ratio could be more specific, adapted to the age category for example. Furthermore, the random assignment reducing the accuracy was used a lot because of this lack of data.

While determining the number of single fathers, the age has been assigned randomly. It could have been more accurate if the real probability distribution was accessible. A distribution could also have been created based on the known average age difference between a father and his child (36 years (Service Public Fédéral Belge, 2019b)). On the other hand, when a child was assigned to a mother, the probability distribution of the age difference was available. However, only the distribution of 2019 has been used while the distribution used should have been dependent on the child’s birth year. Furthermore, the assignment of the gender to a child follows a simple random rule while it could have been based on the gender ratio in the concerned sector or at least in the whole territory of Brussels.

In other to establish the number of students with some delay on their study path, the total number of children with delay in primary (resp. secondary) school has been divided by the six years of this part of the path. Nevertheless, it means that all people repeating a year, repeats the first year of the part in question and keep their delay for the rest of the section. In reality, there is kind of an accumulation with less students with delay in the beginning of the section and with some different children repeating each year. Moreover, once in first year of secondary school, the number of children already having redoubled in primary school should be taken into account.

For the sake of simplicity, all simulated couples are hetero couples. This does not have any impact on the fleet sizing since every household is created at a sector level and not at a real address level. It is thus aggregated. However, it could be improved for readers interested in the household simulation. One could simply invert two household ids in order to create homo couples.

For the reallocation of the too many children with a collective household type, the age difference between the new parents and the child is not taken into account. This could be an improvement. For now, it could indeed result in unrealistic age difference.

For the workplace assignment of people living in Brussels but studying or working outside Brussels, the closest sector being on the periphery of Brussels to their sector of residence was selected. The opposite was done for commuters living outside Brussels but studying or working in Brussels. However, the real direction to the final destination could have been used for more accurate itineraries.

For the creation of commuters living outside Brussels but studying or working in Brussels, many personal attributes have been ignored because they had no impact on the rest of the simulation in order to generate the trips file. Nevertheless, it could have been useful for readers interested in the resulting simulated population.

Concerning the tourists, this was understood at a broad level gathering business trips and holiday together. However, it seems obvious that the daily trip of a holidaymaker and a businessman are not the same. A difference could thus have been done if the trip chain type allocation depended on the work id like in Pr. Kornhauser work (Kornhauser et al., 2012). Nevertheless, this broken-down data was not available in Belgium. It would for sure improve the simulation’s quality for every person simulated. It is indeed logical to think that a baby or a young child does fewer daily trips than a higher education student.

The tourists’ trips from and to a train station or an airport at the beginning and the end of their trip could also have been considered in itself.

With more specific data and more computing power, the analysis could be done at a more specific level even up to the household level. This would give even more realistic results and avoid the users to walk to a station.

During the trips simulation, the temporality is just considered for the trips to be in the right order according to the trip chain. However, it can result in some very short activities because two following trips are close. It could have been improved by incorporating information on the activities’ length per type of activity.

Moreover, the leisure’s’ destinations are determined based on the travels’ length probability distribution. Nevertheless, this distribution concerns all types of trips not only the ones to a leisure place. In the absence of an own probability distribution for leisure’s’ trips only, a probability distribution of the simulated trips to home and work should have been deduced from this probability for more accurate results.

The leisure’s destinations could have been better defined if the same data as those used by Pr. Kornhauser were available. He indeed used the list of leisure places and defined patrons for the ratio of customers per employee per NACEBEL code. The exact position of the leisure places could have been determined with Open Street Map (OpenStreetMap, n.d.) for example. However, being an open source and maintained by a community database, Open Street Map data for Brussels were not complete and cleaned enough. On another note, data on the number of clients per leisure place could have been determined based on the average daily revenue of the place. Unfortunately, this data was not accessible either.

Trips’ distance is computed such as the crow flies. Using the actual roads with Google Maps (Google, 2021) data for example would be more accurate. Same for the speed, only an average speed is used while, in reality, it varies from road to road. The reduction of the number of cars on the road and the fact that all of them are autonomous will probably also impact the average speed.

Also, public transports are nonexistent in the scenario studied. However, it is probably more efficient to keep some autonomous public transport. This improvement can be tackled by including different sizes of vehicles. Nevertheless, multimodality must then be considered.

For the aTaxis fleet simulation to be more accurate, the drop off time could be proportional to the number of passengers who were onboard. It indeed takes more time for four users to get out of the car than it takes to only one.

In this simulation, the charging speed of SAEVs is constant. However, like a phone, a car charges faster when the battery is emptier and takes much more time to reach 100% full. Implementing a charging speed dependent on the battery level would be more realistic.

The relocation method in the simulation is based on the anticipation with a time window of forty minutes. The results could maybe be improved if this time window was expanded. Other relocation strategies could also be tried and compared with this one.

The results here probably overestimate the real number of aTaxis needed because all charging stations, cleaning stations and aTaxis have been created in one simulation of one day. To be more accurate stations should have been created thanks to a first simulation. Then aTaxis should have been generated. Finally, the simulation should run during the equivalent of several days in order to get the characteristic numbers (mainly for the simulation with relocation).

The whole process of simulation should have been repeated several times in order the aggregate the results and assess their stability. There are indeed many random allocations which should be demonstrated as stable.

Another important improvement is to make the code run faster. The whole simulation from the population creation to the fleet sizing indeed takes about ten days to run and many limitations of the fleet simulation are due to this high computation time. On one hand, improvements in the Python code are possible. On the other hand, Python is easy to use but maybe not the best programing language for simulations with so big databases. Translate the code to C++ or Java would probably make it more efficient.

## Future researches

The autonomous vehicles are seen by many as the future and this paper is a first look on its implementation in Brussels. However, AVs impact many sectors and raise many questions. It can be attacked from so many angles; justifying was this section of further possible researches is so long.

Now that the population simulation, the trips file and a first simulation of the behavior of an aTaxis fleet have been done, those can be used for further studies. On the one hand, other analysis can be done on the simulated population. On the other hand, other simulation projects can use the trips file.

One could also work on the prediction of the population in 2030 and run the aTaxis simulation with those new data in order to compare the results obtained with those presented in this thesis.

Furthermore, one could want to visualize all trips from the trips File. Depending on the time, a dynamic visualization of the trips on a real map of Brussels would be useful. This thesis affirms that the total number of vehicles needed in order to satisfy all trips in Brussels is inferior to the current total number of cars riding and that it will thus result in less congestion. However, this dynamic visualization could shed light on some roads congested during peak hours. It could thus lead to other improvements of the simulation.

One could analyze the impact of allowing empty travels with different price penalties. Different parking scenarios could also be study. The inspection of a scenario where all charging and cleaning stations are outside the city could provide valuable conclusions.

Even if charging and cleaning stations are inside the city, far fewer parking spaces will be required since an autonomous taxi can simply drop off a passenger and leave with another one or to another one (if empty trips are allowed). There will also be less vehicles on the roads. Thus, the public space assigned to vehicle could be reduced and reallocated to other use. Our complete environment could be changed. The question arising is how this new environment would be. That could be the topic of another study.

In this thesis, the cleaning is done by humans because automatic carwash would be far too expensive. However, these different hypotheses should be studied in a scenario where empty trips are allowed. Moreover, studies could be conducted in order to develop self-cleaning cars or cheaper autonomous cleaning stations.

In this scenario, children and babies used the aTaxis alone. One of the advantages of AVs is indeed that it gives travel freedom to people unable to drive. However, even if it does not drive, it seems dangerous to let a child alone in a car. Solutions still have to be found in order to give the possibility to the parents not to go with their child but insuring the child is safe.

Brussels Mobility has conducted a multimodal strategic model of the travel for IRIS called MuSti (Camelbeeck, 2018). Unfortunately, the author of this thesis has not been able to access it. However, it would be interesting to compare the results obtained in the Trip File with those of MuSti.

The aTaxis simulation allows now to try more exotic scenarios. One could try different pricing plan such as abonnements, a fix price per trip plus a variable part depending on the number of kilometers traveled, a regressive price depending on the number of people sharing the aTaxi, a pricing system where the passenger can pay more in order to have priority on the road and reach quicker his destinations, or as proposed by Chen et al. (2016), a dynamic pricing penalizing trips resulting in longer relocation miles, … The scenarios are limitless. Nevertheless, it would be interesting to add a demand sensibility analysis dimension to those studies. It is not indeed because one can imagine an exotic scenario that customers will adopt it. A pricing elasticity analysis could be conducted in this purpose.

The pricing plan is one of the economic aspects of the study which can be further developed. However, it is not the only one. The market type can also be simulated differently. Here only a monopoly has been considered. It would be interesting to study the impact of have more than one aTaxis provider in Brussels.

One could inspect the impact of the introduction of autonomous vehicles on the overall welfare of all stakeholders including users and the company but also citizens and the government such as Berrada has done in his doctoral thesis on autonomous cars in Paris (Berrada, 2019).

The insurance industry will be disrupted by the introduction of autonomous vehicles. A specific analysis on the impacts and possible adaptations of this sector to this disruption could be led. Moreover, the well-known question of responsibility in case of accident can also be undertaken.

The charge of SAEVs can lead to overload on the power grid. This is a problem which needs to be tackle and is worth more analyses.

Another aspect which is not studied in this paper, is the opportunities of vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication. In the exotic scenario proposed above where the price depends on the speed of the aTaxi, or simply for emergency vehicles, it could be imagined that vehicles communicate and adapt their itinerary in order to let the priority to such vehicles. On their side, infrastructures warned by the vehicles would make sure that all traffic lights are green when those vehicles arrive near them.

Another simplifying assumption applied in this thesis is the unique aTaxis size (5 seats). The study of the impact of having different sizes of vehicles in the fleet would certainly result in a better profitability. Other parameters impact could be examined like the vehicles’ battery range and the charge speed.

To be even more futurist, one could reproduce the study with charging roads such as those currently developed by Electreon (Huvelin, 2020). This would probably reduce the costs and improve the profitability of aTaxis in Brussels.

This thesis focuses on trips inside Brussels. Nevertheless, it could be interesting to extend the analysis to all trips happening in Belgium. Such a study will probably highlight the differences between urban and rural areas.

Moreover, this thesis jumps ten years ahead once the new environment is set up. However, the transition phase could be studied. Autonomous cars and non-autonomous cars cohabitation is an interesting environment with different impacts on the traffic, the safety and the pollution than an environment where only autonomous vehicles ride (Auld et al., 2017). Also, the last years have seen ZipCar, DriveNow and other carsharing companies leaving Brussels because the Belgian were not ready to jump for the change from owning to sharing (Berckmans, 2019), (RTBF, 2020). One could look deeper in this topic and analyze why and the solution to this obstacle to aTaxis.

Furthermore, this thesis only takes people transport into consideration. Another study could focus on the freight transport by autonomous trucks. Then, both studies could be gathered. More specific analyses on the congestion and pollution resulting from those autonomous vehicles in Brussels could then be conducted.

Finally, after all those studies, one could want to launch a company to manage this whole new transport system. Then new questions arise. One could focus on how to set up this environment, studying if a new player can start this project or whether existing players in the vehicle industry are better placed. A comparison between a public company and a private company can be conducted including the investigation of possible subsidies.

# Conclusion

The goal of this thesis is to assess the profitability of a service provider managing a fleet of shared electric autonomous vehicles with ride sharing (SAEVs) fulfilling all motorized travel needs in the region of Brussels, Belgium. In the scenario depicted in this paper, autonomous taxis (aTaxis) are the only motorized means of transport: no more private cars and no more public transports.

To begin, a literature review has demonstrated the advantages of AVs. AVs will remove accident caused by human error meaning 95% of the current number of accidents. The AVs are thus safer. They also allow the passengers to kind of time since the travel time henceforth becomes efficient time. Moreover, the trips last less time because SAEVs decrease traffic jams. However, some searches do not agree with this last statement. Furthermore, the congestion reduction and AVs’ better way of driving result in a reduction of fuel consumption and greenhouse gas emissions. SAEVs are thus cleaner. They can be even more green if the electricity is produced thanks to renewable energies. Finally, city space will be transformed by the introduction of AVs. It will indeed reduce the need for parking spot by 85% freeing some space for new allocations.

This thesis then presents the creation of the population file gathering personal attributes of all residents, commuters and tourists traveling in Brussels. This population file has confirmed depicting well the population while underestimating the number of commuters by 7.7 %.

From this population simulation ensues the trip file. This file gathers all average daily trips happening in Brussels. Comparisons with literature results have highlighted an underestimation of the total number of daily trips while confirmed their right spatial repartition.

The simulations of the aTaxis fleet needed to fulfill the needs of travels in the municipalities has permitted to investigate the impact of allowing empty rides. Without any surprise, authorizing empty rides increases the efficiency of the fleet. It indeed reduces the number of aTaxis by 74.12% and the number of charging stations by 19.68%. Nevertheless, it increases the total travelled kilometer by 40.34%.

Results for a shorter period of time (423 simulated minutes) have been studied for the whole territory of Brussels. Using results from the Ganshoren’s simulations, the values of pertinent variables (number of aTaxis, number of charging stations, the number of kilometers traveled, …) have been extrapolated to get values for a whole day in the whole territory of Brussels. The conclusions on this simulation are aligned with the literature. A total number of 358,412 aTaxis and 115,588 charging stations are needed to fulfill the needs of the people traveling in Brussels in the scenario forbidding empty rides. This represents a decrease of 1.8% of the current vehicle fleet size. Furthermore, only 92,751 aTaxis and 92,844 charging stations are needed if empty rides are allowed reaching a fleet size reduction of 74.59%. This reduction is similar to the observations from the literature.

Next to that, the service simulated in this thesis proposes a high level of comfort since a user only has to wait 6 to 9 seconds in average before living with his aTaxi to his destination. Moreover, users have seldom to share their trips with strangers since the average number of passengers per trip is 1.08 in both cases.

However, this comfort is not cheap. To be breakeven, the company is forced to request a price (0.269 € / km) increasing the annual travel spending per person by 8.42%. The costs indeed reach 1.262 € / km in the scenario forbidding empty rides and 0.339 € in the scenario allowing them. Those results are higher than the literature’s results notably due to the new costs considered and the incertitude on the insurance costs.

This thesis has thus not yet found a promising project in terms of profitability. Nevertheless, SAEVs bring many other non-monetary advantages as stated in the literature review. Those impacts will maybe increase the willingness to pay of the users or attract subsidies from the state. This paper is a first analysis of the implementation of AVs in Brussels. It opens the door to many possible improvements and further studies needed to finally succeed in defining a sustainable, profitable service answering to the users’ needs.

# Bibliography

Académie de recherche et d’enseignement supérieur. (n.d.-a). *ARES - Inscriptions dans l’enseignement supérieur 2014-15 à 2019-20 (Paysage)*. Retrieved 10 August 2021, from https://ares-digitalwallonia.opendatasoft.com/explore/dataset/ares-saturn-2/table/?disjunctive.periode&disjunctive.co\_type\_etab&disjunctive.zone\_bassin&disjunctive.co\_type&disjunctive.co\_categorie&disjunctive.lib\_section&disjunctive.co\_cycle&disjunctive.co\_annee\_etudes&disjunctive.co\_insmult&disjunctive.co\_finalite&disjunctive.te\_domaine&disjunctive.lib\_etudes\_ares&disjunctive.lib\_pays\_nationalite&disjunctive.lib\_pays\_naissance&disjunctive.lib\_commune&disjunctive.lib\_domicile\_etr&disjunctive.no\_mobilite&disjunctive.typ\_mob&disjunctive.co\_type\_secondaire&disjunctive.no\_acces\_autres\_annees&disjunctive.co\_premiere\_generation&disjunctive.co\_diplome&disjunctive.co\_resultat&sort=periode

Académie de recherche et d’enseignement supérieur. (n.d.-b). *ARES - Référentiel des établissements et des campus*. Retrieved 10 August 2021, from https://ares-digitalwallonia.opendatasoft.com/explore/dataset/carte-campus/table/?disjunctive.libelle\_de\_l\_unite&disjunctive.localite\_de\_l\_etablissement

Académie de recherche et d’enseignement supérieur. (n.d.-c). *Portail Open Data de l’ARES — ARES*. Retrieved 12 August 2021, from https://ares-digitalwallonia.opendatasoft.com/pages/home/

ADT ATO.brussels. (2015). *Panorama de la vie étudiante à Bruxelles: Pratiques urbaines et rapport à la ville—Phase 1—Les universtiés—Juillet 2014 / Décembre 2015*. Agence de Développement Territorial ASBL. https://perspective.brussels/sites/default/files/ADT\_Synt\_Etudiant\_FR\_Ed-02\_v05.pdf

Almroth, A., Berglund, S., Canella, O., Engelson, L., Flötteröd, G., Jonsson, D., Kristoffersson, I., & West, J. (2014). *Further development of SAMPERS and modeling of urban congestion*. Centre for Transport Studies Stockholm. https://www.transportportal.se/swopec/CTS2014-10.pdf

Anderson, J. M., Kalra, N., Stanley, K. D., Sorensen, P., Samaras, C., & Oluwatola, T. A. (2016). *Autonomous Vehicle Technology: A Guide for Policymakers*. https://www.rand.org/pubs/research\_reports/RR443-2.html

assurance.be. (2021). *Simulation de prix de l’assurance auto en Belgique*. Assurance Belgique. https://www.assurance.be/prix-assurance-auto/

Auld, J., Sokolov, V., & Stephens, T. (2017). *Analysis of the impacts of CAV technologies on travel demand*. 16.

Automobile Propre. (2021). *Ford Focus Electric: Prix, autonomie et fiche technique*. https://www.automobile-propre.com/voitures/ford-focus-electric/

Azevedo, C. L., Marczuk, K., Raveau, S., Soh, H., Adnan, M., Basak, K., Loganathan, H., Deshmunkh, N., Lee, D.-H., Frazzoli, E., & Ben-Akiva, M. (2016). Microsimulation of Demand and Supply of Autonomous Mobility On Demand. *Transportation Research Record: Journal of the Transportation Research Board*, *2564*(1), 21–30. https://doi.org/10.3141/2564-03

Babicheva, T., Burghout, W., Andréasson, I., & Faul, N. (2019, June 10). The matching problem of empty vehicle redistribution in autonomous taxi systems. *International Journal of Traffic and Transportation Management*, 1–8.

Bartlett, J. (2012, January 30). *Survey: Consumers express concerns about electric, plug-in hybrid cars*. https://www.consumerreports.org/cro/news/2012/01/survey-consumers-express-concerns-about-electric-plug-in-hybrid-cars/index.htm

BCSS. (2019, December 31). *Chiffres locaux—Résultats—BCSS*. https://www.bcss.fgov.be/samilc/resultPage.xhtml

Berckmans, M. (2019, January 23). *Pourquoi Zipcar quitte-t-il Bruxelles?* RTBF Info. https://www.rtbf.be/info/economie/detail\_pourquoi-est-ce-que-zipcar-quitte-bruxelles?id=10126549

Berrada, J. (2019). *Technical-Economic Analysis of Services Based on Autonomous Vehicles*. Paris-Est.

Bischoff, J., Maciejewski, M., & Nagel, K. (2017). City-wide shared taxis: A simulation study in Berlin. *2017 IEEE 20th International Conference on Intelligent Transportation Systems (ITSC)*, 275–280. https://doi.org/10.1109/ITSC.2017.8317926

Bösch, P. M. (2018). *Autonomous Vehicles—The next Revolution in Mobility* [Doctoral Thesis, ETH Zurich]. https://doi.org/10.3929/ethz-b-000296870

Brimont, L., Saujot, M., & Sartor, O. (2017). Accelerating Sustainable Mobility with Autonomous Vehicles. *Field Actions Science Reports. The Journal of Field Actions*, *Special Issue 17*, 22–25.

Bullis, K. (2011, October 24). *How Vehicle Automation Will Cut Fuel Consumption*. MIT Technology Review. https://www.technologyreview.com/2011/10/24/190538/how-vehicle-automation-will-cut-fuel-consumption/

Burghout, W., & Andréasson, I. (2015). *Impacts of Shared Autonomous Taxis in a Metropolitan Area*. . Proceedings of the 94th annual meeting of the Transportation Research Board. https://www.researchgate.net/publication/298346251\_Impacts\_of\_Shared\_Autonomous\_Taxis\_in\_a\_Metropolitan\_Area

Burns, L. D. (2013). A vision of our transport future. *Nature*, *497*(7448), 181–182. https://doi.org/10.1038/497181a

Burns, L. D., Jordan, W. C., & Scarborough, B. A. (2012). Transforming Personal Mobility. *The Earth Institute, Columbia University*, 42.

Calendrier 365.be. (n.d.). *Les années bissextiles*. Retrieved 14 August 2021, from https://www.calendrier-365.be/annees-bissextiles.html

Cambier. (2018, June 12). Qui va payer cette voiture autonome à Bruxelles ? *BECI*. https://www.beci.be/qui-va-payer-cette-voiture-autonome-a-bruxelles/

Cambio Brussels. (n.d.-a). *Cambio autodelen | Vlaanderen*. Retrieved 10 August 2021, from https://www.cambio.be/nl-vla

Cambio Brussels. (n.d.-b). *Cambio Brussels: About | LinkedIn* [LinkedIn]. Retrieved 14 August 2021, from https://www.linkedin.com/company/cambio-brussels/about/

Camelbeeck, M. (2018, November 13). *Modèle multimodal stratégique de déplacement pour IRIS (MuSti): Description et enjeux*. https://environnement.brussels/sites/default/files/user\_files/02\_pres\_20181106-musti-quiet.brussels\_nl.pdf

CAMPO. (2021). *CAMPO*. CAMPO. https://www.campotexas.org/

Centre des Liaisons Européennes et Internationales de Sécurité Sociale. (2019). *Le régime belge de sécurité sociale (salariés) 6—Pensions de vieillesse et de survivants*. https://www.cleiss.fr/docs/regimes/regime\_belgique\_s6.html

Chang, D., Erstad, D., Lin, E., Falken Rice, A., Goh, C. T., Tsao, A.-A. (Angel), & Snyder, J. (2012). *Financial Viability Of Non-Residential Electric Vehicle Charging Stations*. UCLA Luskin School of Public Affairs, Luskin Center for Innovation, UCLAAnderson School of Management. https://innovation.luskin.ucla.edu/wp-content/uploads/2019/03/Financial\_Viability\_of\_Non-Residential\_EV\_Charging\_Stations.pdf

Chen, T. D., Kockelman, K. M., & Hanna, J. P. (2016). Operations of a shared, autonomous, electric vehicle fleet: Implications of vehicle & charging infrastructure decisions. *Transportation Research Part A: Policy and Practice*, *94*(C), 243–254.

CIRB-CIBG. (2021). *Les institutions européennes à Bruxelles*. be.brussels. https://catalogue.be.brussels/fr/search-standalone/be.brussels

Clean cities, U. S. D. of E. (2021). *Plug-In Electric Vehicle Handbook for Public Charging Station Hosts*. https://afdc.energy.gov/files/pdfs/51227.pdf

Cornelis, E., Hubert, M., Huynen, P., Lebrun, K., Patriarche, G., De Witte, A., Creemers, L., Declercq, K., Janssens, D., Castaigne, M., Hollaert, L., & Walle, F. (2012). *Belgian Daily Mobility 2012—BELdam Rapport*. https://mobilit.belgium.be/sites/default/files/downloads/Rapport\_final\_beldamfr.pdf

Creatests.com, E. de marché en ligne. (2015). *Résultats d’étude—Station de lavage automobile* (Résultat d’étude No. 2001; pp. 1–35). https://www.creatests.com/reseau/include/resultats/1990.pdf

De Bleser, P. (2016, September 14). *Le premier test national de conduite en peloton pour les véhicules à haut degré d’autonomie s’est déroulé avec succès*. AON Empower Results. https://www.aon.com/belgium/fr/newsroom/communiques-de-presse/le-premier-test-national-de-conduite-en-peloton.jsp

Derauw, S., Gelaes, S., & Pauwels, C. (2019). *Enquête MONITOR sur la mobilité des Belges* (D/2019/13.831/10). Service public fédéral Mobilité et Transports, Direction générale Politique de Mobilité durable et ferroviaire, Direction Mobilité - Service Études et Enquêtes. https://mobilit.belgium.be/sites/default/files/partie\_mobilite\_novembre\_2019\_final.pdf

Direction de l’information légale et administrative (Premier ministre). (2020, August 19). *Existe-t-il une surface minimale pour un poste de travail ?* https://www.service-public.fr/professionnels-entreprises/vosdroits/F24505

Du Brulle, C. (2014, May 12). Bruxelles est la principale ville étudiante de Belgique. *Daily Science*. https://dailyscience.be/12/05/2014/bruxelles-est-la-principale-ville-etudiante-de-belgique/

Environnement, durabilité et bien-être. (2021). *Circonférence de la Terre et rayon: Mesure - Recherches - 2021*. https://fr.clubdeportivoazuqueca.com/3769-circumference-of-the-earth-and-radius-measure.html

Exchange-Rates.org. (n.d.). *Dollar américain—Euro—Historique des Taux de Change*. Retrieved 16 August 2021, from https://fr.exchange-rates.org/history/USD/EUR/T

Fagnant, D. J., & Kockelman, K. M. (2014). The travel and environmental implications of shared autonomous vehicles, using agent-based model scenarios. *Transportation Research Part C: Emerging Technologies*, *40*, 1–13. https://doi.org/10.1016/j.trc.2013.12.001

Fagnant, D., & Kockelman, K. (2015). Preparing a nation for autonomous vehicles: Opportunities, barriers and policy recommendations. *Transportation Research Part A: Policy and Practice*, *77*. https://doi.org/10.1016/j.tra.2015.04.003

Fagnant, D., & Kockelman, K. (2016). Dynamic ride-sharing and fleet sizing for a system of shared autonomous vehicles in Austin, Texas. *Transportation*, 1–16.

Fagnant, D., Kockelman, K., & Bansal, P. (2015). Operations of Shared Autonomous Vehicle Fleet for Austin, Texas, Market. *Transportation Research Record: Journal of the Transportation Research Board*, *2536*, 98–106. https://doi.org/10.3141/2536-12

Famifed. (2019). *Par région | Famifed*. https://bruxelles.famifed.be/fr/statistics/263?year=2014

Fédération Belge et Luxembourgeoise de l’Automobile et du Cycle. (2020). *Datadigest 2020*. https://www.febiac.be/public/statistics.aspx?FID=23&lang=FR

Fédération Wallonie-Bruxelles. (n.d.). *Enseignement.be—L’enseignement à domicile et assimilé*. Enseignement.be. Retrieved 14 August 2021, from http://www.enseignement.be/index.php?page=28188&navi=4580

Fédération Wallonie-Bruxelles. (2018, May 9). *École Nationale Supérieure des Arts Visuels de La Cambre*. http://www.artsplastiques.cfwb.be/index.php?id=16690

Gaudy, G. (2021, July 1). *Europe. 70 % des bornes de recharge concentrées dans seulement 3 pays*. www.largus.fr. https://www.largus.fr/actualite-automobile/europe-70-des-bornes-de-recharge-concentrees-dans-seulement-3-pays-10660410.html

Ginckel, L. V. (2018, May 9). *Campus Bloemenhof bij het Bloemenhofplein*. Office Management Blogt. http://blogs.management-media-maatschappij.be/om/campus-bloemenhof-bij-het-bloemenhofplein/

GitHub Inc. (n.d.). *GitHub: Where the world builds software*. GitHub. Retrieved 14 August 2021, from https://github.com/

Google. (2021). *Google Maps*. Google Maps. https://www.google.be/maps/@50.817087,4.3413301,14z

Gurumurthy, K. M., & Kockelman, K. M. (2018). Analyzing the dynamic ride-sharing potential for shared autonomous vehicle fleets using cellphone data from Orlando, Florida. *Computers, Environment and Urban Systems*, *71*, 177–185. https://doi.org/10.1016/j.compenvurbsys.2018.05.008

Heilig, M., Hilgert, T., Mallig, N., Kagerbauer, M., & Vortisch, P. (2017). Potentials of Autonomous Vehicles in a Changing Private Transportation System – a Case Study in the Stuttgart Region. *Transportation Research Procedia*, *26*, 13–21. https://doi.org/10.1016/j.trpro.2017.07.004

Hope, A. (2019, July 12). *Toyota to test autonomous cars on Brussels roads*. The Brussels Times. https://www.brusselstimes.com/news/business/60548/toyota-to-test-autonomous-cars-on-brussels-roads/

Hörl, S. (2018). *An integrated simulation environment for autonomous mobility on demand in Zurich* [Application/pdf]. 1 p. https://doi.org/10.3929/ETHZ-B-000264643

Huvelin, G. (2020, June 2). *Les routes qui rechargent votre voiture électrique, une technologie qui progresse à son allure*. Frandroid. https://www.frandroid.com/produits-android/automobile/voitures-electriques/717557\_les-routes-qui-rechargent-votre-voiture-electrique-une-technologie-qui-progresse-a-son-allure

Hyland, M., & Mahmassani, H. S. (2018). Dynamic autonomous vehicle fleet operations: Optimization-based strategies to assign AVs to immediate traveler demand requests. *Transportation Research Part C: Emerging Technologies*, *92*, 278–297. https://doi.org/10.1016/j.trc.2018.05.003

IBSA. (n.d.). *Institut Bruxellois de Statistique et d’Analyse | IBSA*. Retrieved 12 August 2021, from https://ibsa.brussels/

IBSA. (2018). *Méthodologie—Ménages* (p. 16).

IBSA. (2019a). *Enquête sur le budget des ménages | IBSA | Tableau 2.2.2.1.* https://ibsa.brussels/themes/revenus-et-depenses-des-menages/enquete-sur-le-budget-des-menages

IBSA. (2019b). *Ménages | IBSA | Tableaux 1.4.4.1, 1.4.3.4. & 1.4.3.5*. https://ibsa.brussels/themes/population/menages

IBSA. (2019c). *Offre de soins de santé et offre d’hébergement pour personnes âgées | IBSA | Tableau 4.2.1.3.* https://ibsa.brussels/themes/sante/offre-de-soins-de-sante-et-offre-d-hebergement-pour-personnes-agees

IBSA. (2019d). *Origine-destination des élèves | IBSA | Tableaux 6.3.2.2., 6.3.2.3. & 6.3.2.4.* https://ibsa.brussels/themes/enseignement/origine-destination-des-eleves

IBSA. (2019e). *Parcours scolaires | IBSA | Tableaux 6.4.3.3. & 6.4.3.7.* https://ibsa.brussels/themes/enseignement/parcours-scolaires

IBSA. (2019f). *Population scolaire | IBSA | Tableaux 6.1.2.4. & 6.1.5.1.* https://ibsa.brussels/themes/enseignement/population-scolaire

IBSA. (2019g). *Sécurité routière | IBSA | Tableau 14.2.1.2*. https://ibsa.brussels/themes/securite/securite-routiere

IBSA. (2019h). *Structure par âge | IBSA | Tableaux 1.2.1.2 & 1.2.1.3*. https://ibsa.brussels/themes/population/structure-par-age

IBSA. (2019i). *Tourisme | IBSA | Tableau 15.1.1.6.* https://ibsa.brussels/themes/tourisme-et-culture/tourisme

INASTI. (2021). *Nomenclature et codes des professions | INASTI*. https://www.inasti.be/fr/nomenclature-et-codes-des-professions

INASTI - Service Statistiques. (2019, December 31). *Statistiques de base et tableaux de détail Indépendant—RSVZ*. https://websta.rsvz-inasti.fgov.be/fr/statistical/insured

ITF. (2015). *Urban Mobility System Upgrade: How shared self-driving cars could change city traffic*. OECD. https://www.itf-oecd.org/sites/default/files/docs/15cpb\_self-drivingcars.pdf

Johnson, B. (n.d.). *Disruptive mobility*. Barclays. Retrieved 16 August 2021, from https://www.investmentbank.barclays.com/content/dam/barclaysmicrosites/ibpublic/documents/investment-bank/global-insights/barclays-disruptive-mobility-pdf-120115-459kb.pdf

Julien. (2021, April 26). *Marche Normale: Quelle Est la Vitesse Moyenne ?* IronTimePieces. https://www.irontimepieces.fr/blog/course-et-marche/marche-normale-vitesse-moyenne.html

Jursch, S. (2021). *Sustainability in the automotive industry*. PwC. https://www.pwc.de/en/sustainability/sustainability-in-the-automotive-industry.html

Kockelman, K., Boyles, S., Stone, P., Fagnant, D., Patel, R., Levin, M. W., Sharon, G., Simoni, M., Albert, M., Fritz, H., Hutchinson, R., Bansal, P., Domnenko, G., Bujanovic, P., Kim, B., Pourrahmani, E., Agrawal, S., Li, T., Hanna, J., … Li, J. (2017). *An Assessment of Autonomous Vehicles: Traffic Impacts and Infrastructure Needs—Final Report* (FHWA/TX-17/0-6847-1; pp. 1–184). Center for Transportation Research The University of Texas at Austin. https://library.ctr.utexas.edu/ctr-publications/0-6847-1.pdf

Kok, I., Zou, S. Y., Gordon, J., & Mercer, B. (2017). *RethinkX Disruption, Implications and Choices—Rethinking Transportation 2020-2030—The Disruption of Transportation and the Collapse of the Internal-Combustion Vehicle and Oil Industries*. https://static1.squarespace.com/static/585c3439be65942f022bbf9b/t/591a2e4be6f2e1c13df930c5/1494888038959/RethinkX+Report\_051517.pdf

Kornhauser, A. L., Acciarito, P., Brownell, C., Clemens, B., Fox, C., Germain, S., Kumar, A., Markiewicz, M., Wenzlau, T., Quintero, L., Stroeble, S., Webb, N., Delgado-Medrano GS, H., Mufti GS, T., & Alamanda, B. (2012). *Synthesizing Individual Travel Demand in New Jersey* (p. 70). Department of Operations Research & Financial Engineering Princeton University.

Kornhauser, A. L., Chang, I., Clark, C., Gao, J., Korac, D., Leibowitz, B., Oasis, P., Xu, Z., Zachariah, J., Harpalani, N., Lee, E., Lin, A., Miles, A., Rajeshwar, H., Wang, L., Wright, C., Bergeson, K., Darnis, F., Shackleford, M., … Swoboda, A. (2013). *Uncongested Mobility for All—New Jersey’s Area-wide aTaxi System—ORF467F12 Report*. Department of Operations Research & Financial Engineering Princeton University.

Kornhauser, A. L., Marocchini, K., Roth, T., Zhu, S., Bressler, M., Byrne, T., Filipowicz, A., Gladstone, K., Jian, N., Jones, K., Ju, K., Kinn, I., Lamb, A., Manyara, K., McDonald, E., Osborne, T., Oslin, B., Quansah, E., Radke, J., … Zou, J. (2016). *ORF467F15 Final Report: Fleet Management of Area-Wide Ride-Sharing: A first look at what it would take to serve New Jersey’s Mobility Needs*. Department of Operations Research & Financial Engineering Princeton University.

Kwanten, M. (2017). *Kilomètres parcourus par les véhicules belges en 2017* (p. 37). Service public fédéral Mobilité et Transports.

La Redaction. (2014, April 27). L’emplacement de l’hôtel reste le critère de choix n°1 des voyageurs d’affaires. *Déplacements Pros*. https://www.deplacementspros.com/L-emplacement-de-l-hotel-reste-le-critere-de-choix-n-1-des-voyageurs-d-affaires\_a27052.html

Lafon, L. (2020, August 10). *Calcul de distance avec latitudes et longitudes*. http://villemin.gerard.free.fr/aGeograp/Distance.htm#bilan

Lebrun, K., Hubert, M., Huynen, P., De Witte, A., & Macharis, C. (2013). *Cahiers de l’Observatoire de la mobilité de la Région de Bruxelles-Capitale—Cahier 2*. Brussels UrbIS CIRB. https://mobilite-mobiliteit.brussels/sites/default/files/cahiers\_mobilite-2\_.pdf

Lebrun, K., Hubert, M., Huynen, P., & Patriarche, G. (2014). *Cahiers de l’Observatoire de la mobilité de la Région de Bruxelles-Capitale—Cahier 3*. Brussels UrbIS CIRB. https://mobilite-mobiliteit.brussels/sites/default/files/les\_pratiques\_de\_deplacement\_a\_bruxelles\_analyses\_approfondies.pdf

Lesage, N. (2019, April 14). *Uber: Comment est calculé le prix d’une course ?* Numerama. https://www.numerama.com/vroom/478932-uber-comment-est-calcule-le-prix-dune-course.html

Leurent, F. (2019). *Microeconomics of a taxi service in a ring-shaped city*. https://hal.archives-ouvertes.fr/hal-02047269

Levin, M. W., Kockelman, K. M., Boyles, S. D., & Li, T. (2017). A general framework for modeling shared autonomous vehicles with dynamic network-loading and dynamic ride-sharing application. *Computers, Environment and Urban Systems*, *64*, 373–383. https://doi.org/10.1016/j.compenvurbsys.2017.04.006

Litman, T. (2021). Implications for Transport Planning. *Victoria Transport Policy Institute*, 46.

Liu, J., Kockelman, K., Boesch, P., & Ciari, F. (2017). Tracking a system of shared autonomous vehicles across the Austin, Texas network using agent-based simulation. *Transportation*, 1261–1278.

Loeb, B., & Kockelman, K. (2019). Fleet performance and cost evaluation of a shared autonomous electric vehicle fleet: A case study for Austin, Texas. *Transportation Research Part A*, 374–385.

Loeb, B., Kockelman, K., & Liu, J. (2018). Shared autonomous electric vehicle (SEAV) operations across the Austin, Texas network with a focus on charging infrastructure decisions. *Transportation Research Part C: Emerging Technologies*, 222–233.

Ma, J., Li, X., Zhou, F., & Hao, W. (2017). Designing Optimal Autonomous Vehicle Sharing and Reservation Systems: A Linear Programming Approach. *Transportation Research Part C Emerging Technologies*, *84*. https://doi.org/10.1016/j.trc.2017.08.022

Martinez, L. M., & Viegas, J. (2016). *Shared Mobility Innovation for Liveable Cities*. https://doi.org/10.1787/5jlwvz8bd4mx-en

Martinez, L. M., & Viegas, J. M. (2017). Assessing the impacts of deploying a shared self-driving urban mobility system: An agent-based model applied to the city of Lisbon, Portugal. *International Journal of Transportation Science and Technology*, *6*(1), 13–27. https://doi.org/10.1016/j.ijtst.2017.05.005

M.B. (2018, December 8). *La création de crèches à Bruxelles a pris du retard—Édition digitale de Bruxelles*. La Capital. https://lacapitale.sudinfo.be/318381/article/2018-12-08/la-creation-de-creches-bruxelles-pris-du-retard

Microsoft. (2021a). *Create & Edit Word Docs with Microsoft 365 | Microsoft Word*. https://www.microsoft.com/en-gb/microsoft-365/word

Microsoft. (2021b). *Microsoft Access Database & Application Software*. https://www.microsoft.com/en-gb/microsoft-365/access

Microsoft. (2021c). *PowerPoint—Free Download | PowerPoint*. https://www.microsoft.com/en-gb/microsoft-365/powerpoint

Microsoft. (2021d). *Spreadsheet Software | Microsoft Excel*. https://www.microsoft.com/en-gb/microsoft-365/excel

Monitoring des quartiers. (2018). *Nombre de places en milieu d’accueil par enfant de moins de trois ans*. https://monitoringdesquartiers.brussels/indicators/nombre-de-places-en-milieux-daccueil-par-enfant/

Monitoring des quartiers. (2019a). *Capacité d’accueil scolaire relative du territoire (maternel)*. https://monitoringdesquartiers.brussels/indicators/capacite-daccueil-scolaire-relative-maternel/

Monitoring des quartiers. (2019b). *Capacité d’accueil scolaire relative du territoire (primaire)*. https://monitoringdesquartiers.brussels/indicators/enseignement-capacite-daccueil-relative-primaire/

Monitoring des quartiers. (2019c). *Monitoring des Quartiers de la Région de Bruxelles Capitale*. https://monitoringdesquartiers.brussels/

Monitoring des quartiers. (2019d). *Part des 5-9 ans de sexe féminin dans la population totale*. https://monitoringdesquartiers.brussels/indicators/part-des-5-9-ans-sexe-feminin-dans-population-totale/

Monitoring des quartiers. (2019e). *Part des 5-9 ans de sexe masculin dans la population totale*. https://monitoringdesquartiers.brussels/indicators/part-des-5-9-ans-de-sexe-masculin-dans-population-totale/

Monitoring des quartiers. (2019f). *Part des 10-14 ans de sexe féminin dans la population totale*. https://monitoringdesquartiers.brussels/indicators/part-des-10-14-ans-sexe-feminin-dans-population-totale/

Monitoring des quartiers. (2019g). *Part des 10-14 ans de sexe masculin dans la population totale*. https://monitoringdesquartiers.brussels/indicators/part-des-10-14-ans-de-sexe-masculin-dans-population-totale/

Monitoring des quartiers. (2019h). *Part des 15-19 ans de sexe féminin dans la population totale*. https://monitoringdesquartiers.brussels/indicators/part-des-15-19-ans-sexe-feminin-dans-population-totale/

Monitoring des quartiers. (2019i). *Part des 15-19 ans de sexe masculin dans la population totale*. https://monitoringdesquartiers.brussels/indicators/part-des-15-19-ans-de-sexe-masculin-dans-population-totale/

Monitoring des quartiers. (2019j). *Part des 20-24 ans de sexe féminin dans la population totale*. https://monitoringdesquartiers.brussels/indicators/part-des-20-24-ans-de-sexe-feminin-dans-population-totale/

Monitoring des quartiers. (2019k). *Part des 20-24 ans de sexe masculin dans la population totale*. https://monitoringdesquartiers.brussels/indicators/part-des-20-24-ans-de-sexe-masculin-dans-population-totale/

Monitoring des quartiers. (2019l). *Part des 25-29 ans de sexe féminin dans la population totale*. https://monitoringdesquartiers.brussels/indicators/part-des-25-29-ans-de-sexe-feminin-dans-population-totale/

Monitoring des quartiers. (2019m). *Part des 25-29 ans de sexe masculin dans la population totale*. https://monitoringdesquartiers.brussels/indicators/part-des-25-29-ans-de-sexe-masculin-dans-population-totale/

Monitoring des quartiers. (2019n). *Part des 30-34 ans de sexe féminin dans la population totale*. https://monitoringdesquartiers.brussels/indicators/part-des-30-34-ans-de-sexe-feminin-dans-population-totale/

Monitoring des quartiers. (2019o). *Part des 30-34 ans de sexe masculin dans la population totale*. https://monitoringdesquartiers.brussels/indicators/part-des-30-34-ans-de-sexe-masculin-dans-population-totale/

Monitoring des quartiers. (2019p). *Part des 35-39 ans de sexe féminin dans la population totale*. https://monitoringdesquartiers.brussels/indicators/part-des-35-39-ans-de-sexe-feminin-dans-population-totale/

Monitoring des quartiers. (2019q). *Part des 35-39 ans de sexe masculin dans la population totale*. https://monitoringdesquartiers.brussels/indicators/part-des-35-39-ans-de-sexe-masculin-dans-population-totale/

Monitoring des quartiers. (2019r). *Part des 40-44 ans de sexe féminin dans la population totale*. https://monitoringdesquartiers.brussels/indicators/part-des-40-44-ans-de-sexe-feminin-dans-population-totale/

Monitoring des quartiers. (2019s). *Part des 40-44 ans de sexe masculin dans la population totale*. https://monitoringdesquartiers.brussels/indicators/part-des-40-44-ans-de-sexe-masculin-dans-population-totale/

Monitoring des quartiers. (2019t). *Part des 45-49 ans de sexe féminin dans la population totale*. https://monitoringdesquartiers.brussels/indicators/part-des-45-49-ans-de-sexe-feminin-dans-population-totale/

Monitoring des quartiers. (2019u). *Part des 45-49 ans de sexe masculin dans la population totale*. https://monitoringdesquartiers.brussels/indicators/part-des-45-49-ans-de-sexe-masculin-dans-population-totale/

Monitoring des quartiers. (2019v). *Part des 50-54 ans de sexe féminin dans la population totale*. https://monitoringdesquartiers.brussels/indicators/part-des-50-54-ans-de-sexe-feminin-dans-population-totale/

Monitoring des quartiers. (2019w). *Part des 50-54 ans de sexe masculin dans la population totale*. https://monitoringdesquartiers.brussels/indicators/part-des-50-54-ans-de-sexe-masculin-dans-population-totale/

Monitoring des quartiers. (2019x). *Part des 55-59 ans de sexe féminin dans la population totale*. https://monitoringdesquartiers.brussels/indicators/part-des-55-59-ans-de-sexe-feminin-dans-population-totale/

Monitoring des quartiers. (2019y). *Part des 55-59 ans de sexe masculin dans la population totale*. https://monitoringdesquartiers.brussels/indicators/part-des-55-59-ans-de-sexe-masculin-dans-population-totale/

Monitoring des quartiers. (2019z). *Part des 60-64 ans de sexe féminin dans la population totale*. https://monitoringdesquartiers.brussels/indicators/part-des-60-64-ans-de-sexe-feminin-dans-population-totale/

Monitoring des quartiers. (2019aa). *Part des 60-64 ans de sexe masculin dans la population totale*. https://monitoringdesquartiers.brussels/indicators/part-des-60-64-ans-de-sexe-masculin-dans-population-totale/

Monitoring des quartiers. (2019ab). *Part des 65-69 ans de sexe féminin dans la population totale*. https://monitoringdesquartiers.brussels/indicators/part-des-65-69-ans-de-sexe-feminin-dans-population-totale/

Monitoring des quartiers. (2019ac). *Part des 65-69 ans de sexe masculin dans la population totale*. https://monitoringdesquartiers.brussels/indicators/part-des-65-69-ans-de-sexe-masculin-dans-population-totale/

Monitoring des quartiers. (2019ad). *Part des 70-74 ans de sexe féminin dans la population totale*. https://monitoringdesquartiers.brussels/indicators/part-des-70-74-ans-de-sexe-feminin-dans-population-totale/

Monitoring des quartiers. (2019ae). *Part des 70-74 ans de sexe masculin dans la population totale*. https://monitoringdesquartiers.brussels/indicators/part-des-70-74-ans-de-sexe-masculin-dans-population-totale/

Monitoring des quartiers. (2019af). *Part des 75-79 ans de sexe féminin dans la population totale*. https://monitoringdesquartiers.brussels/indicators/part-des-75-79-ans-de-sexe-feminin-dans-population-totale/

Monitoring des quartiers. (2019ag). *Part des 75-79 ans de sexe masculin dans la population totale*. https://monitoringdesquartiers.brussels/indicators/part-des-75-79-ans-de-sexe-masculin-dans-population-totale/

Monitoring des quartiers. (2019ah). *Part des 80-84 ans de sexe féminin dans la population totale*. https://monitoringdesquartiers.brussels/indicators/part-des-80-84-ans-de-sexe-feminin-dans-population-totale/

Monitoring des quartiers. (2019ai). *Part des 80-84 ans de sexe masculin dans la population totale*. https://monitoringdesquartiers.brussels/indicators/part-des-80-84-ans-de-sexe-masculin-dans-population-totale/

Monitoring des quartiers. (2019aj). *Part des 85-89 ans de sexe féminin dans la population totale*. https://monitoringdesquartiers.brussels/indicators/part-des-85-89-ans-de-sexe-feminin-dans-population-totale/

Monitoring des quartiers. (2019ak). *Part des 85-89 ans de sexe masculin dans la population totale*. https://monitoringdesquartiers.brussels/indicators/part-des-85-89-ans-de-sexe-masculin-dans-population-totale/

Monitoring des quartiers. (2019al). *Part des 90-94 ans de sexe féminin dans la population totale*. https://monitoringdesquartiers.brussels/indicators/part-des-90-94-ans-de-sexe-feminin-dans-population-totale/

Monitoring des quartiers. (2019am). *Part des 90-94 ans de sexe masculin dans la population totale*. https://monitoringdesquartiers.brussels/indicators/part-des-90-94-ans-de-sexe-masculin-dans-population-totale/

Monitoring des quartiers. (2019an). *Part des 95 ans et plus de sexe féminin dans la population totale*. https://monitoringdesquartiers.brussels/indicators/part-des-95-ans-et-plus-de-sexe-feminin-dans-population-totale/

Monitoring des quartiers. (2019ao). *Part des 95 ans et plus de sexe masculin dans la population totale*. https://monitoringdesquartiers.brussels/indicators/part-des-95-ans-et-plus-de-sexe-masculin-dans-population-totale/

Monitoring des quartiers. (2019ap). *Part des couples avec enfants dans le total des ménages privés*. https://monitoringdesquartiers.brussels/indicators/part-des-couples-avec-enfants-dans-le-total-des-menages-prives/

Monitoring des quartiers. (2019aq). *Part des couples sans enfants dans le total des ménages privés*. https://monitoringdesquartiers.brussels/indicators/part-des-couples-sans-enfants-sans-le-total-des-menages-prives/

Monitoring des quartiers. (2019ar). *Part des enfants du quartier scolarisés en maternel à proximité de leur résidence*. https://monitoringdesquartiers.brussels/indicators/analysis/Part-des-enfants-du-quartier-scolarises-en-maternel-proximite-de-leur-residence/

Monitoring des quartiers. (2019as). *Part des enfants du quartier scolarisés en primaire à proximité de leur résidence*. https://monitoringdesquartiers.brussels/indicators/Part-des-enfants-du-quartier-scolarises-en-primaire-proximite-de-leur-residence/

Monitoring des quartiers. (2019at). *Part des enfants du quartier scolarisés en secondaire à proximité de leur résidence*. https://monitoringdesquartiers.brussels/indicators/Part-des-enfants-du-quartier-scolarises-en-secondaire-proximite-de-leur-residence/

Monitoring des quartiers. (2019au). *Part des enfants du territoire (quartier ou commune) inscrits dans une école maternelle située en dehors de la Région*. https://monitoringdesquartiers.brussels/indicators/Part-eleves-du-quartier-inscrits-dans-ecole-maternelle-en-dehors-de-la-RBC/

Monitoring des quartiers. (2019av). *Part des enfants du territoire (quartier ou commune) inscrits dans une école primaire située en dehors de la Région*. https://monitoringdesquartiers.brussels/indicators/Part-eleves-du-quartier-inscrits-dans-ecole-primaire-en-dehors-de-la-RBC/

Monitoring des quartiers. (2019aw). *Part des enfants du territoire (quartier ou commune) inscrits dans une école secondaire située en dehors de la Région*. https://monitoringdesquartiers.brussels/indicators/Part-eleves-du-quartier-inscrits-dans-ecole-secondaire-en-dehors-de-la-RBC/

Monitoring des quartiers. (2019ax). *Part des femmes de 20-49 ans en couple sans enfant (sur les femmes de 20-49 ans)*. https://monitoringdesquartiers.brussels/indicators/part-des-femmes-de-20-49-ans-en-couple-sans-enfant-sur-femme-20-49-ans/

Monitoring des quartiers. (2019ay). *Part des femmes de 20-59 ans en couple avec enfant (sur les femmes de 20-59 ans)*. https://monitoringdesquartiers.brussels/indicators/part-des-femmes-de-20-59-ans-en-couple-avec-enfant-sur-femme-20-59-ans/

Monitoring des quartiers. (2019az). *Part des femmes de 60 ans et plus en couple sans enfant (sur les femmes de 60 ans et plus)*. https://monitoringdesquartiers.brussels/indicators/part-des-femmes-de-60-ans-et-plus-en-couple-sans-enfant-sur-femme-de-60-ans-et-plus/

Monitoring des quartiers. (2019ba). *Part des isolés de 30 ans et plus dans le total des ménages privés*. https://monitoringdesquartiers.brussels/indicators/part-des-isoles-de-30-ans-et-plus-dans-le-total-des-menages-prives/

Monitoring des quartiers. (2019bb). *Part des isolés de 65 ans et plus dans le total des ménages privés*. https://monitoringdesquartiers.brussels/indicators/part-des-isoles-de-65-ans-et-plus-dans-le-total-des-menages-prives/

Monitoring des quartiers. (2019bc). *Part des isolés parmi les 18-29 ans*. https://monitoringdesquartiers.brussels/indicators/part-des-isoles-parmi-les-18-29-ans/

Monitoring des quartiers. (2019bd). *Part des ménages monoparentaux dans le total des ménages privés*. https://monitoringdesquartiers.brussels/indicators/part-des-menages-monoparentaux-dans-le-total-des-menages-prives/

Monitoring des quartiers. (2019be). *Part des mères seules de 20-49 ans (sur les femmes de 20-49 ans)*. https://monitoringdesquartiers.brussels/indicators/part-des-meres-seules-de-20-49-ans-sur-les-femmes-20-49-ans/

Monitoring des quartiers. (2019bf). *Part des moins de 5 ans de sexe féminin dans la population totale*. https://monitoringdesquartiers.brussels/indicators/part-moins-5-ans-sexe-feminin-dans-population-totalepop/

Monitoring des quartiers. (2019bg). *Part des moins de 5 ans de sexe masculin dans la population totale*. https://monitoringdesquartiers.brussels/indicators/part-des-moins-de-5-ans-de-sexe-masculin-dans-population-totale/

Monitoring des quartiers. (2019bh). *Tableaux Statistiques en Région Bruxelles Capitale*. https://monitoringdesquartiers.brussels/tables/

Monitor@Vias. (2016). *MONITOR Data*. https://mobility.vias.be/fr/monitor/

Nissan. (2021). *Nissan LEAF - Voiture familiale 100 % électrique | Nissan*. https://fr.nissan.be/vehicules/neufs/leaf.html?&cid=psm6qxATc95\_dc|D|pgrid|94776000170|ptaid|kwd-7695905545|pcrid|427707911233|slid||intent=EV

Odile. (2014, June 12). *Chiffres à Bruxelles* [Text]. Bruxelles Environnement. https://environnement.brussels/thematiques/mobilite/la-mobilite-bruxelles/chiffres

OpenStreetMap. (n.d.). *OpenStreetMap*. OpenStreetMap Belgium. Retrieved 13 August 2021, from https://openstreetmap.be/en/

Parlement européen. (2019, April 16). *Décès sur les routes en Europe: Les chiffres (infographie) | Actualité | Parlement européen*. https://www.europarl.europa.eu/news/fr/headlines/society/20190410STO36615/deces-sur-les-routes-en-europe-les-chiffres-infographie

Poulhès, A., & Berrada, J. (2019). Single Vehicle Network Versus Dispatcher: User Assignment in an Agent-Based Model. *Transportmetrica A: Transport Science*, *16*, 1–43. https://doi.org/10.1080/23249935.2019.1570383

29 MARS 2007. - Arrêté du Gouvernement de la Région de Bruxelles-Capitale relatif aux services de taxis et aux services de location de voitures avec chauffeur., Pub. L. No. 2007031181, 23526 (2007).

Reiter, M., & Kockelman, K. (2017). Emissions and exposure costs of electric versus conventional vehicles: A case study for Texas. *International Journal of Sustainable Transportation*, 486–492.

RG Invest. (n.d.). *L’évolution des prix des bureaux à Bruxelles. RG INVEST vous conseil en immobilier*. Retrieved 16 August 2021, from http://www.rginvest.be/page/evolution-prix-bureaux-bruxelles-fr\_185.htm

Rossel & Cie. (2015, June 4). *Redoubler en 3e maternelle sera bientôt (quasi) impossible*. Le Soir. https://www.lesoir.be/345/article/2015-06-04/redoubler-en-3e-maternelle-sera-bientot-quasi-impossible

RTBF. (2020, January 4). *DriveNow s’en va, Cambio et Poppy restent: S’y retrouver dans les voitures partagées à Bruxelles*. RTBF Info. https://www.rtbf.be/info/economie/detail\_drive-now-s-en-va-cambio-et-poppy-restent-s-y-retrouver-dans-les-voitures-partagees-a-bruxelles?id=10399927

RTBF. (2021, June 25). *Plus de véhicules diesel en 2030 et essence en 2035 à Bruxelles: Que feront les navetteurs ?* RTBF Info. https://www.rtbf.be/info/belgique/detail\_plus-de-vehicules-diesel-en-2030-et-essence-en-2035-a-bruxelles-que-feront-les-navetteurs?id=10791595

SAE International. (2018). *J3016B: Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles - SAE International*. https://www.sae.org/standards/content/j3016\_201806/

Schultz, C., Salas, O., & Holm, L. (2014). *Let the Cars Drive Themselves.* 38.

Selectra. (2019, August 13). *Voiture électrique: Prix, autonomie, bornes de recharge*. Kelwatt.fr. https://www.kelwatt.fr/guide/conso/voiture-electrique

Seow, K. T., Dang, N. H., & Lee, D.-H. (2010, August). *A Collaborative Multiagent Taxi-Dispatch System*. 607–616.

Service Public Fédéral Belge. (2017a). *Census 2011—Matrice des déplacements domicile-travail par secteur statistique | Statbel*. https://statbel.fgov.be/fr/open-data/census-2011-matrice-des-deplacements-domicile-travail-par-secteur-statistique

Service Public Fédéral Belge. (2017b). *Secteurs statistiques | Statbel*. https://statbel.fgov.be/fr/propos-de-statbel/methodologie/classifications/secteurs-statistiques

Service Public Fédéral Belge. (2019a). *Mariages | Statbel | Tableau 11*. https://statbel.fgov.be/fr/themes/population/partenariat/mariages#figures

Service Public Fédéral Belge. (2019b). *Naissances et fécondité | Statbel | Tableau 12*. https://statbel.fgov.be/fr/themes/population/naissances-et-fecondite#figures

Service Public Fédéral Belge. (2019c). *Salaires mensuels bruts moyens | Statbel*. https://statbel.fgov.be/fr/themes/emploi-formation/salaires-et-cout-de-la-main-doeuvre/salaires-mensuels-bruts-moyens

Service Public Fédéral Belge. (2021a). *Obligation scolaire | Belgium.be*. https://www.belgium.be/fr/formation/enseignement/droits\_et\_devoirs/obligation\_scolaire

Service Public Fédéral Belge. (2021b). *Offre d’enseignement supérieur | Belgium.be*. https://www.belgium.be/fr/formation/enseignement/superieur/offre\_d\_enseignement

Spieser, K., Treleaven, K., Zhang, R., Frazzoli, E., Morton, D., & Pavone, M. (2014). Toward a Systematic Approach to the Design and Evaluation of Automated Mobility-on-Demand Systems: A Case Study in Singapore. In G. Meyer & S. Beiker (Eds.), *Road Vehicle Automation* (pp. 229–245). Springer International Publishing. https://doi.org/10.1007/978-3-319-05990-7\_20

Spyder. (2020). *Home—Spyder IDE*. https://www.spyder-ide.org/

Sudinfo. (2020, September 11). *Coronavirus en Belgique: Chronologie de sept mois de crise*. sudinfo.be. https://www.sudinfo.be/id249069/article/2020-09-11/coronavirus-en-belgique-chronologie-de-sept-mois-de-crise

T, C. (2019, July 11). *Toyota teste une voiture autonome dans le quartier européen de Bruxelles*. RTBF Info. https://www.rtbf.be/info/regions/bruxelles/detail\_toyota-va-tester-la-conduite-autonome-sur-des-routes-bruxelloises-ouvertes-au-public?id=10268551

Taxis Verts. (2019, April 2). Comment se calcule le prix d’une course de taxi à Bruxelles ? *Taxis Verts*. https://taxisverts.be/fr/comment-se-calcule-le-prix-dune-course-de-taxi-a-bruxelles/

Taylor, N. B. (2003). The CONTRAM Dynamic Traffic Assignment Model. *Networks and Spatial Economics*, *3*, 297–322.

*Taylor—The CONTRAM Dynamic Traffic Assignment Model.pdf*. (n.d.). Retrieved 14 August 2021, from https://link.springer.com/content/pdf/10.1023/A:1025394201651.pdf

Toint, P. (1999). *Mobilité quotidienne en Belgique*.

Touzot. (2021, July 2). Énergie: Une voiture électrique sera toujours plus propre qu’une thermique. *Automobile Propre*. https://www.automobile-propre.com/energie-une-voiture-electrique-sera-toujours-plus-propre-quune-thermique/

Treiber, M., Kesting, A., & Thiemann, C. (2007). *How Much does Traﬃc Congestion Increase Fuel Consumption and Emissions? Applying a Fuel Consumption Model to the NGSIM Trajectory Data*. 17.

Ubertarif. (n.d.). *Taxi Prix UBER Bruxelles*. Retrieved 10 August 2021, from http://uber-prix-brussels-be.ubertarif.com/

United States Census Bureau. (n.d.). *Explore Census Data*. Retrieved 14 August 2021, from https://data.census.gov/cedsci/

Université Catholique de Louvain. (2021). *Rapport Annuel—Les étudiants*. UCLouvain. https://uclouvain.be/fr/rapport-annuel/les-etudiants.html

U.S. Department of Transportation Federal Highway Administration. (2017). *National Household Travel Survey*. https://nhts.ornl.gov/

Van Leeuw, V., & Leroy, C. (2020). *Santé périnatale en Région bruxelloise—Année 2019*. Centre d’Épidémiologie Périnatale. https://www.cepip.be/pdf/rapport\_CEPIP\_Bxl2019\_FR\_2tma.pdf

Vlaanderen is onderwijs & vorming. (2018, 2019). *Dataloep mobiliteit en aantrekkingskracht BaO en SO*. https://dataloep-publiek.vlaanderen.be/QvAJAXZfc/notoolbar.htm?document=LP-Publiek%2FPubliek\_AantrekkingMobiliteit.qvw&host=PubliekQVS%40cwv100163&anonymous=true

Volvo Car Group, Affaires publiques, SE-405 31 Göteborg. (2018). *Volvo 360c Concept foto| Motor1.com France*. https://fr.motor1.com/photo/3240235/volvo-360c-concept/

Volvo Car Group, Affaires publiques, SE-405 31 Göteborg. (2021). *Volvo 360c Interior Office*. https://www.media.volvocars.com/be/fr-be/media/photos/237052/volvo-360c-interior9

Vosooghi, R., Puchinger, J., Jankovic, M., & Vouillon, A. (2019, June 18). *Shared Autonomous Vehicle Simulation and Service Design*. https://www.researchgate.net/publication/333865752\_Shared\_Autonomous\_Vehicle\_Simulation\_and\_Service\_Design

Wadud, Z. (2017). Fully automated vehicles: A cost of ownership analysis to inform early adoption. *Transportation Research Part A: Policy and Practice*, *101*, 163–176. https://doi.org/10.1016/j.tra.2017.05.005

Wen, J., Chen, Y. X., Nassir, N., & Zhao, J. (2018). Transit-oriented autonomous vehicle operation with integrated demand-supply interaction. *Transportation Research Part C: Emerging Technologies*, *97*, 216–234. https://doi.org/10.1016/j.trc.2018.10.018

Wikipedia. (2021). ICHEC Brussels Management School. In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=ICHEC\_Brussels\_Management\_School&oldid=1001263394

Zachariah, J. J. (2013). *Are We There Yet? A Proposal for an Autonomous Taxi System in New Jersey and a Preliminary Foundation for Empty Vehicle Routing*. Princeton University.

Zhang, W., Guhathakurta, S., Fang, J., & Zhang, G. (2014). The Performance and Benefits of a Shared Autonomous Vehicles Based Dynamic Ridesharing System: An Agent-Based Simulation Approach. *Transportation Research Board 94th Annual Meeting*, 15.

Zhu, S. (2016). *Make American Transportation Great Again: Autonomous Taxi Fleet Management Strategies*. Princeton University.

# Appendix

## Figures

### Appendix 1: Distribution of trips through time per category of destination

Figure 16 Distribution of the trips to a leisure place through time

Figure 17 Distribution of the trips to home through time (Cornelis et al., 2012)

Figure 18 Distribution of the trips to a study place through time (Cornelis et al., 2012)

Figure 19 Distribution of the trips to a workplace through time (Cornelis et al., 2012)

### Appendix 2: Modal share according to the trip length

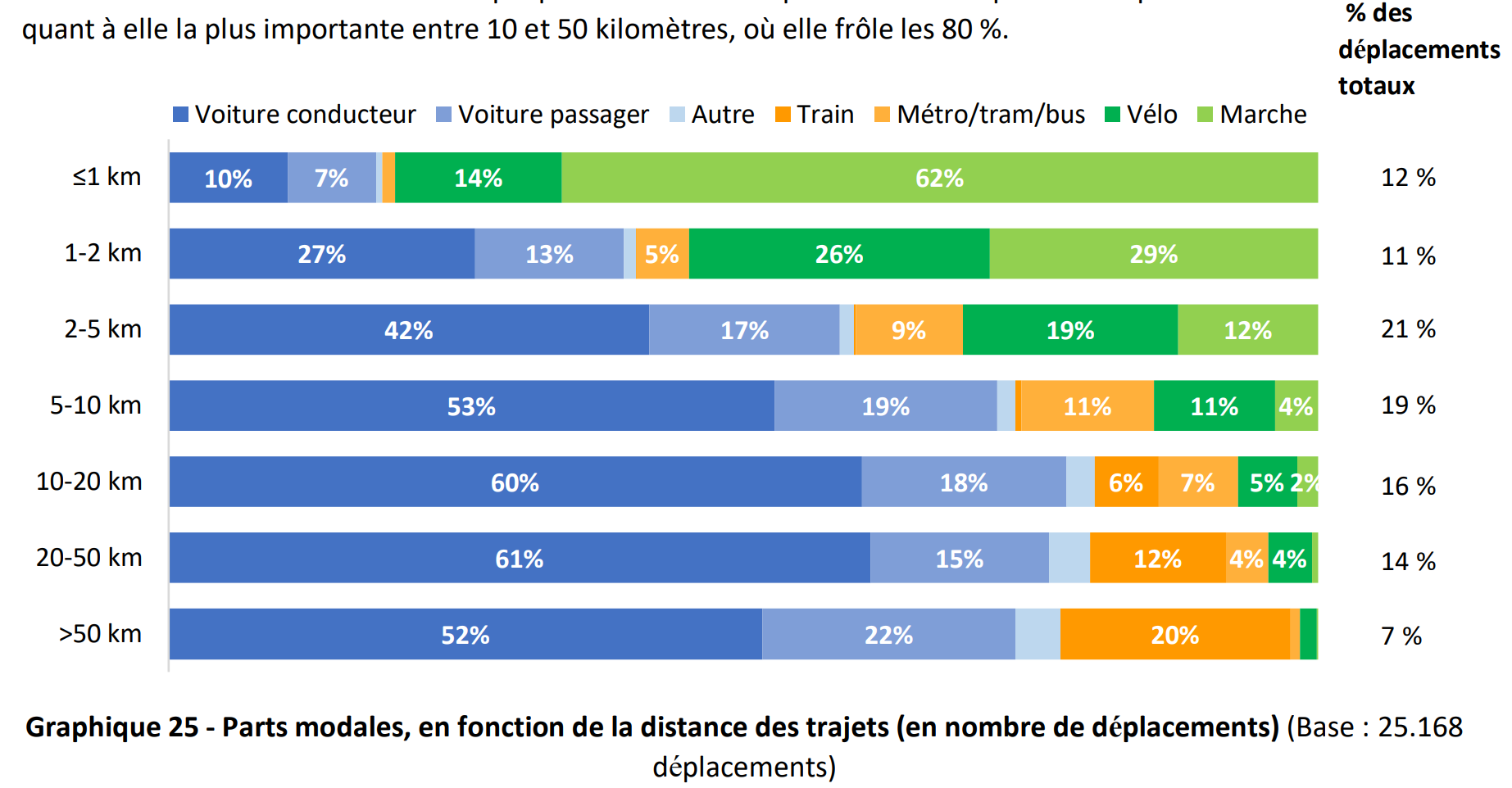


Figure 20 Modal share according to the trip length (Derauw et al., 2019)

## Tables

### Appendix 3: Literature review comparison table

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Paper | Geographic region | Travel demand data | Tool | Roads / stations representation | Mar-ket Pene-tra-tion | Imple-menta-tion model | Fuel | Detour | Maximum waiting time | Pre-order | Nea-rest vehi-cle | Request rejection | Vehicle size |
| Kornhauser et al., 2016 & Kornhauser et al., 2013 | New Jersey (USA) | U.S. Census data | / | Grid of squares of 0.5 miles (805 m) x 0.5 miles and Manhattan distance | Not full – Multi-mo-dal | Car and ride sharing | Gasoline | 20% increase of the travel time allowed | / | No | Yes | No | 5 seats |
| Zachariah, 2013 | New Jersey (USA) | U.S. Census data | / | Grid of squares of 0.5 miles (805 m) x 0.5 miles and Manhattan distance | Not full – Multi-mo-dal | Car and ride sharing | Gasoline | 20% increase of the travel time allowed | / | No | Yes | No | 5 seats |
| Zhu, 2016 | New Jersey (USA) | U.S. Census data | / | Grid of squares of 0.5 miles (805 m) x 0.5 miles and Manhattan distance | Not full – Multi-mo-dal | Car and ride sharing | Gasoline | 20% increase of the travel time allowed | / | No | Yes | No | 3; 6; 15 and 50 seats scena-rios |
| Bösch, 2018 | Zurich (Switzer-land) |  | MatSim | Roads and speed characteristics from OpenStreetMap | 10% | Private AV, car sharing only and car and ride sharing | Gasoline |  | / | No | Yes | If waiting time superior to 10 minutes | one-seater, midsi-ze, van and mini-bus |

Table 6 Literature review comparison table

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Paper | Geographic region | Travel demand data | Tool | Roads / stations representation | Mar-ket Pene-tra-tion | Imple-menta-tion model | Fuel | Detour | Maximum waiting time | Pre-order | Nea-rest vehi-cle | Request rejection | Vehicle size |
| Burns, 2013 | Small to medium town: Ann Arbor, Michigan (USA) Suburban: Babcock Ranch, Florida (USA) Urban: Manhattan, New York (USA) | Attrac-tion model propor-tional to the popula-tion density | / | beelines for distances | Full | Car sharing | Gasoline and electric vehicles | No |  | No | Yes |  | Medium sedans for 1 or 2 people |
| D. Fagnant & Kockelman, 2015 | Literature review focusing on USA |  | / |  | 10%; 50% and 90% scena-rios | Private AV, car sharing only and car and ride sharing | Gasoline and electric vehicles |  |  |  |  |  |  |
| D. Fagnant & Kockelman, 2016 | Austin, Texas (USA) | NHTS and U.S. Census data | MatSim | Roads and speed characteristics from OpenStreetMap | Less than 10% | Car and ride sharing | Gasoline and electric vehicles |  |  |  | Yes |  | 4 seats |

Table 6 Literature review comparison table

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Paper | Geographic region | Travel demand data | Tool | Roads / stations representation | Mar-ket Pene-tra-tion | Imple-menta-tion model | Fuel | De-tour | Maxi-mum waiting time | Pre-order | Nea-rest vehi-cle | Request rejection | Vehicle size |
| Litman, 2021 | Literature review |  | / |  | Not full – Multimo-dal | Car sharing and car and ride sharing | Gasoline and electric vehicles |  |  |  |  |  |  |
| Wadud, 2017 | UK |  | / |  | Not full – Multimo-dal | Private AV | Gasoline | No |  |  |  |  | Cars; SUVs; taxis and 3 types of trucks |
| Loeb & Kockelman, 2019 | Austin, Texas (USA) | NHTS and U.S. Census data | MatSim | Roads and speed characteristics from OpenStreetMap | 2% | Car and ride sharing | Gasoline; hybrid and electric vehicles |  |  |  |  |  | Sedans |
| Liu et al., 2017 | Austin, Texas (USA) | NHTS and U.S. Census data | MatSim | Roads and speed characteristics from OpenStreetMap |  | Car sharing | Gasoline | No |  |  |  |  |  |
| Leurent, 2019 | Orbicity | Homogeneous simula-ted demand | Orbicity | Ring shape city with homogeneous population density | Not full – Multimo-dal | Car sharing | Gasoline and electric vehicles | No |  |  |  |  |  |
| Poulhès & Berrada, 2019 | Palaiseau, Saclay (France) | Poisson distribu-tion |  | 11 stations and real roads | One line of bus | Car and ride sharing | Gasoline | No |  |  |  |  | 5 seats |
| Vosooghi et al., 2019 | Rouen, Normandie (France) |  | MatSim | Roads and speed characteristics from OpenStreetMap | Not full – Multimo-dal | Car and ride sharing | Gasoline and electric vehicles |  |  |  |  |  | 4 seats |

Table 6 Literature review comparison table

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Paper | Geographic region | Travel demand data | Tool | Roads / stations representation | Mar-ket Pene-tra-tion | Imple-menta-tion model | Fuel | De-tour | Maxi-mum waiting time | Pre-order | Nea-rest vehi-cle | Request rejection | Vehicle size |
| Burghout & Andréasson, 2015 | Stockholm (Sweden) | CONTRAM (*Taylor - The CONTRAM Dynamic Traffic Assignment Model.Pdf*, n.d.) and REGENT (Almroth et al., 2014) | / |  | Not full – Multi-modal | Car and ride sharing | Gasoline | 30% inc-rease of the travel time allo-wed | 5; 8; 10 and 15 minutes scena-rios | Yes |  |  | 4 seats |
| Spieser et al., 2014 | Singapore | Survey; taxi data and Poisson distribution | Sim-Mobility | Roads and speed characteristics from OpenStreetMap |  | Car sharing | Gasoline | No |  |  |  |  |  |
| Auld et al., 2017 | Chicago (USA) | POLARIS |  |  |  | Not driverless cars |  | No |  |  |  |  |  |
| ITF, 2015 | Lisbon (Portugal) |  |  | 6 stations | 50%; 90%; 100% | Car sharing and car and ride sharing | Gasoline and electric vehicles |  |  |  |  |  | 2; 5 and 8 seats |
| D. J. Fagnant & Kockelman, 2014 | Austin, Texas (USA) | Factor of attractiveness and Poisson distribution | MatSim | Grid of squares of 0.25 miles (402 m) x 0.25 miles and Manhattan distance | 2% | Car sharing | Gasoline and electric vehicles | No |  |  | Yes |  | 4 seats |
| Hörl, 2018 | Zurich (Switzerland) |  | MatSim | Roads and speed characteristics from OpenStreetMap | Not full - Multimodal | Car sharing and car and ride sharing | Gasoline |  |  |  |  |  | 4 seats |

Table 6 Literature review comparison table

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Paper | Geographic region | Travel demand data | Tool | Roads / stations representation | Mar-ket Pene-tra-tion | Imple-menta-tion model | Fuel | De-tour | Maxi-mum waiting time | Pre-order | Nea-rest vehi-cle | Request rejection | Vehicle size |
| Hyland & Mahmassani, 2018 | Chicago (USA) |  |  | Grid of squares of 4 miles (6.437 km) x 4 miles; 8 miles (12.874 km) x 8 miles and 16 miles (25.750 km) x 16 miles | Not full - Multimodal | Car sharing | Gasoline | No |  | No | Yes | No |  |
| Chen et al., 2016 | Austin, Texas (USA) | NHTS and U.S. Census data | MatSim | Grid of squares of 0.25 miles (402 m) x 0.25 miles | 0.1% | Car sharing | Electric vehicles | No |  |  | Yes |  |  |
| Levin et al., 2017 | Austin, Texas (USA) | Cellphone data | MatSim |  |  |  |  |  |  |  |  |  |  |
| Martinez & Viegas, 2017 | Lisbon (Portugal) | Survey |  |  |  | Car sharing and car and ride sharing |  |  |  |  |  |  | 6 seats |
| Bischoff et al., 2017 | Berlin (Germany) |  | MatSim | Roads and speed characteristics from OpenStreetMap |  |  |  |  |  |  | Yes |  |  |
| Babicheva et al., 2019 | Palaiseau, Saclay (France) | Poisson distribution | / | 11 stations and real roads | One line of bus | Car and ride sharing | Gasoline | No | Disutility function | Yes |  |  | 5 seats |

Table 6 Literature review comparison table

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Paper | Geographic region | Travel demand data | Tool | Roads / stations representation | Mar-ket Pene-tra-tion | Imple-menta-tion model | Fuel | De-tour | Maxi-mum waiting time | Pre-order | Nea-rest vehi-cle | Request rejection | Vehicle size |
| Loeb et al., 2018 | Austin, Texas (USA) | NHTS and U.S. Census data | MatSim | Grid of squares of 0.25 miles (402 m) x 0.25 miles | 0.1% | Car sharing | Electric vehicles | No |  | 5 minutes before the departure time |  | If waiting time superior to 10 minutes |  |
| D. Fagnant et al., 2015 | Austin, Texas (USA) | NHTS and U.S. Census data | MatSim |  |  | Car sharing |  | No |  |  |  | If waiting time superior to 10 minutes |  |
| Azevedo et al., 2016 | Singapore |  | SimMo-bility |  |  | Car sharing |  | No |  |  |  |  | Mid-size sedans |
| Gurumurthy & Kockelman, 2018 | Orlando, Floride (USA) | Cellphone data |  |  |  |  |  |  |  |  |  |  |  |
| Berrada, 2019 | Orbicity and Palaiseau, Saclay (France) | Homogeneous simulated demand and Poisson distribution |  | Ring shape city with homoge-neous population density and 11 stations and real roads | Not full – MultiMo-dal and One line of bus | Car sharing and car and ride sharing | Gasoline and electric vehicles | No | Disuti-lity fun-ction | Yes |  |  |  |

Table 6 Literature review comparison table

### Appendix 4: Possible combinations of age category, status in the household, household type and work id

|  |  |  |  |
| --- | --- | --- | --- |
| **Age Category (years old)** | **Status in the household** | **Household Type** | **Work ID** |
| 0 – 2 | Child | Couple with child | Nursery |
| Stay at home |
| Single with child | Nursery |
| Stay at home |
| Collective | Hospital |
| 3 – 5 | Child | Couple with child | Kindergarten |
| Primary school |
| Stay at home |
| Single with child | Kindergarten |
| Primary school |
| Stay at home |
| Collective | Hospital |
| 6 – 11 | Child | Couple with child | Primary school |
| Secondary school |
| Single with child | Primary school |
| Secondary school |
| Collective | Hospital |
| 12 – 14 | Child | Couple with child | Primary school |
| Secondary school |
| Single with child | Primary school |
| Secondary school |
| Collective | Hospital |
| 15 – 17 | Child | Couple with child | Secondary school |
| Single with child | Secondary school |
| Parent | Couple with child | Worker |
| Couple without child | Worker |
| Single | Worker |
| Single with child | Worker |
| In flatsharing | Higher education on campus |
| Worker |
| Child or Parent | Collective | Prison |
| Hospital |

Table 7 Possible combinations of age category, status in the household, household type and work id

|  |  |  |  |
| --- | --- | --- | --- |
| **Age Category (years old)** | **Status in the household** | **Household Type** | **Work ID** |
| 18 – 20 | Child | Couple with child | Secondary school |
| Higher education off campus |
| Single with child | Secondary school |
| Higher education off campus |
| Parent | Single with child | Worker |
| Couple with child | Higher education on campus |
| Higher education off campus |
| Worker |
| Stay at home |
| Couple without child | Higher education on campus |
| Higher education off campus |
| Worker |
| Stay at home |
| Single | Higher education on campus |
| Higher education off campus |
| Worker |
| Stay at home |
| Child or Parent | Collective | Prison |
| Hospital |

Table 7 Possible combinations of age category, status in the household, household type and work id

|  |  |  |  |
| --- | --- | --- | --- |
| **Age Category (years old)** | **Status in the household** | **Household Type** | **Work ID** |
| 21 – 64 | Child | Couple with child | Higher education off campus |
| Worker |
| Stay at home |
| Single with child | Higher education off campus |
| Worker |
| Stay at home |
| Parent | Couple with child | Higher education off campus |
| Worker |
| Stay at home |
| Couple without child | Higher education on campus |
| Higher education off campus |
| Worker |
| Stay at home |
| Single | Higher education on campus |
| Higher education off campus |
| Worker |
| Stay at home |
| In flatsharing | Higher education on campus |
| Higher education off campus |
| Worker |
| Stay at home |
| Child or Parent | Collective | Prison |
| Hospital |

Table 7 Possible combinations of age category, status in the household, household type and work id

|  |  |  |  |
| --- | --- | --- | --- |
| **Age Category (years old)** | **Status in the household** | **Household Type** | **Work ID** |
| 65 – 99 | Parent | Couple with child | Worker |
| Stay at home |
| Couple without child | Worker |
| Stay at home |
| Single | Worker |
| Stay at home |
| Single with child | Worker |
| Stay at home |
| In flatsharing | Worker |
| Stay at home |
| Collective | Prison |
| Hospital |
| Nursing home |

Table 7 Possible combinations of age category, status in the household, household type and work id

### Appendix 5: Trip Chain Types probability distribution

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| WorkerID | 0-6 | 7 & 11 | 8-10 |  |
| Groupe | **Resident Worker** | **Activity** | **Immobile** | **Commuters** |
| TripChainID |  |  |  |  |
| 0 | 0.16 | 0.16 | 1.00 | 0.16 |
| 1 | 0.48 | 0 | 0 | 0.78 |
| 2 | 0.12 | 0 | 0 | 0 |
| 3 | 0.07 | 0 | 0 | 0 |
| 4 | 0.03 | 0 | 0 | 0 |
| 5 | 0.03 | 0 | 0 | 0.06 |
| 6 | 0.02 | 0 | 0 | 0 |
| 7 | 0.02 | 0 | 0 | 0 |
| 8 | 0.01 | 0 | 0 | 0 |
| 9 | 0.01 | 0 | 0 | 0 |
| 10 | 0.01 | 0 | 0 | 0 |
| 11 | 0.01 | 0 | 0 | 0 |
| 12 | 0.01 | 0 | 0 | 0 |
| 13 | 0.01 | 0 | 0 | 0 |
| 14 | 0.01 | 0 | 0 | 0 |
| 15 | 0 | 0 | 0 | 0 |
| 16 | 0 | 0.43 | 0 | 0 |
| 17 | 0 | 0.09 | 0 | 0 |
| 18 | 0 | 0.09 | 0 | 0 |
| 19 | 0 | 0.06 | 0 | 0 |
| 20 | 0 | 0.06 | 0 | 0 |
| 21 | 0 | 0.03 | 0 | 0 |
| 22 | 0 | 0.02 | 0 | 0 |
| 23 | 0 | 0.01 | 0 | 0 |
| 24 | 0 | 0.01 | 0 | 0 |
| 25 | 0 | 0.01 | 0 | 0 |
| 26 | 0 | 0.01 | 0 | 0 |
| 27 | 0 | 0.01 | 0 | 0 |
| 28 | 0 | 0.01 | 0 | 0 |
| 29 | 0 | 0.00 | 0 | 0 |
| 30 | 0 | 0.00 | 0 | 0 |
| 31 | 0 | 0.00 | 0 | 0 |

Table 8 Trip Chain Types probability distribution

## Complementary folders

### Appendix 6: Details on the methodology of the create of the residents and their household

This section will first present how the number of people in each category has been determined and then how the households have been conceived.

#### Define numbers

The first attribute to be allocated to the Brussels’ residents is the age according to their gender. The neighborhood’s monitoring offers the number of men and women per category of age (grouped by 5 years) and sector of living (Monitoring des quartiers, 2019bf), (Monitoring des quartiers, 2019bg), (Monitoring des quartiers, 2019d), (Monitoring des quartiers, 2019e), (Monitoring des quartiers, 2019f), (Monitoring des quartiers, 2019g), (Monitoring des quartiers, 2019h), (Monitoring des quartiers, 2019i), (Monitoring des quartiers, 2019j), (Monitoring des quartiers, 2019k), (Monitoring des quartiers, 2019l), (Monitoring des quartiers, 2019m), (Monitoring des quartiers, 2019n), (Monitoring des quartiers, 2019o), (Monitoring des quartiers, 2019p), (Monitoring des quartiers, 2019q), (Monitoring des quartiers, 2019r), (Monitoring des quartiers, 2019s), (Monitoring des quartiers, 2019t), (Monitoring des quartiers, 2019u), (Monitoring des quartiers, 2019v), (Monitoring des quartiers, 2019w), (Monitoring des quartiers, 2019x), (Monitoring des quartiers, 2019y), (Monitoring des quartiers, 2019z), (Monitoring des quartiers, 2019aa), (Monitoring des quartiers, 2019ab), (Monitoring des quartiers, 2019ac),(Monitoring des quartiers, 2019ad), (Monitoring des quartiers, 2019ae), (Monitoring des quartiers, 2019af), (Monitoring des quartiers, 2019ag), (Monitoring des quartiers, 2019ah), (Monitoring des quartiers, 2019ai), (Monitoring des quartiers, 2019aj), (Monitoring des quartiers, 2019ak), (Monitoring des quartiers, 2019al), (Monitoring des quartiers, 2019am), (Monitoring des quartiers, 2019an), (Monitoring des quartiers, 2019ao), (Monitoring des quartiers, 2019bh). Those numbers have been uniformly spread among the 5 years of each category. It has been chosen that the highest possible age for a woman if 99 years. There are indeed only 186 women oldest than 100 (IBSA, 2019h) which is negligeable in front of the 1.2 million of residents in Brussels. The number of women aged between 95 and 99 comes from the IBSA’s data (IBSA, 2019h) and are transposed from a municipal level to the sectors’ level using the ratio of women living in a given sector to the number of women living in the corresponding municipality (the population ratio) (Monitoring des quartiers, 2019bh). Similarly, for men, the oldest man possible in this simulation is 94 years old because there are only 475 men older than 94 years in Brussels (IBSA, 2019h) which is also negligeable.

The number of people for each category of age and gender in each sector have been determined, the household type repartition has now yet to be determined.

The starting point is to compute the number of couples living with at least one child is the part of women aged between 20 and 59 years living in couple with at least one child (Monitoring des quartiers, 2019ay). It is multiplied by the number of women aged between 20 and 59 years. Then, knowing the total number of couples in each sector living with at least one child from the part of households being of this type (Monitoring des quartiers, 2019ap) and the total number of households (Monitoring des quartiers, 2019bh), the number of women aged between 15 and 19 or between 60 and 70 living in couple with at least one child can be extracted. The hypothesis that no one aged less than 15 years old can live without parent (meaning living being himself the parent in the household) is taken because before 15 years, full time school is compulsory making it impossible to manage a job paying the required rent (Service Public Fédéral Belge, 2021a), (IBSA, 2018). A second assumption is that no one lived at their parent’s home once the mother reaches 70 years. It means indeed that the child is about 38 years of age (the average age difference between a mother and his child being 32 years (Service Public Fédéral Belge, 2019b)). IBSA (IBSA, 2019b) states that only around 1,700 persons older than 38 years still live with their parents. Those can therefore be neglected. Finally, the number of women living in a couple with child per age category are uniformly spread among each age category.

The same logic is used for the number of couples living without child. The only difference is that the available data are for the 20-49 and 60+ age categories (Monitoring des quartiers, 2019ax), (Monitoring des quartiers, 2019az). The difference between the number of couples without child (Monitoring des quartiers, 2019aq) and the sum of those two categories gives the number of women aged between 15 and 19 living in couple without child.

The same process is applied to determine the number of women living alone with at least one child. The only available data being for the age category 20-49 (Monitoring des quartiers, 2019be), the number of women aged between 15 and 19 or 50 and 70 is figured out from the total number of households being “single mother with child” (Monitoring des quartiers, 2019bd). The same assumptions still apply concerning mothers younger than 15 years or older than 70.

For the single fathers living with at least one child, it is more complex. There is no information about their age repartition. The only available data is the part of households being ‘single father with child” (Monitoring des quartiers, 2019bd). These percentages are brought back to absolute numbers thanks to the total number of households (Monitoring des quartiers, 2019bh) and the age of the father is randomly picked between 15 and 70 following the same assumptions as explained here above.

For the people living alone, the neighborhood’s monitoring provides the part of household being “single” per gender and per age category (18-29; 30-64; 65+) (Monitoring des quartiers, 2019bc), (Monitoring des quartiers, 2019ba), (Monitoring des quartiers, 2019bb). Thus, those percentages are multiplied by the total number of household (Monitoring des quartiers, 2019bh) and uniformly spread among the ages in each category. The assumption is taken that no one younger than 18 years lives alone. They are in fact about 200 (IBSA, 2019b) but it can be neglected.

Finally, the number of men and women living in flatshare are provided at a municipal level by the IBSA (IBSA, 2019b). They are spread among the sectors using the ratio of men (resp. women) living in a given sector out of the number of men (resp. women) living in the corresponding municipality (Monitoring des quartiers, 2019bh).

#### Create people and households

People living alone are simply created following the numbers defined in the previous section.

To associate couples, the woman is firstly created and looks then for a man older of three years than his spouse. The average age difference in couples is indeed 3 years in Brussels (Service Public Fédéral Belge, 2019a). If there is no such man still available in the concerned sector, the simulation looks for the first available man in the sector with the age closest to the desired one. Note that only hetero couples are created for a question of simplicity. This could be an improvement for readers interested in the household simulation. However, for the fleet sizing goal of this thesis, it does not have any impact since every household is created at a sector level and not at a real address level. It is therefore aggregated, and one could simply invert two household ids in order to create homo couples.

To create household of a single parent with at least one child, the script first determines the number of children living in the household. This number is randomly picked according to the probability distribution of number of children per household provided by Famifed (2019). This information dates of 2014. It has been assumed that this distribution of probabilities has not changed much between 2014 and 2019. Each child is then created, receive a gender (randomly picked) and an age. The age is allocated following the probability distribution of the age difference between a mother and her child (Van Leeuw & Leroy, 2020). For the creation of a “single father with child” household, the probability distribution is slighted with 3 years more to represent the average age difference in a couple (Service Public Fédéral Belge, 2019a). Following the same process as for the husband explained above, if no more children with the desired age is available in the concerned sector, the first child available with the closest age to the mother age minus 32 (resp. the father age minus 36) is chosen. This 32 (resp. 36) represents the average age difference between a mother (resp. father) and her (resp. his) child (Service Public Fédéral Belge, 2019b). If it is still not possible to find such a child and that it is not the first child allocated to the household, the number of children in this household is simply scaled down.

The creation of households with a couple and children is simply a mix between the creation of a couple and the allocation of children to their mother as explained above.

The creation of shared households follows the same logic as the allocation of children to a household. A first flat mate is created, then the number of roommates in the household is randomly picked between 3 and 8. Three is the minimum otherwise the household would be considered as a couple without child. Next, the gender and the age (between 15 and 70) of the flat mates are randomly taken. Following the same process as for the husband and children explained above, if no more flat mates with the desired age is available in the concerned sector, the first person available with the closest age to the first flat mate created is chosen.

Finally, after the creation of all the households, the household type for the remaining people is defined as “collective”. According to the IBSA conventions (IBSA, 2018), this refers to people being in the hospital, in prison or in a nursing home. Those people are still and stay always at their living place. They are therefore excluded for the rest of the process because useless in order to simulate the average daily trips. They are however included in the results’ analysis.

### Appendix 7: Details on the methodology of the allocation of a work ID and a workplace to the simulated people

The structure of this section follows the classical study / career path in Belgium. A child can go to nursery while aged between 0 and 2 years but it is not compulsory. He could also stay at home. From 3 to 5 years old, a child goes to kindergarten before the primary school from 6 to 11. Then, the teenager is in secondary school until 17 years old. As already mentioned, full time study is compulsory until 15 years old (Service Public Fédéral Belge, 2021a). Between 15 and 18 years, the teenager can work part-time with his study (Service Public Fédéral Belge, 2021a). As from 18 years, adults can study or work. Studies generally last 5 years. The retirement age is at 65 years for the moment (Centre des Liaisons Européennes et Internationales de Sécurité Sociale, 2019).

Depending on the data, the workplace is directly allocated to each person at the same time as his work id or first the work id is assigned and in a second time, the workplace is. All work id can not be allocated to every person. It depends on the resident’s age and household type as shown on the Figure 21.

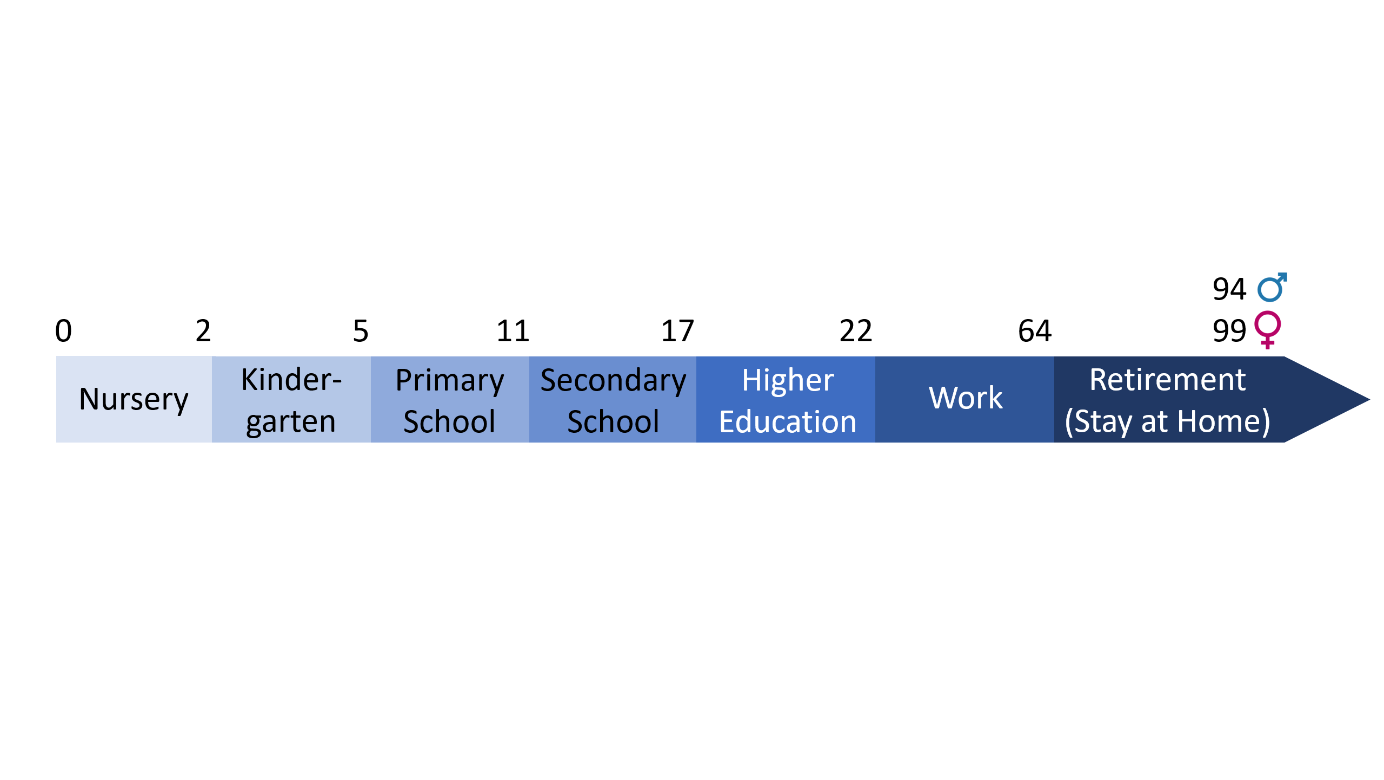


Figure 21 Classical study / work path in Belgium. The numbers above the timeline represent the ages while the word inside the arrow the study / work status corresponding to the given age class.

#### Work ID and workplace when possible

The nurseries’ capacity per sector in 2018 is available in the neighborhood’s monitoring as a ratio between the capacity and the number of children of aged below 3 living in the sector (Monitoring des quartiers, 2018). With this information, it is easy to compute the absolute capacity. No new places have been created between 2018 and 2019 (M.B., 2018).Therefore 2018’s numbers can be used. To assign each baby of the simulated population from section XVII.C.1.b), the important assumption is that a baby goes to the closest nursery to his household with available places. For the babies for whom there is no places any more in any nursery, they are staying at home.

According to the table 6.1.5.1. of IBSA (IBSA, 2019f), (Fédération Wallonie-Bruxelles, n.d.), 275 children between 3 and 17 years study at home. They are therefore randomly picked in the simulated population from section XVII.C.1.b..

The table 6.4.3.3. of IBSA (IBSA, 2019e) presents the number of children per municipality and gender being in primary school with some advance compared to the normal study path. This number has been uniformly spread among the six years of primary school. Those computations give the number of children with an age of 5 years old while being already in primary school when they should be in third kindergarten. Those numbers remain low. The children have been randomly picked at a municipal level instead of breaking the numbers down to the sectors. The breaking down and the compulsory rounding (in order to have “full” children) result to only null values. On the other hand, there is no children in kindergarten with delay in their study path since the minister Milquet has decided in 2015 to limit and make exceptional the grade repetition in kindergarten (Rossel & Cie, 2015). The chosen in advance children were assigned to the primary school work id while all the other children aged between 3 and 5 years receive the work id corresponding to kindergarten.

The same logic is applied for children being 11 years old and in advance in their study path based on the data for students in advance while in secondary school (IBSA, 2019e). They are therefore assigned the secondary school work id instead of the primary school one. All other children aged between 6 and 11 years receive the primary school work id.

Children with one (resp. two) year of delay in primary school (IBSA, 2019e) are also uniformly spread among the six years. However, this time the numbers are brought down to the sector level using the population ratio per gender before being randomly picked among the population of concerned children (aged of 12 (resp. 13)). Those teenagers should be in secondary school but remain in primary school. The secondary school work id is assigned to all other teenagers aged between 12 and 15 years.

Teenagers aged between 15 and 17 years with the status of parent in their household receive the work id corresponding to workers. Having the status of parent means indeed that they work half time and go to secondary school the other half of the time (Service Public Fédéral Belge, 2021a). The worker profile takes over. The same logic for the youngsters of 17 years in advance in their study path is applied than earlier for children aged of 11. They are already at the university instead of still following classes in secondary school. All other adolescents between 15 and 17 are assigned to the secondary school work id.

Like for their younger counterparts, adults aged between 18 and 20 having a parent status in their household have a worker work id. The difference is that here they work full time. Such as for secondary students with some delay in their study path, the same numbers are used here to allocate some 18- and 19-years adults to the secondary school work id.

In Brussels, the higher education is organized by two different federations for the French speaking and the Dutch speaking part (Service Public Fédéral Belge, 2021b). The data and methodology used are different for each federation.

Ares (Académie de recherche et d’enseignement supérieur, n.d.-c) provides the list of campus with their geographic position (Académie de recherche et d’enseignement supérieur, n.d.-b) as well as the number of students per municipality studying in each municipality per age and gender (Académie de recherche et d’enseignement supérieur, n.d.-a). Unfortunately, this matrix is not available at a campus level and the number of students per campus is not available either. This last piece information has been found for the biggest campus thanks to other sources (Université Catholique de Louvain, 2021), (ADT ATO.brussels, 2015), (Wikipedia, 2021), (Fédération Wallonie-Bruxelles, 2018). Those numbers do not always date from 2019 but only the range of magnitude matters here so those numbers can be used. For campus where the information is not available, the total number of students commuting to the municipality is simply uniformly spread among all the campus of the concerned municipality. These data have been combined with the percentage of students living in Brussels among the number of students studying in Brussels: 37% (Du Brulle, 2014). The combination of all those data results in the number of students living in a municipality studying in a specific campus in Brussels or outside Brussels per age and gender. The students have been picked from the population simulated in section XVII.C.1.b. and assigned to the work id higher education.

Two different work ids exist for higher education students in Pr. Kornhauser methodology because their probability distribution for the trip chain type allocation is different whether they are living on campus or off campus (Kornhauser et al., 2012). Unfortunately, the probability distribution for the trip chain type allocation in Brussels is not available according to the work id. This distinction therefore has no impact on the trips. However, for the readers interested in the resulting simulated population it is worth explaining. A student having a household type ‘single’ or ‘flatsharing’ and having his residence sector identical to his workplace is considered has living on campus while all the others are considered as living off campus.

Note that here, students have also already received their workplace because of the format of the data. Since this thesis only focuses on trips happening in Brussels, for people studying (or working) outside Brussels, their workplace corresponds to the closest sector being on the periphery of Brussels to their sector of residence. This corresponds to the assumption that people studying (or working) outside Brussels leave Brussels as soon as possible with the idea of reaching the fast lines as soon as possible. In the GPS’ language this corresponds to choosing the “fastest itinerary” instead of the “shortest” one.

Data from the Dutch Federation are far less specific. Dataloep (Vlaanderen is onderwijs & vorming, 2018) only provides the number of students studying in Brussels per age and gender and the number of students living in Brussels and studying somewhere also per age and gender. By taking 37% (Du Brulle, 2014) of the people studying in Brussels, the number of students living and studying in Brussels is obtained. Next to that, the difference between this last number and the number of students living in Brussels and studying somewhere gives the number of students living in Brussels and studying outside Brussels. Those students are randomly picked from the simulated population (XVII.C.2.a).

BCSS (BCSS, 2019) provides data on the worker status (independent, employee, unemployed) per municipality, age and gender. Moreover, INASTI’s data (INASTI, 2021), (INASTI - Service Statistiques, 2019) state that 37% of the independents practice a liberal profession and 2% works in the agriculture sector. Those 39% of the independents on top of the number of unemployed people are broken down to the sector level using the population ratio. People are then pick from the simulated population (section XVII.C.1.b) and are seen has staying at home. It means that their workplace is the same as their living place.

After assigning secondary school students, higher education students and young adults staying at home because unemployed or independents, all the other people aged between 18 and 20 receive the work id corresponding to worker.

The exact same process is applied for people aged between 19 and 64 years. Some receive the higher education work id, others the “stay at home” work id and all the others are assigned to the worker work id.

For seniors older than 64 years, the same data from INASTI (INASTI, 2021), (INASTI - Service Statistiques, 2019) are used while the number of people working significantly decreased compared to the previous age category. As a result, the majority of the elderly people receive the work id “Stay at home”.

#### Workplace alone

After the assignment of the work ids, babies, students from the higher education in the francophone federation and people staying at home already have their workplace. However, it still has to be determined for all the other residents.

The neighborhoods’ monitoring provides data on the part of kindergarten students studying outside Brussels per neighborhood of residence (Monitoring des quartiers, 2019au). These numbers multiplied by the number of children living in each neighborhood result in the absolute number of kindergarten students studying outside Brussels. Those children are randomly picked from the children with kindergarten work id and living in the concerned neighborhood. Those numbers are not broken down to the sectors level because too few children are concerned. As explained above, since they are studying outside Brussels, their workplace is the closest sector being on the periphery of Brussels to their sector of residence.

Furthermore, the neighborhoods’ monitoring issues the school capacity for kindergarten per neighborhood as a ratio between the number of kindergarten students studying in the neighborhood and the number of students registered to any kindergarten school (in or outside the concern neighborhood) living in the concerned neighborhood (Monitoring des quartiers, 2019a). A simple multiplication with the number of students registered to any kindergarten school (in or outside the concern neighborhood) living in the concerned neighborhood coming from the population simulation and the work id assignment gives the absolute number. It is then broken down to the sector level using the population ratio.

Another interesting statistic produced by the neighborhoods’ monitoring is the proportion of children going to a kindergarten school being in an adjacent neighborhood to their living neighborhood (Monitoring des quartiers, 2019ar). This number is available at a neighborhood level. Once again, a simple multiplication results in the absolute number. Children from a given neighborhood are randomly picked and allocated to a kindergarten school from an adjacent neighborhood where there are still enough places.

As a complement, the IBSA (IBSA, 2019d), provides a matrix of the flows between the municipality of residence and the municipality of the kindergarten where the children are going. After deduction of the children already assigned to a workplace, those numbers allow the allocation of a sector in the concerned municipality as workplace for the remaining children (i.e., the children studying in a kindergarten inside Brussels but not being in an adjacent neighborhood to their living neighborhood).

The exact same process is applied for primary school students except that the data used (IBSA, 2019d), (Monitoring des quartiers, 2019b), (Monitoring des quartiers, 2019as), (Monitoring des quartiers, 2019av) are different. All children should have been allocated to a workplace. However, because of the rounding error throughout the whole simulation 286 children with a primary school work id remain. They are henceforth randomly assigned to a workplace.

The method is similar but not exactly the same for secondary students because the school capacity per neighborhood is not available. However, the school capacity is available at a municipality level (IBSA, 2019f). The population ratio between the number of teenagers from the simulated population (section XVII.C.1.b) with a secondary school work id (section XVII.C.2.a) living in each sector and the total number of teenagers from the simulated population (section XVII.C.1.b) with a secondary school work id (section XVII.C.2.a) living in the corresponding municipality is used to brought down the capacity at a sector level. Then, the process is exactly the same as for kindergarten and primary students with other data (IBSA, 2019d), (Monitoring des quartiers, 2019at), (Monitoring des quartiers, 2019aw).

The francophone students already have their workplace, but their Dutch speaking counterparts only have their work id. The campuses’ capacities have been determined thanks to different sources (Ginckel, 2018),(ADT ATO.brussels, 2015). Those numbers do not always date from 2019 but only the range of magnitude matters here so those numbers can be used. For campus where the information is not available, the total number of students studying in Brussels is simply uniformly spread among all the campus. Like for the francophone students, these data have been combined with the percentage of students living in Brussels among the number of students studying in Brussels: 37% (Du Brulle, 2014). Since no other information about the provenance of the students per campus is available, the students have been randomly assigned to a workplace respecting the capacity computed. Of course, the distinction being students living on and off campus is respected. Therefore, people living on campus receive a workplace identical to their sector of residence. For students living in Brussels and studying outside Brussels the same methodology is still applied with the closest sector being on the periphery of Brussels to their sector of residence.

Very specific data are available for the workers commuting. The census 2011 (Service Public Fédéral Belge, 2017a) indeed provides a matrix of the number of workers per sector of residence and sector of workplace. However, those data dates of eight years from 2019 … Thus, they have been used in the form of ratios. For example, if there were 4 workers commuting from the sector “Résistance” to the sector “Kleinmolen” in 2011 out of the total 370,380 workers living in Brussels in 2011, this ratio of 1.36 is applied to the total 504,523 workers living in Brussels in the simulated population to result in 5 workers commuting from the sector “Résistance” to the sector “Kleinmolen” in 2019. Some data are aggregated at a neighborhood or municipality level. In those cases, the specific sector is picked randomly. The same logic is used for people living in Brussels but working outside Brussels. Once again, the closest sector being on the periphery of Brussels to their sector of residence is assigned as workplace.

#### Commuters living outside Brussels

Some people do not live in Brussels but work in it. Their trips have to be taken into account. This section focuses on them.

For babies and children below 18 years, the process is based on the remaining places in nurseries, kindergarten, primary and secondary schools. The neighborhoods’ monitoring and the IBSA indeed define the capacity as if it was fully used (Monitoring des quartiers, 2019a), (Monitoring des quartiers, 2019b). For each place still available, one commuter is created. Not all personal parameters (such as the age, gender, household type, …) are defined because they are useless for the trip simulation. They are nevertheless assigned to a sector of residence. Since this one should be outside Brussels, the opposite logic is applied compared to people living in Brussels and working outside Brussels: their residency sector is the closest sector being on the periphery of Brussels to their workplace.

For high education students, ARES (Académie de recherche et d’enseignement supérieur, n.d.-a) provides the same data as presented above for students living outside Brussels and studying in Brussels. The same process to define the residency sector as just explained in the above paragraph is therefore used. For their Dutch counterparts, the methodology is identical to what has been explained in section XVII.C.2.b) but with 63% (Du Brulle, 2014), the percentage of students living in Brussels and studying outside Brussels this time.

Concerning the workers, the same 2011 census matrix is available for people working in Brussels and living outside the city (Service Public Fédéral Belge, 2017a). The exact same process is then applied.

#### Tourists

People making some trips inside Brussels are not only residents and commuters. Brussels also welcomes some tourists. The word tourist must be understood at a broad sense since it includes all kind of travelers (business trips, people on vacation, …). In order to quantify the average number of tourists that has to be taken into account, the table 15.1.1.6 from the IBSA (IBSA, 2019i) helps. This table indeed gives the number of arrivals per year per municipality. By dividing those numbers by 365 (2019 is not a bissextile year (Calendrier 365.be, n.d.)), the average daily number is obtained. The population ratio (Monitoring des quartiers, 2019bh) is useless in this case in order to break down the number of arrivals per municipality to the sector level. Indeed, more people living in a sector does not mean more tourists coming to this sector. The surface ratio between the sector and the municipality it belongs to (Monitoring des quartiers, 2019bh) is used as proxy in this part of the simulation. For tourists, the workplace is identical to their place of residency. This assumes that “tourists” on a business trips opt for a hotel closed (meaning in the same sector as) to their workplace. This is confirmed by La Redaction of "déplacementspros.com" (2014).