Decision making for urban mobility: a macro, meso and micro analysis

Omar Lucas Torres

A Thesis
In
The Concordia Institute
for
Information Systems Engineering

Presented in Partial Fulfillment of the Requirements
For the Degree of
Master of Applied Science (Quality Systems Engineering) at
Concordia University
Montreal, Quebec, Canada

February 2020

CONCORDIA UNIVERSITY

School of Graduate Studies

This is to certify that the thesis prepared

By: Omar Lucas Torres

Entitled: Decision making for urban mobility: a macro, meso and micro analysis

and submitted in partial fulfillment of the requirements for the degree of

Master of Applied Science (Quality Systems Engineering)

complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

Signed by the final Examining Committee:

______________________ Chair
Jia Yuan Yu

______________________ External Examiner
Chunyan Lai

______________________ Internal Examiner
Jun Yan

______________________ Supervisor
Anjali Awasthi

Approved by ____

Dr. Mohammad Mannan, Graduate Program Director

February 18, 2020 ________________________________

Dr. Amir Asif, Dean,

Gina Cody School of Engineering and Computer Science

ABSTRACT

Decision making for urban mobility: a macro, meso and micro analysis

Omar Lucas Torres

Urban congestion is a challenge that cities commonly suffer across the globe. Traffic congestion and longer commutes are linked with poor cardiovascular and metabolic health, along with decreased energy and increased stress among the users. This is further translated into productivity and economic loss, an increase in health service expenses and a general decrease in the quality of social wellbeing.

To improve this condition, the municipality administration has the role of implementing solutions to strategically address urban mobility. However, this is a complex task to achieve and normally involves limited resources, which make real-world deployments have a great inherited risk. Thus, decision-making is a task that has to be carefully addressed by different factors and scales.

This thesis approaches multiple tools for analytics on urban mobility using skills in SQL, R and Python, and open-source software such as QGIS for spatial analysis and SUMO (Simulation of Urban Mobility) for microsimulation. The methodology includes the analysis of urban mobility in Montreal from different levels of analysis.

At the **macro** level, the MTL Trajet dataset provides insight of mobility behaviour of participants through their trip coordinates. Using geometry datasets of quarter and boroughs of Montreal, the analysis is framed and processed via SQL and QGIS. Data visualization is presented in Choropleth maps, Flow maps and Chord diagrams using origin and destination of trips. Supporting processing task such as reverse geocoding to join attributes between datasets are used. The macro analysis helps to identify a primary area of analysis seeking the most transited region. The quarter of René-Lévesque in/and the borough of Ville-Marie are the most accessed areas in this study.

In the **meso** level, street network information from OpenStreetMap allows making relations among the elements of the area, such as universities and their proximity to pedestrian zones.

Resulting maps aid decision-making from a meso perspective, choosing the area of Concordia University as a suitable space for microfocus.

At the **micro-**level, four areas of opportunity interpreted as transit policy-testing were identified. A custom micro-network and synthetic demand for this area were used to simulate the impacts of these scenarios. The measures tested to improve urban mobility in the area are the restriction of street lanes for specific vehicle types and the inclusion of pedestrian areas. Experimentations with different levels of user modal share and shift are presented.

Results of macro, meso and micro analyses are included to provide recommendations for the administration of the city of Montreal. The inclusion of multiple restrained lanes for buses and high-occupancy vehicles around Concordia University and a pedestrian zone will allow to save time to road users, as long as single-passenger vehicle shifts towards public transit and shared–vehicles.

Keywords: urban mobility, decision-making, demand modelling, simulation, transit-policy

ACKNOWLEDGEMENTS

This thesis would not have been possible without the inspiration and support of wonderful people, my thanks and appreciation to all of them for being part of this journey and making this thesis possible.

I express my appreciation to my supervisor, Dr. Anjali Awasthi, who guided me throughout this project and gently understood my questions and concerns as an international student. I wish to acknowledge as well the help provided by the members of the Concordia Institute for Information Systems Engineering (CIISE).

I would like to show my gratitude to Dr. Peter Wagner, my research advisor in Berlin, Germany, who provided me with expertise in SUMO and offered deep insight into the study. I appreciate the contribution of Yara Abu Awad of guiding me in the usage of R for a component of my work.

Finally, my deep and sincere gratitude to my family for their continuous and exceptional love, help and support. I am grateful to my parents, Eugenia and Enrique, for never stop supporting me throughout this journey, financially, motivationally and emotionally. They have always believed in me and gave me the opportunities and experiences that have made me who I am today. The gratitude is also for my brother Enrique, my sisters Thania and Myriam, my nephews Aldebaran, Grecia, Alondra and Saul, and to my relatives and friends in Mexico and Canada who supported me along this process. They selflessly encouraged me to explore new directions in life and seek my destiny.

I dedicate this life and professional milestone to the individuals mentioned above.

¡Muchas gracias!

Omar

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Nomenclature

A text highlighted in blue Consolas font and gray background encases a `computer program`, a `programming language`, a `file extension` or a `script`.

A text highlighted in gray Courier New font encloses a `code argument` or a `table field` reference.

Glossary

AFC	Automated fare collection
AMoD	Automated mobility-on-demand system
AV	Autonomous vehicles
EV	Electric vehicles
ITS	Intelligent Transportation System
MoD	Mobility on-demand system
OD	Origin-Destination Matrix
PA	Planning alternatives

Chapter 1

Introduction

The effects of the increasing world population are gaining more attention as problems reach unmanageable levels and exhibit difficulties to maintain social welfare and sustainable development.

The increasing number and density of the human population in cities aggravate traffic congestion as more vehicles try to use the same infrastructure at the same time (Bazzan & Klügl, 2009). Excessive traffic volume is linked with the main causes of deterioration of cities such as contamination, delays and noise. It also exposes individuals to deficient safety due to risky driver's manoeuvres (Alonso et al., 2017; Bazzan & Klügl, 2009), accidents, transportation delays, loss in their economy, low air quality, and degradation on their physical and mental health.

Authorities have the active role of implementing solutions to strategically alleviate impacts of urban mobility in a sustainable manner. Nevertheless, endeavours are constrained towards selected objectives as challenges are complex, stakeholder's jurisdiction is limited and costs have to be optimized. In this topic, the main interest is achieving free-flowing greener cities with a smarter and more accessible urban transport system (Grimaldo et al., 2012, 2011). Hence, efforts must be assessed according to regulatory measures and organization schemes, in terms of cost, impact, logistic efficiency, sustainable objective, or other criteria (adapted from Jlassi et al., 2018).

In the literature, authors consistently recommend new social behaviour, mobility preferences and transport policies to achieve objectives. Unsustainable collective conduct is primarily based on the extensive use of heavy motorized transportation (hence, energy) to transport a single person, where shared and public transportation is the answer (European Commission, 2016).

Digitization, automation and the integration of state-of-the-art technologies to society disrupt the market rapidly (Hofer et al., 2018), including mobility modes and business models. Awareness of this innovation layer is not a trivial aspect, as it is essential for the horizon of the policy-making in urban mobility. Scant evidence exists to anticipate the effects that these disruptions will have on sustainability.

A global movement

The world has seen in recent years a boom in sustainability matters, highlighting the relevance and immediacy of taking actions to improve future living conditions which are not optimistic. Individuals urge global actions led by governments in order to achieve radical changes.

In the area of urban mobility, governments across the globe have already taken radical actions using transit policies as listed in (Garfield, n.d.):

- Oslo implemented a car ban in the city center in 2019, following a ban on petrol-powered cars by 2025.
- Madrid is banning cars from a certain area in its city center where 24 of the city's busiest streets for walking rather than driving.
- In Chengdu, China, a new residential area was designed from its conception to be walking its main mode of transportation to ensure most destinations within a 15-minute walk.
- Hamburg is making walking and biking its dominant mode of transportation within the next two decades
- Paris is intended to allow only electric vehicles in selected streets by 2020, following a ban from the city center of cars made before 1997 in 2016.
- London deprecates the use of diesel engines by charging a daily "congestion charge" to diesel cars entering some areas during peak hours.
- Berlin created a 34 square miles low-emission zone banning cars that do not meet national emission standards plus a "bike super-highways" network.
- Mexico City local government decided to restrict circulation into the city center on a day-schedule based on license plate numbers.
- Montreal is planning to construct a carbon-neutral neighbourhood heavy on public transport and pursuing car-free residents during the decade of the ’20s (Bruemmer et al., 2019).

Structure of the thesis

This thesis is organized into the following chapters:

- Chapter 1 contains the **Introduction** to the subject of the thesis.
- Chapter 2 includes the **Problem definition** and justifies the scope of this thesis.
- Chapter 3 is the summary of the **Literature Review** regarding simulation techniques in urban mobility useful to support policy-making. Two subsections are crucial for this work: the objectives section focus on the output desired by the researchers (the why). The policy section delivers applied actions used to reach the objectives (the how).
- Chapter 4 describes the **Solution Approach** macro analysis and the steps performed to model demand in Montreal, as well as the search for the area of analysis and the properties of the chosen place.
- Chapter 5 contains **Application Results** applied to the analyses at meso and micro levels. It describes the scenarios constructed for the simulations, including all the set-up required to run these experiments. Results and recommendations are provided.
- Chapter 6 presents the **Conclusion and Future Work** summarizing the work achieved in this master's degree thesis and provides the future direction of research.

Chapter 2

Problem definition

By 2050, 68% of the world population is projected to live in urban areas, in contrast to the 55% registered in 2018 (United Nations, 2018). By 2100, 9.6bn of people are estimated to exist (Vallati et al., 2016). With current levels of inhabitants, traffic congestion is already a challenge for major cities and it's expected to worsen as cities get denser and current patterns of mobility remain.

Usual solution approaches focus on generating the conditions for seamless transportation and improving the flow of vehicles in the streets. Although reducing the halting time per vehicle it's an effective achievement, less attention is invested in high-occupancy modes of transportation. Analysts at Morgan Stanley estimated that passenger and light-duty vehicles worldwide spend approximately 400 billion hours in transit, with an increase if counting by occupancy level (Bodde & Jianan Sun, 2016).

The unsustainable collective conduct is primarily based on the extensive use of heavy motorized transportation (hence, energy) to transport a single person (P. Wagner, personal communication, July 2019). This is why scientists insist on shared and public transportation. Also, the cost of car driving is six times more expensive than cycling, not just for the driver but for society as a whole (Gössling & Choi, 2015).

2.1. Aim of this thesis

Montreal is one of the worst cities in Canada for peak hours spent in traffic congestion (Henriquez, 2017), being chosen as the city of study. The purpose of this work is to analyze urban mobility in Montreal at macro, meso and micro scales to understand user mobility behaviour and propose solutions to decrease time loss spent in traffic congestion.

By measuring the effects of four proposed scenarios by simulation, urban transit-policies are applied to seek positively impact the highest number of people. This research work proposes prioritizing high-occupancy and green modes of transportation by giving arguments for incentivizing the user-shift to these modes. Figure 1 provides a visual example of this thesis.

Figure 1: “The Commuter Toolkit” poster (edited)
200 people commuting in 177 cars (upper left), their bikes (upper right), 3 buses (bottom left) or one light rail train (bottom right). Produced by International Sustainable Solutions (ISS) for the International Sustainability Institute (ISI) (i-SUSTAIN, 2008; Rivenburgh & Chase, Patricia, 2019)

2.2. Research contribution

Increased usage of high-occupancy modes of transportation is a usual approach found in the literature to tackle congestion. However, proposals usually assume a user-voluntarily shift from these modes. The approach in this work is to incentivize and push users to this state by applying divergent transit-policies to public transit and private high-occupancy modes inside the city network.

Chapter 3

Literature Review

This chapter presents a **categorical literature review** of solutions aiming urban mobility issues based on simulation techniques, providing arguments to support transit policy-making. In this format of review, works are presented by subject categories (grouping related studies) without regard to chronological order (UC San Diego, n.d.). The information in this chapter was published in a book chapter (Lucas Torres & Awasthi, 2019).

3.1. Review methodology

The following steps were executed to compose the literature review, as adapted from the methodology found in (2018). Figure 2 presents the workflow overview. The outcome of the categorical review is presented in the following sections by adapting and extending an analytical framework (Jlassi et al., 2018).

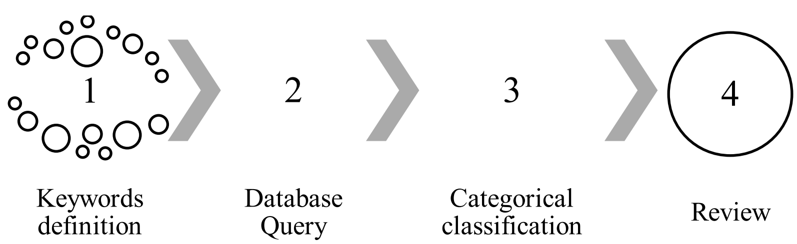


Figure 2: Categorical literature review workflow

Step 1: Keyword definition

The initial action for a literature review is the identification of noteworthy keywords that enclose the field. For this exercise, it consists of two components: (1) The *initial keys* (A) are used to narrow the area, and they include "urban mobility" and "simulation". The *specific keys* (B) are used to create keyword combinations for the next steps. They are illustrated in Table 1.

Step 2: Database Query

Engineering Village is a research database encompassing publications in engineering topics. Access was provided by Concordia University, and it was used as the reference database. This platform provides a searchable index of comprehensive engineering literature and patent information available (*Engineering Village Database*, n.d.). At the time of the exercise, it offers access to 12 databases. Resulting keywords from step 1 were used as the query parameters using the function "AND". The results of each instance are presented in Table 1.

Table 1: Query keywords and search results
Date retrieved: April 2019

Initial Keys (A)		
urban mobility	simulation	
Specific Keys (B)		
urban corridor (10)	congestion (56)	planning (176)
restricted lane (2)	decision support (32)	demand (92)
emergency vehicles (26)	decision making (67)	

Step 3: Categorical classification

This phase involves the classification of the publications using categorical variables. They represent types of data that can be divided into groups in a limited number of possible values (*Categorical Data*, n.d.). During the practice, it was observed that authors provide their solutions without necessarily expressing all the components listed in this work (e.g. data sources, level of analysis, techniques used). Hence, labelling is at the authors' interpretation. The categorical criteria are consolidated in Table 2. An *exploratory* stage allows one to freely tag all aspects of each reviewed work, and decide if it meets the requirements of inclusion. Then, a *consolidation* step enables grouping the tags under similar topics (i.e. categories) to compose the final categories of analysis. The extracted information was entered into an online spreadsheet-relational database hybrid. In this way, each publication can be "labelled" and referenced to registries in other tables.

Step 4: Review

The query resulted in an initial set of 461 papers. After removing duplicates, including pertinent extended references and selecting publications, a final set of 55 were consolidated at the categorical literature review. An overview of each is presented in Table 3.

Table 2: Criteria for categorical classification

Criteria	Categorical set	n
Year	Publications from the last 20 years (2000-2019)	20
Objectives	Improve operations, Reduce energy and emissions, Decrease trip number and distance, Achieve free-flowing, Respond to emergencies	5
Policy group	Public Transportation, Collaborative Models, Behavioral, Infrastructure, Intersections, Autonomous Vehicles, System properties, Framework, Circulation permissions, Priority vehicles, Dynamic Pricing, Active and green modes, Urban Sprawl, Parking, Technological, Electric Vehicles, Urban Logistics, Teleworking, Quality of Service, Road configuration, Alternative Fuels, Rebalancing & Scheduling, Data Privacy, Population Growth, Accessibility	25
Stakeholder	Authorities, Digital entity, End-user, End-user Cohort, Infrastructure & Transit Planners, Service Providers, Technology Suppliers	7
Technique	Agent-Based Simulation (ABS), Discrete Event Simulation (DES), Instance generation (IGS), Machine Learning (ML), Monte Carlo Simulation (MCS), System Dynamics (SD)	6
Data type	Adapted, Historic, Synthetic	3
Data source	Census & Statistics, Environmental, Incidents, Interviews, Repositories, Service suppliers, Social media, Surveys, Traffic counts, User Location, Vehicle communications	11
Level	Micro, Meso, Macro	3
Software	Per instance	n
Source	Conference Proceedings, Scientific Journal, Book Chapter	3

Table 3: Summary of reviewed papers

Problem: Authors (Year)	Stakeholders	Technique	Data	Level
Assessment of three policy measures to address different city challenges: Alonso et al. (2017)	Authorities	SD (Vensim-MARS model)	Historic	Macro
Deploy a multi-agent transport simulation using aggregated telco data.: Anda et al. (2018)	Service Providers, Infrastructure & Transit Planners	ABS + ML (MATSim)	Historic	Meso
Support carpooling and car-sharing modes: Ayed et al. (2015)	Authorities, End-user	ABS (MATSim)	Historic	Micro
Estimate optimal public transport (PT) to passenger car (PC) usage ratios: Basaric et al. (2015)	Authorities, Service Providers	IGS (PTV Visum-NOSTRAM)	Historic	Macro
Use emerging wireless vehicle communications transmitted by individual vehicles for traffic light control and incident detection.: Bastani et al. (2014)	Digital entity, Technology Suppliers	DES + ABS (Paramics)	Synthetic	Micro
Model city mobility to establish a framework for social behavioural change policies: Batur & Koç (2017)	Authorities, End-user	ABS (PTV Vissim)	Historic	Micro
Resource allocation to reduce demand response time (e.g. ambulances, bikes): Bhatia et al. (2018)	Service Providers	ML (OpenAI Gym: BSS + ERSLE; DDPG-Algorithm)	Adapted	Micro
Mitigate the risk of entrepreneurial business environments integrating shared, automated, electric vehicles by understanding simulation models: Bodde & Sun (2016)	Authorities, Service Providers, Technology Suppliers	Framework for emergent simulation environments		Macro
Evaluate the impact on air quality of different PAs: Borrego et al. (2011)	Authorities, Infrastructure & Transit Planners	IGS-DSS (URBAIR)	Historic	Meso
Assess the impact of bicycle infrastructure investments: Buil et al. (2015)	Authorities, Infrastructure & Transit Planners	ABS (FUPOL)	Historic	Micro
Propose an OD-methodology to use open data for urban mobility insights and transport policy: Caiati et al. (2016)	Infrastructure & Transit Planners, Authorities	IGS (PTV Visum)	Historic	Macro
Assess the impacts of illegal double parking: Chrysostomou et al. (2019)	Infrastructure & Transit Planners, Authorities	ABS (AIMSUN)	Historic	Micro, Meso

Table 3. (Continued)

Problem: Authors (Year)	Stakeholders	Technique	Data	Level
Test a method for governing AVs interactions at intersections: Dresner & Stone (2004)	Digital entity, Infrastructure & Transit Planners, Technology Suppliers	ABS (Custom simulator)	Synthetic	Micro
Test a method for controlling AVs at intersections accommodating human-operated vehicles.: Dresner & Stone (2007)	Digital entity, Infrastructure & Transit Planners, Technology Suppliers	ABS (Custom simulator)	Synthetic	Micro
Present a Cooperative Intelligent Transport System (C-ITS) for urban mobility improvement: Edwards et al. (2018)	Technology Suppliers, Infrastructure & Transit Planners, Digital entity, Authorities	ABS (AIMSUN, SUMO, PTV Vissim)	Adapted	Micro
A policy framework to assess the effectiveness of corridor parking restrictions: Elahi et al. (2016)	Authorities, Infrastructure & Transit Planners	IGS (Synchro)	Historic	Micro
Simulation to support a selection of EV charging points: Elbanhawy et al. (2013)	Authorities, Service Providers	Hybrid ABS + DES (AnyLogic)	Historic	Meso
Model social interaction influence on the household location, mobility and activity choice: Ettema et al. (2011)	Authorities	ABS (PUMA-LUTI model)	Synthetic	Micro
Test a policy decision tool with maximization objectives of mobility and equity: Feng & Timmermans (2014)	Authorities, Infrastructure & Transit Planners	ML (MATLAB-Genetic Algorithm)	Historic	Macro
Develop a large scale transportation simulation model to address energy consumption: Fournier et al. (2018)	Authorities	MCS + ABS (SimMobility-TripEnergy)	Adapted	Meso
ABS decision-making in social-ecological systems (ABSS) to achieve free-flow state: Grimaldo et al. (2011)	End-user	ABS-MARA (J-MADeM)	Adapted	Micro, Macro
ABS decision-making in social-ecological systems (ABSS) to achieve free-flow state: Grimaldo et al. (2012)	Infrastructure & Transit Planners	ABS-MARA (J-MADeM)	Adapted	Micro, Macro

Table 3. (Continued)

Problem: Authors (Year)	Stakeholders	Technique	Data	Level
Develop a framework of an agent-based approach focusing on the dynamic formation and dissolution of (location) choice sets: Han et al. (2008)	Infrastructure & Transit Planners, End-user	ABS (Aurora model) + MCS + ML principles (FEATHERS model)	Synthetic	Micro
Assess the impact of different policies on CO2 emissions: Hofer et al. (2018)	Authorities, End-user	ABS (Own implementation)	Historic	Micro
Evaluate operational policies for AMoD System: Hörl et al. (2019)	Service Providers, Digital entity	ABS (MATSim)	Adapted	Micro
Evaluate the efficiency of urban traffic signal control algorithm: Houli et al. (2010)	Digital entity	Hybrid ML + ABS (Q-Learning based)	Synthetic	Micro
Policy framework for the ageing population: Kanaroglou et al. (2008)	End-user Cohort, Authorities	IGS (IMPACT)	Historic	Micro
Simulation of jointly improvement of public transit, smart growth development, and vehicle ownership decrease.: Khan et al. (2016)	Authorities, Infrastructure & Transit Planners, End-user	IGS (NLOGIT)	Historic	Macro
Intersection control policy for AV & EV: Kristensen & Ezeora (2017)	Digital entity	ABS + ML (JADE & SUMO)	Synthetic	Micro
Assess areas most impacted by routing apps: Lazarus et al. (2018)	Authorities, Infrastructure & Transit Planners, Digital entity	IGS (RIDER DSS)	Historic	Meso
Evaluate policies aiming at increasing bike-sharing mode choice: Li & Kamargianni (2018)	Authorities, End-user	IGS	Adapted	Macro
Rebalancing policies for AMOD System: Marczuk et al. (2016)	Service Providers, Digital entity	ABS (SimMobility)	Synthetic	Micro
Assess policies aiming low-carbon urban development: Menezes et al. (2017)	Authorities, End-user, End-user Cohort, Infrastructure & Transit Planners, Service Providers, Technology Suppliers	SD (Vensim: ForFITS)	Historic	Macro
Model travel demand impacts of fare-free public transport policy: Mocanu et al. (2018)	Authorities, Service Providers	IGS (DEMO)	Historic	Macro

Table 3. (Continued)

Problem: Authors (Year)	Stakeholders	Technique	Data	Level
Analysis of Transit incentives & private cars disincentives strategies: Musso & Corazza (2006)	End-user, Authorities, Service Providers	IGS (Miracles project)	Historic	Micro
Elaboration of MAS model encompassing cognitive abilities of agents: Occelli & Staricco (2009)	Infrastructure & Transit Planners, End-user	ABS (SWARM Simulation System)	Synthetic	Micro
Assess public policies using a generic architecture coupling a world simulation and a policy manager using multi-agent modelling: Pageaud et al. (2018)	Authorities, Service Providers	ABS + ML (Repast Simphony Platform-SmartGov model)	Historic	Micro, Macro
Robotic re-balancing policy testing for MOD system: Pavone et al. (2012)	Digital entity, Service Providers	IGS (MATLAB)	Synthetic	Micro
Analyze mixed-fleet policies under novel business models (i.e. cargo bikes): Perboli & Rosano (2019)	Service Providers	MCS-DSS	Historic	Macro
Validate and compare car-sharing company tariffs using traffic simulation: Perboli et al. (2018)	Service Providers	MCS (Concorde TSP Solver)	Historic	Macro, Micro
Present a protocol for smart intersections with a real-time simulation policy evaluation: Perronnet et al. (2013)	Infrastructure & Transit Planners, Digital entity	ML (Voxelia Simulate)	Synthetic	Micro
Ridepooling AV fleet: Samaranayake et al. (2018)	Service Providers, Digital entity	IGS (Python-MILP)	Historic	Micro
Pricing policy simulation for the smart grid of power infrastructure used by Online EVs: Sarker et al. (2017)	Service Providers, Technology Suppliers	ABS + IGS (SUMO)	Historic	Micro
SD model to evaluate the impact of regulatory policies for sustainable transport planning in vehicle trip reduction: Sayyadi & Awasthi (2017)	Infrastructure & Transit Planners, Authorities	SD (DYNAMO)	Synthetic	Macro
Integrated approach for evaluating and ranking sustainable transport policies: Sayyadi & Awasthi (2018)	Infrastructure & Transit Planners, Authorities	SD (DYNAMO) + ANP	Synthetic	Macro

Table 3. (Continued)

Problem: Authors (Year)	Stakeholders	Technique	Data	Level
Intention-aware decision-making algorithm at uncontrolled intersection with AVs: Song et al. (2016)	Digital entity, Infrastructure & Transit Planners	ML (PreScan) + Human input	Historic	Micro
MAS simulation model to analyze the effect of a real road-user charge policy: Takama (2009)	Service Providers, End-user, End-user Cohort	IGS + ML (Own implementation)	Historic	Micro
Evaluate policy impacts through weighted index simulation to give recommendations: Tsiropoulos et al. (2019)	Authorities, Infrastructure & Transit Planners	IGS (Composite Index)	Historic	Macro
Use mixed discrete-continuous planning to deal with unexpected circumstances in urban traffic control.: Vallati et al. (2016)	Infrastructure & Transit Planners	IGS (UPMurphi+PDDL+ encoding) + ABS (SUMO validation)	Historic	Macro
Support evidence for policy interventions that address land-use as a means of influencing mobility behaviour: Vance & Hedel (2007)	Authorities, Infrastructure & Transit Planners	IGS (Stata-2PM Model)	Historic	Meso
Taxi redistribution policy: Volkov et al. (2012)	Infrastructure & Transit Planners, Service Providers	MCS (MATLAB)	Historic	Micro, Meso
Develop a data-driven simulation model for decision-making during hurricanes: Wang & Taylor (2016)	Authorities, Infrastructure & Transit Planners	ABS (ArcGIS & Python)	Historic	Micro, Meso, Macro
Propose a simulation-tool for urban rail transit network for traffic policies: Yao et al. (2015)	Service Providers, Infrastructure & Transit Planners	ABS-based (SURPASS)	Historic	Micro, Macro
Large-scale Smart City Simulator for subway infrastructure changes: Zambom Santana et al. (2018)	Service Providers, Authorities	ABS (InterSCSimulator)	Adapted	Micro
AVs anticipation of interaction with other traffic participants: Zhou et al. (2018)	Technology Suppliers, Digital entity	ML (DESPOT & FORCES Professional)	Synthetic	Micro

3.2. Timeline

For this work, the last 20 years (2000-2019) were selected. 85% of the endeavours have been published in the last 10 years, suggesting the increasing interest of simulation techniques in this area, and perhaps, their maturity.

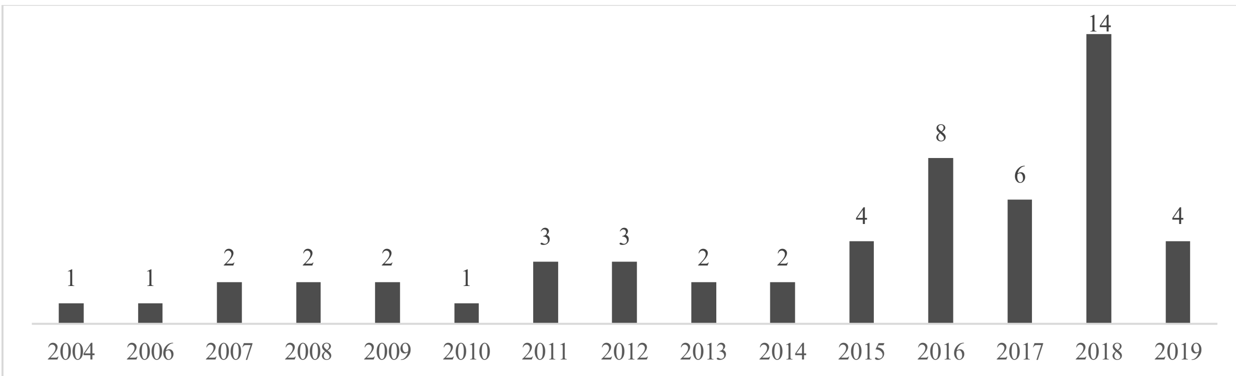


Figure 3: Publications by Year

3.3. Location

The region of study of the publications was tracked. Authors applied their case studies to specific, multiple, or no location in specific. In the latter, the affiliation location of the main authors is used. It is also common that publications are joint efforts from authors at different locations.

Half of the publications (53%) were deployed in European contexts, followed by American countries (28%). Per country, the United States of America, Italy and China lead the research area.

Table 4: Publications by location

Continent	Country	Frequency	Percentage
America 20 (28%)	Brazil	2	3%
	Canada	4	6%
	Mexico	2	3%
	United States of America	12	17%
Asia 13 (18%)	China	5	7%
	Iran	1	1%
	Japan	1	1%
	Malaysia	1	1%
	Singapore	4	6%
	Turkey	1	1%

Table 4. (Continued)

Continent	Country	Frequency	Percentage
Europe 38 (53%)	Austria	1	1%
	Belgium	1	1%
	Denmark	1	1%
	Finland	1	1%
	France	3	4%
	Germany	2	3%
	Greece	5	7%
	Italy	7	10%
	Luxembourg	1	1%
	Netherlands	4	6%
	Poland	1	1%
	Portugal	1	1%
	Republic of Macedonia	1	1%
	Serbia	1	1%
	Spain	3	4%
	Switzerland	1	1%
	United Kingdom	4	6%
Oceania 1 (1%)	Australia	1	1%
Grand Total		72	100%

3.4. Scale of analysis

In urban mobility simulation, there are three traditional levels for traffic modelling and network representation. An extensive review of these models can be found in (Ferrara et al., 2018).

Macro models describe traffic streams with characteristics such as density, flow, mean speed etc. These models are conventionally generated by means of aggregated variables. They can also be pictured as Top-down approaches, which use less computational resources, but regularly struggle in flexibility to evaluate different scenarios (Hofer et al., 2018).

Meso models are usually conceived as the bridge between micro and macro approaches. They describe the traffic flow dynamics in an aggregated representation keeping the individual driver behaviour using probability distribution functions.

Micro models describe the behaviour of each vehicle and model their interaction with other traffic participants within the road infrastructure. These models are dynamic in nature and let estimate the behaviour at a decision level, in contrast to traditional macro-economic models that assume equilibrium and only describe the final state of a spatial system (Ettema et al., 2011).

The publications included in this overview were classified according to their level of representation, being micro modelling the most frequent level of analysis (64%), followed by macro (36%) and Meso (16%). Some of the studies are presented from multiple perspectives; as a result, the percentages do not add up to 100%. Figure 4 summarizes findings in a Venn diagram to visualize intersections, summing 100%.

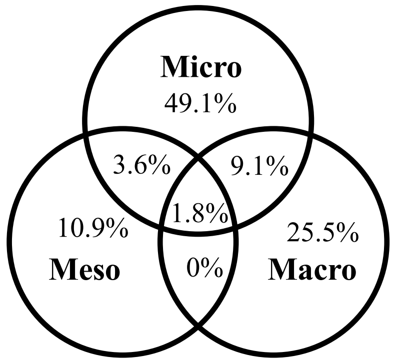


Figure 4: Scale of analysis

3.5. Stakeholders

In order to achieve success and proper deployment of the suggested policy, a certain type of stakeholder need to intervene. Seven categories were used:

- **Authorities**: actors with official responsibility involved in public decisions and policy-making to promote a virtuous society, regularly government and city administrators.
- **Digital entity**: this category places the non-human players that decide in the real world, such as AI algorithms, conceptual intersection managers and routing services.
- **End-user**: certain policies depend entirely on the active participation of citizens and positive reception.
- **End-user cohort**: similar to the end-user category, this one concerns a specific population minority (e.g. teleworkers, ageing group).

- **Infrastructure & transit planners**: participants responsible to design, deploy and evaluate strategies aiming to improve urban mobility. This category includes intelligence solution providers (e.g. optimization, programmers, and systems architecture designers).
- **Service providers**: players in charge of delivering a service in exchange for monetary return such as parking administrators and taxi fleet companies. Also, emerging parties involved in deploying shared mobility systems (traditional/AV/electric) and infrastructure (grids of power) are included.
- **Technology suppliers**: industry partners that provide the technological enablers for the policy execution (e.g. infrastructure devices, engine improvements, alternative energies).

Figure 5 shows the stakeholder needed to intervene in the publications. Authorities (55%), Infrastructure & transit planners (47%) and Service providers (36%) are the recurrent participants. Most of the studies are dependent on multiple actors; as a result, the percentages do not add up to 100%.

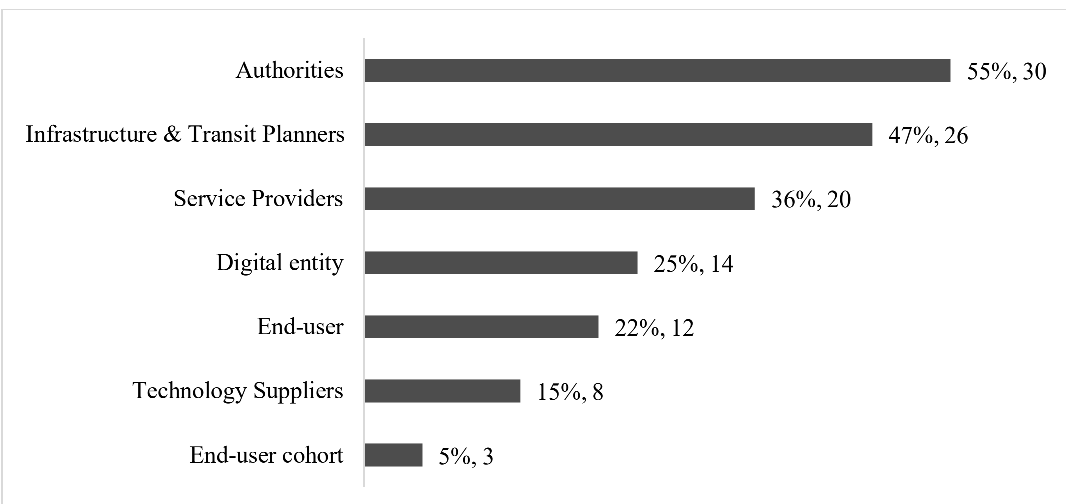


Figure 5: Stakeholders

Authorities

The results of this literature review make it evident that the execution of half of the solutions depends on their participation. A noteworthy example is the simulation study aiming to quantify the impacts of illegal double parking in a city, where the authors insist on the importance of law enforcement and measures aimed at reducing and eventually eliminating this situation to enhance traffic conditions and air quality along the urban corridor (Chrysostomou et al., 2019).

Infrastructure & transit planners

Simulation can aid problems regarding travel demand forecasting using telecom data (Anda et al., 2018) or open data (Caiati et al., 2016), plan ahead for the appearance of unexpected circumstances in urban traffic (Vallati et al., 2016), model for decision-making during hurricanes (Wang & Taylor, 2016b, 2016a), estimate effects of different solutions in air quality (Borrego et al., 2011), evaluate the impact of bicycle infrastructure investments (Buil et al., 2015) or the changes in urban mobility dynamics with the introduction of new mobility systems using V2I/V2V protocols (Edwards et al., 2018), assess the effectiveness of parking restrictions (Elahi et al., 2016), improve the tools to understand the influences of land-use in urban transit (Feng & Timmermans, 2014; Vance & Hedel, 2007) or model decisions made by the citizens about mobility preferences (Grimaldo et al., 2012, 2011; Occelli & Staricco, 2009).

Service providers

Actors in charge of delivering a service in exchange for monetary return such as parking administrators and taxi fleet companies, as well as emerging parties involved in deploying shared mobility systems (AV/electric) and infrastructure (smart grid of power). They must follow the administrative regulations, as they are the bridge between consumers and industry. Also, they are in charge of deploying the economic development of urban mobility.

Digital entity

A part of the transition to smart cities corresponds to urban mobility and will be possible through the extensive use of ITS. Here, technology and data are expected to support and eventually govern decision-making and deliver complex solutions through digital entities designed to facilitate work for humans.

In the literature, the higher attention belonged to Autonomous Vehicles. Scenarios look for communication between vehicles and roadside infrastructure to deliver more intelligent traffic management (Edwards et al., 2018; Bastani et al., 2014), relying on wireless communications technologies of type Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I). Others create a digital manager at intelligent intersections (Kristensen & Ezeora, 2017; Perronnet et al., 2013; Houli et al., 2010). From the vehicle perspective, movement decision-making such as lane change maneuver and crossing through uncontrolled intersections are addressed through intention-aware decision-making algorithms to anticipate interaction with other traffic participants (Zhou et al., 2018; Weilong Song et al., 2016).

In emergent mobility systems, intelligent entities manage a fleet of AVs in an AMoD system assuming that any vehicle can be tracked and controlled online (Hörl et al., 2019; Samaranayake et al., 2018; Marczuk et al., 2016). These scenarios involve car-sharing and ridepooling models. Another solution considers empty robotic vehicles autonomously driving between stations to rebalance non-AVs in the traditional MoD system (Pavone et al., 2012).

In the area of digital assistants, a civic debate exists whether mobile routing services alter negatively the design of the transit network by the influx of “selfishly” routed drivers seeking the fastest route (Lazarus et al., 2018).

End-user

In most of the cases, end-users did not play an active role in policy-making, but learning from their collective and individual behaviour was essential to ensure the pertinence and success of the measures, especially the ones promoting a change in their habits.

In traffic planning and modelling, obtaining detailed information from users in a disaggregated manner is a promising (yet costly) solution to understand mobility systems. The presented works gathered and processed user data to solve research questions from different angles: to explain user social interaction and their mobility reasoning (Batur & Koc, 2017; Grimaldo et al., 2012, 2011; Occelli & Staricco, 2009), to promote change at the mode-choice towards collaborative models (Batur & Koc, 2017; Ayed et al., 2015; Musso & Corazza, 2006), public transportation (Batur & Koc, 2017; Menezes et al., 2017; Khan et al., 2016; Musso & Corazza, 2006) or active modes (Li & Kamargianni, 2018; Khan et al., 2016), and to make assumptions at strategies aiming to reduce vehicle ownership (Khan et al., 2016; Musso & Corazza, 2006).

Technology suppliers

The current trend of automation and data exchange in ITS are changing the transportation business practices, and thus, their framework of regulations. Technology suppliers have to comply with new regulations (e.g. for AV safety) since their solutions are strongly connected to user privacy, operations safety and cyber-security.

In the literature, simulation served to test solutions deploying vehicle communications (Edwards et al., 2018; Zhou et al., 2018; Bastani et al., 2014), controlled intersection scenarios with

AVs (Dresner & Stone, 2004, 2007), assess novel business environments integrating disruptive technologies (Bodde & Jianan Sun, 2016) and technology replacement of fossil fuels by alternative sources of energy (Menezes et al., 2017). In (Sarker et al., 2017) a pricing policy simulation was done to assess a new type of power infrastructure for Online EVs (wireless charging grid).

End-user cohort

Policy-making is not a trivial task as it isn't a fit for everyone. Certain clusters of the population must be evaluated independently to narrow cases undefined by general policies or to support groups impacted negatively by new policies. That is the case of a road-charge policy evaluated in a national park using a simulation model (Takama, 2009), giving exemptions to elderly visitors in an effort to keep their comfort (allowed to use nearby parking lots) without sacrificing that of younger visitors significantly.

3.6. Data

The data source and type were registered on a non-comprehensive basis. In this categorical variable, the emphasis is on data inputted in the simulation. The categories for classification are:

- **Historic**: a collection of data extracted from a real environment over a certain period of time. Sources vary.
- **Synthetic**: the population is generated artificially and does not represent a real-world instance.
- **Adapted**: historic data with a redirected context (e.g. change of mode of transportation from car to bus). Sample-public datasets fit in this category.

Most of the papers (58%) used Historic data. The rest made use of Synthetic (25%), Adapted (15%) or unspecified (2%). Data sources are presented in Table 5 by frequency crossed with the level of analysis. Travel surveys and service supplier data were the most used sources, especially for micro models. In general, user data was manipulated to aggregated and/or disaggregated forms to compose regions of analysis in the form of layers.

Table 5: Data source by the level of analysis

	Micro	Meso	Macro
Census & Statistics	2	2	2
Environmental	1	0	0
Incidents	1	1	0
Interviews	0	0	2
Repositories	1	0	3
Service suppliers	8	3	3
Social media	1	1	1
Surveys	8	5	5
Traffic counts	5	2	3
User Location	0	1	0
Vehicle communications	3	0	0

3.7. Software

If classifying by software usage, 44 publications make use of one or multiple programs to compute their results, making 62 instances of the 44 computational packages. Table 6 presents them by frequency of appearance, being `SUMO` (Simulation of Urban Mobility) the software most used in the revised literature of this topic. `MATSim` and `MATLAB` follow.

Under the current angle of analysis, 52% of the instances are by "popular" software packages, meaning more than one use. The other 48% (*n=30*) is used by a single publication, meaning a fragmentation in the available simulation tools. The lack of a leading tool/language can potentially restrain the development and maturity of this technique.

Also, understanding the features and methods of each software is not in the scope of this paper. Several models are implemented as modules in existing software or it is unclear which programs (and how) applied the simulation step. Thus, this supports the fragmentation argument and lets to consider this section merely as an early overview.

Table 6: Software solutions

Type	Mixed	Each	Software
Popular (32, 52%)	4 (6.5%)	4 (6.5%)	SUMO
	6 (9.7%)	3 (4.8%)	MATSim, MATLAB
	22 (35.5%)	2 (3.2%)	AIMSUN, DYNAMO, GIS Simulation toolset, Google Maps Matrix, J-MADeM, OMNeT++, PTV Vissim, PTV Visum, SimMobility, Veins, Vensim
Single-use (30, 48%)	30 (48%)	1 (1.6%)	AnyLogic, Concorde TSP Solver, Cube Dynasim, DEMO, DESPOT, EnViVer, FEATHERS, FORCES Professional, FUPOL, IMPACT, InterSCSimulator, JADE, NLOGIT 4.0, OpenAI Gym-BSS, OpenAI Gym-ERSLE, Paramics, PDDL, PreScan, PUMA, Repast Simphony Platform, RIDER DSS, Stata, SURPASS, SWARM Simulation System, Synchro simulation tool, TraCI, TraSMAPI, UPMurphi, URBAIR, Voxelia Simulate

Finally, both of the most "popular" packages, SUMO and MATSim, use the Agent-Based Simulation technique. SUMO was chosen for the purpose of this research. Chapter 5 presents the results of simulations using this software.

3.8. Techniques

What is the difference between modelling and simulation? The former is a simplified representation of a system (Jlassi et al., 2018) and the latter is the operation of the model that can experiment changes in the variables to understand how the system it represents can perform over time.

Six categories of simulations are found in this literature review (Lucas Torres & Awasthi, 2019): Agent-Based Simulation (ABS), Discrete Event Simulation (DES), Instance generation (IGS), Machine Learning (ML), Monte Carlo Simulation (MCS) and System Dynamics (SD).

The simulation techniques used by each publication are listed in Table 3. Table 7 presents the techniques used in the publications.

Table 7: Simulation techniques

General

	Frequency	Percentage
ABS	27	42%
DES	2	3%
IGS	18	28%
MCS	4	6%
ML	10	15%
SD	4	6%

By combination

	Frequency	Percentage
ABS	18	33%
IGS	15	25%
ML	5	9%
SD	4	7%
ABS + ML	4	7%
MCS	3	5%
ABS + DES	2	4%
ABS + IGS	2	4%
ABS + MCS	1	2%
ML + IGS	1	2%

Agent-Based Simulation (ABS)

Permits the representation of actions and interactions of autonomous entities that follow their own rules and objectives (Jlassi et al., 2018) and it is commonly considered as a Bottom-up approach by building the behaviour of individual autonomous heterogynous entities and aggregate to obtain a macro-scale result (Elbanhawy et al., 2013; Hofer et al., 2018). In this technique group, Multi-Agent Systems (MAS) are addressed using a simulation approach, although it is more associated to the domain of Artificial Intelligence (Niazi & Hussain, 2011) as it accounts for the construction of complex systems involving multiple agents and mechanisms for modelling of independent Intelligent agents' behaviours (Dresner & Stone, 2007) such as their perception and response to changes in the environment, the exhibition of a goal-directed behaviour by taking initiatives and their social ability and autonomy (Kristensen & Ezeora, 2017).

Discrete Event Simulation (DES)

It uses the concept of entities, resources and block charts where queuing, waiting, servicing, and processing events occur while the system changes instantaneously in response to certain events (Jlassi et al., 2018). It represents quantitatively the real world and simulates its dynamics on an event-by-event basis (Babulak & Ming Wang, 2009). Although it has been traditionally applied to the manufacturing sector, applications in the service sector are rising while business operation challenges get more complex.

Instance generation (IGS)

Encloses a broad number of solutions executing tests on configurations of scenarios (perhaps non-exhaustive) to estimate the performance of the system, its built-in algorithms and/or the impacts of specific criteria in the experiment output (Jlassi et al., 2018).

Machine Learning (ML)

Many publications included in this work apply ML approaches to formulate numerical solutions to urban simulation problems, and then they use other simulation techniques to prove the feasibility of their conclusion. Simulation models are built "process-centric" while ML models are built "data-centric" (Schumann, 2018). Jones et al. suggest that machine learning methods can reduce the number of simulation instances and obtain similar results in comparison with more costly computational alternatives (Jones et al., 2019). As expressed on their blogs, Schumann and Hill suggest that ML is imminently joining simulation techniques (Hill, 2018; Schumann, 2018). For this, this technique category was added to the reference framework.

Monte Carlo Simulation (MCS)

Generates random objects or processes by means of a computer arisen 'naturally' as part of the modelling of a real-world system, and then they are introduced "artificially" to solve deterministic problems (Kroese et al., 2014). In essence, MC makes use of random sampling from particular probability distributions and statistical analysis to compute results (Jlassi et al., 2018).

System Dynamics (SD)

System dynamics performs the analysis of a system as a whole. The core concept is understanding how all the objects in a system interact among themselves (MIT SDEP, 1997). This technique is mainly used in the area of the engineering design process (Elbanhawy et al., 2013).

3.9. Scenarios of analysis

The 55 publications were classified according to 2 main criteria: Objectives and Policies. These are similar, dependent and different concepts. For example, measures aiming to attract users to bike usage (policy) may be originated with the expressed back-end intention of decreasing emissions and reduce heavy motorized trips (objectives).

3.9.1. *Objectives*

Half of the publications involving simulation for policy-making pursue the improvement of operations, followed by a third seeking to reduce energy, emissions, number of trips and distance. The results are summarized in Table 8. Notice that several of the reviewed works pursue multiple objectives; as a result, the percentages do not add up to 100%.

Table 8: Goal frequency by category appearance

ID	Goal	Count	%
O1	Improve operations	29	53%
O2	Reduce energy and emissions	19	35%
O3	Decreasing trips and distance	18	33%
O4	Pursuing free-flowing	12	22%
O5	Emergency response	4	7%

A two-dimensional comparison in Table 9 lists the relation of 2 main components. For example, from all the 29 works seeking the improvement of operations (O1), 17 pursue O1 only, when 4 pursues O1+O2+C and 5 pursue O1+O3+C. Here, C represents a third or more objective sought.

Table 9: Objectives matrix, 2 main components

	O1	O2	O3	O4	O5
O1	17				
O2	4	7			
O3	5	8	2		
O4	4	2	4	4	
O5	1	0	0	1	2

Improving the operations (O1)

Improvement of the operations is the objective most sought by the simulation works. This category encloses publications working with novel business models and technologies to understand the integration with current mobility systems, evaluating the effects of operational changes. In general, they have the following properties:

- **Conceptual operations**: comprehension of system behaviour by applying theoretical control policies tests for AMoD systems (Hörl et al., 2019; Marczuk et al., 2016), AV ridepooling fleet (Samaranayake et al., 2018), AV interacting with its environment (Weilong Song et al., 2016; Zhou et al., 2018) or the infrastructure executing control over them (Dresner & Stone, 2004, 2007; Perronnet et al., 2013)
- **Emerging business models**: testing of emerging (perhaps also conceptual) operations to quantify benefits or utilities, such as for a smart grid of power used by Online EVs (receiving power on the go) (Sarker et al., 2017), a mixed-fleet for last-mile parcel delivery (e.g. cargo bikes, AVs and drones) (Perboli & Rosano, 2019), evaluation of multiple car-sharing tariffs (Perboli et al., 2018) or carpooling/car-sharing systems (Ayed et al., 2015) and risk mitigation for entrepreneurial business environments integrating these new technologies (Bodde & Jianan Sun, 2016).
- **Optimization**: seeking solutions to increase the yield of systems, such as a redistribution policy to anticipate the demand of taxis by zone (Volkov et al., 2012), ambulances/bikes (Bhatia et al., 2018) or AVs in AMoD system (Marczuk et al., 2016).
- **Insights**: simulation models built to understand interrelations and trigger areas of opportunities from the learnings. Efforts include the impact assessment of phenomena such as routing apps (Lazarus et al., 2018) and illegal double parking (Chrysostomou et al., 2019), the understanding of agent behaviour (Han et al., 2009; Occelli & Staricco, 2009) and response to policy changes (i.e. road toll) (Takama, 2009) and the deployment of simulation models using big data (Anda et al., 2018; Caiati et al., 2016).
- **Planning**: involves simulation models strongly aiming to support decision-making in planning stages for bicycle infrastructure investments (Buil et al., 2015), improvements in public/urban rail transit (Yao & Morikawa, 2015; Zambom Santana et al., 2018), localization of EV charging points (Elbanhawy et al., 2013), re-evaluation of permits for

the ageing population (Kanaroglou et al., 2008) and induced mobility behaviour by household location (Ettema et al., 2011).

Reducing energy and emissions (O2)

Environmental preservation is nowadays a key pillar for urban studies, and it is consistent with the objective trend of the selected studies. Although is a common criterion for 35% of research efforts, local authorities still struggle to find the appropriate tools for modelling emissions (Hofer et al., 2018). Learnings from this objective are:

- **Policy environmental assessment**: a common task while solving urban mobility problems is to assess the impact of the solutions in the environment. Specific cases involve the estimation of energy consumption and emissions of air pollutants derived from a phenomenon of illegal double parking in Greece (Chrysostomou et al., 2019) and general cases involve the selection of different planning alternatives according to their effect in the environment (Alonso et al., 2017; Borrego et al., 2011; Fournier et al., 2018; Hofer et al., 2018; Menezes et al., 2017; Sayyadi & Awasthi, 2017, 2018; Tsiropoulos et al., 2019).
- **Intelligent Transport Systems** promise operational benefits that reduce idling, over-circulation due to lack of information and other types of human error that worsen congestion, as found in (Edwards et al., 2018).
- **Alternative sources of energy**: simulation environments also integrate novel technologies for their analysis. Findings suggest that dense areas tend to have a low fuel economy (Fournier et al., 2018). Examples of projects are the infrastructure pricing simulation of a smart grid of power for online EVs to avoid energy demand congestion (Sarker et al., 2017) and the reduction in GHG emissions through enhancement of energy efficiency and a rise in the use of biofuels (Menezes et al., 2017).
- **Greener modes of transportation**: another learning from this objective is the intention to reduce emissions through more active and dense modes of transportation. Researchers study the increase of use of bike-sharing (Li & Kamargianni, 2018) or public transport (Basaric et al., 2015; Mocanu, 2018) through optimal usage ratios and fare-free service.

Decreasing trips and distance (O3)

Congestion is caused by the saturation of vehicles in the network and the authority of the car. Transporting a single person in a motorized vehicle (more than 1000 kg) is not a sustainable practice as it uses a high ratio of fuel, space and energy compared with other modes. This objective category encloses strategies to shift user share from low-occupancy motorized trips to other modes, mostly by discouraging car ownership and motivating collaborative models, transportation alternatives and sensitizing the increasing cost of the use of private vehicles (Ayed et al., 2015). Although reducing private motorized trips have promising effects, the key challenge is surpassing the low acceptance from users over these disincentives (Musso & Corazza, 2006). Policies addressing the reduction of the number of circulating cars were found to lead to significant results if 30% of car users change their mobility behaviour and/or transport modes but allows only a 10% decrease in fuel consumption and CO2 emissions for what does not seem the most effective solution for decreasing pollutants in the cities (Carteni & De Luca, 2014). The works seeking this goal have the following efforts:

- **Increase vehicle occupancy and reduce circulating vehicles**: researchers promote vehicle trips with a higher number of occupants, assuming a natural reduction of cars in the system through this. They evaluate scenarios with increased vehicle occupancy (Menezes et al., 2017) especially for home-to-work trips (Musso & Corazza, 2006), the higher integration of carpooling and carsharing systems in society (Ayed et al., 2015) including robotic-fleet scenario (Hörl et al., 2019; Marczuk et al., 2016; Pavone et al., 2012; Samaranayake et al., 2018), the economic feasibility of these measures (Perboli et al., 2018) and integrated mixed-scenarios (Batur & Koc, 2017; Khan et al., 2016; Sayyadi & Awasthi, 2018, 2017).
- **Shifting user-share to greener or denser modes of transportation**: some authors look for increasing bike usage (Li & Kamargianni, 2018), estimate optimal public transport to passenger car shift ratios (Basaric et al., 2015) or analyze transit incentives (Musso & Corazza, 2006) with more radical cases such as fare-free regional public transport (Mocanu, 2018).
- **Rethinking city layout**: in the context of the relation between city layout and-user mobility choice, the spatial analysis of certain cases of simulation support evidence for

land-use policy interventions (Vance & Hedel, 2007) important to succeed in trip-distance reduction and mode choice shift.

- **Justifying environmental benefit**: an inherited contribution of these measures.

Pursuing free-flowing (O4)

When addressing urban mobility challenges, reducing congestion is by default an objective. This objective category focuses on publications aiming at manipulating the road flow performance to achieve free-flow. Learnings include:

- **Parking worsens congestion**: the illegal parking case (Chrysostomou et al., 2019) suggests improvement of traffic conditions through road layout redesign (to the legal layout). In (Elahi et al., 2016) parking operations and restrictions are evaluated to balance destination accessibility and road mobility.
- **Emerging ITS** will improve flow through wireless vehicle communications acting in traffic light control, incident detection (Bastani et al., 2014) and user traffic awareness to improve routing.
- **Optimization techniques** for resource allocation in city logistics or emergent mobility models reduce response time, exiting vehicles faster from the system (Bhatia et al., 2018; Volkov et al., 2012).
- **Crowdsource usage of digital assistants** generates a social phenomenon that changes the dynamics of the city, as mentioned in (Lazarus et al., 2018).
- **Circulation restrictions and fees** are effective car disincentives (Musso & Corazza, 2006).
- **Expansion of infrastructure** is not a suggested measure (Hofer et al., 2018).

Responding at Emergencies (O5)

Emergencies are difficult to anticipate and adapt to urban mobility planning since every situation has its own nature, forms of impact and challenges. Researchers have used simulation in very specific scenarios that contribute to this area, with the following key learnings:

- **Modelling human mobility behaviour** applies also in emergency situations as suggested in the perturbed scenarios during a hurricane (Wang & Taylor, 2016a, 2016b).

- **Emergency resource allocation** can be optimized for better response times during emergencies (Bhatia et al., 2018).
- **Infrastructure can be also emergency-ready** to reduce the waiting time of emergency vehicles at road intersection points, and also improve the travel time of other vehicles (Kristensen & Ezeora, 2017).

3.9.2. *Policies*

As stated before, each objective is sought by applying measures that intend to modify the dynamics of the city, where the criteria vary accordingly to the priorities of each region analyzed. In this literature review, most of the measures (i.e. policies) are suitable for simulation.

This section presents 25 categories of policies. Table 10 lists the usage of each policy in the included publications, as well as the stakeholder aggregation for each policy group. As an example, a policy of teleworking (included in 7% of the publications) requires the involvement of 36% by the authorities, 27% by the end-user, and 9% each by a cohort of users, planners, service providers and technology suppliers. Notice that several of the reviewed works make use of multiple policies; as a result, the policy percentages do not add up to 100%. The stakeholder aggregation does. Little attention (at least when using simulation) is paid to emergencies and population growth policies.

The resulting categories were divided into 3 groups of sparsity: Frequent (49.7%), Regular (42.2%) and Other (8.1%) categories.

Public Transportation

The top measure to improve urban mobility is the shift of user share to public transportation (PT). Authors consistently suggest the implementation of PT measures in combination with others such as higher parking fees and awareness campaigns (Basaric et al., 2015) to ensure cohesive effectiveness. For the public transportation industry, coverage, quality of the delivered service and-user satisfaction are fundamental to increase adoption rates.

In large cities problems with inhabitant mobility are usual. Several factors make complex to make PT a solution for everyone. According to Gwilliam and as cited in (Zambom Santana et al., 2018), low-income populations and unfavored neighbourhoods struggle with public transit coverage as it is infrequently oriented to serve these areas due to the need for subsidies to make

Table 10: Transit-policies used in publications
Percentages, counted by row

N = 55	Total	Authorities	Digital entity	End-User	End-User Cohort	Infrastructure & Transit Planners	Service Providers	Technology Suppliers
Public Transportation	27	34	3	16	3	22	19	3
Collaborative Models	25	24	12	15	3	12	27	6
Behavioural	20	26	4	30	4	22	4	9
Infrastructure	20	41	5	5	0	27	14	9
Intersections	18	5	43	0	0	29	0	24
Autonomous Vehicles	18	5	41	0	0	18	18	18
System properties	16	39	0	11	0	39	6	6
Framework	15	41	0	6	6	24	18	6
Circulation permissions	15	39	6	17	6	22	11	0
Priority vehicles	11	18	36	0	0	18	9	18
Dynamic Pricing	13	31	0	19	6	6	31	6
Active and green modes	13	38	0	23	0	23	15	0
Urban Sprawl	11	45	0	18	9	27	0	0
Parking	11	38	0	15	8	15	23	0
Technological	7	15	15	15	8	8	23	15
Electric Vehicles	7	33	0	11	0	0	33	22
Urban Logistics	7	14	14	14	0	0	57	0
Teleworking	7	36	0	27	9	9	9	9
Quality of Service	7	29	0	0	0	29	43	0
Road configuration	5	43	14	0	0	43	0	0
Alternative Fuels	5	20	0	10	10	10	30	20
Rebalancing & Scheduling	5	0	17	0	0	33	50	0
Data Privacy	4	20	20	0	0	40	20	0
Population Growth	2	50	0	0	0	50	0	0
Accessibility	2	50	0	0	0	50	0	0

fare cost-effective. Also, the network should offer efficient and comfortable transfers in interchanges, but perceived quality under pedestrian flows and movement constraints discourage their use (Ramos & de Abreu e Silva, 2019).

In the literature, most of the scenarios conceive a gradual shift of user share from private motorized trips to public transit. A radical scenario expecting more rewarding results was done in Germany, where fare-free regional public transportation was evaluated (Mocanu, 2018). Although results show a substantial increase in public transit trips, private car trips seemed to decrease moderately with only small reductions on urban emissions (objective of the study). Naturally, results vary per deployed location. In some cities such as Tallinn, Estonia, a fare-free service has been offered since 2013.

On the technological side, reducing the average age of public transportation vehicles is another measure to achieve a sustainable state with a fleet fulfilling the requirements for zero-emission standards (Musso & Corazza, 2006).

Collaborative Models

In the last decade, private-shared transportation (carpooling and car-sharing systems) have gained popularity and acceptance among consumers. It promises the attractiveness of alternative modes and the reduction of car ownership. Due to their network setup, many cities cannot solve the urban mobility problems solely with Public transportation, and active modes (e.g. walking and cycling) are relevant only for short distances and moderate weather conditions (Ayed et al., 2015). Here, collaborative models can timely solve the gap.

The principle of these models is the increase in average user occupancy per vehicle. In richer countries, the trend shows a decrease in the average of the already low occupancy per vehicle (Menezes et al., 2017). However, some cities such as Florence, Milan and Turin are propitiating this environment (perhaps by their user density), where data from the Mobility Observatory shows a high ratio of car-sharing companies and vehicles per every private car (Perboli & Rosano, 2019).

Other aspects of this measure account for the rebalancing operations. Although collaborative models are expected to reduce the number of private trips and car ownership, the nature of its execution increases the total vehicle mileage driven throughout the system (Samaranayake et al., 2018), which makes its performance vary per each location.

High-occupancy vehicle (HOV) lanes seek to incentivize collaborative models. They have the potential for reducing traffic and hyper-congestion by incentivizing high-occupancy mode use and reduce travel demand during peak travel times while combined with toll lanes, spatial and/or temporal road use pricing, cordon tolling, and digital impact fees (Lazarus et al., 2018).

Behavioural

Scenarios modelling human mobility behaviour are the third place of interest for researchers, where the main questions are the factors affecting the trip itinerary and how users make travel decisions.

The study of this area is wide and abstract: the policy-making process is dependent on this knowledge, in order to ensure policy effectiveness. By performing a "mental simulation" of the users, researchers analyze how they identify, react and integrate signals from new policies into their behaviour (Occelli & Staricco, 2009).

Applications include the study of cognitive abilities of users (Batur & Koc, 2017; Grimaldo et al., 2012, 2011; Occelli & Staricco, 2009), specific cases dealing with disturbed scenarios such as modelling human behaviour during hurricanes (Wang & Taylor, 2016b, 2016a), the influence of city layout in the mobility and activity choice (Ettema et al., 2011) and the behavioural inclusion of novel technologies such as AV, where predicting motion behaviour of other users (i.e. human drivers) is essential. Finally, other approaches urge a more radical change by establishing a framework for social behavioural change policies (Batur & Koc, 2017).

Infrastructure

This policy group state the link with infrastructural requirements to execute solutions, either in the type of transportation (roads, bridges, cycle highways, rail etc.) or technological (networks, sensors, embedded devices).

The simulation has helped to evaluate the impact of infrastructure investments for bicycle and public transportation (Buil et al., 2015; Zambom Santana et al., 2018), increase of road infrastructure focusing initially on most congested road sections (Hofer et al., 2018), support for network design of EV charging locations (Elbanhawy et al., 2013), evaluate infrastructural alternatives with environmental objectives (Borrego et al., 2011; Hofer et al., 2018) and assess a load balancing policy to address the peaks in the demand of a smart grid of power infrastructure for Online EVs (Sarker et al., 2017).

Intersections

The nature of the current junctions creates queueing points in urban traffic. Novel approaches to improve the flux of vehicles includes mechanisms for traffic light control, smart lights powered by AI and managed vehicle crossings. In the latter, a conceptual design of an intersection manager governing crossings of AVs (Dresner & Stone, 2004, 2007; Perronnet et al., 2013) suggests delays can be reduced dramatically (Dresner & Stone, 2004, 2007). Solutions also focus on the vehicle perspective, where the AV takes the crossing and movement decision in uncontrolled intersections (Zhou et al., 2018; Weilong Song et al., 2016). Finally, some consider a triggered crossing (e.g. for emergency vehicles) (Kristensen & Ezeora, 2017).

Autonomous Vehicles

In the previous policy groups, AVs are mentioned for its pertinence with new business/usage models, infrastructure requirements and roadside inclusion. Most of the reviewed works make the assumption of a fully mature state as exemplified in (Dresner & Stone, 2004). Nevertheless, these proposals delivering optimistic and visionary systems ignore the transition period, the time during which AV must share road space with human-driven vehicles (Bodde & Jianan Sun, 2016). In (Dresner & Stone, 2007) a *reservation system* for intersection crossing contemplates scenarios with AV and AV + Human-driven vehicles.

System properties

Solving urban mobility problems is not a trivial nor simple task. Leveraging areas don't emerge with ease. Therefore, some studies were executed to understand the influences and impact of each element inside the system among the others, to elaborate the most promising alternative given a set of findings, objectives and resources. Noteworthy examples include the previously mentioned hurricane Sandy scenario under mobility perturbation (Wang & Taylor, 2016a, 2016b) and the testing of disruptive business models to mitigate risk during the social-technical transition (Bodde & Jianan Sun, 2016).

Other categories

Together with the frequent categories surpass the 91.9% threshold, by choosing all categories with at least 4 mentions in the literature.

- **Framework**: these studies re-examine the system functioning. Examples include the policy framework for the ageing population (Kanaroglou et al., 2008) and the policy framework to assess the effectiveness of corridor parking restrictions (Elahi et al., 2016).
- **Circulation permissions**: implicates the deliberation of rights of access, such as goods load/unloading areas, circulation restrictions and driver licence grant. Common measures

are traffic restriction periods for central areas while prevailing public transit services, as found in (Musso & Corazza, 2006).

- **Priority vehicles**: certain vehicle trips in specific contexts have a higher degree of importance (e.g. police or ambulances in emergencies). Some approaches for managing flows through the network target this public by using measures such as the ability to deliver signal priority for them (Edwards et al., 2018).
- **Dynamic pricing**: these measures are often used as demotivators for vehicle ownership. Reduction in private car usage can be feasible via a considerable increase in parking fees (Basaric et al., 2015). Other cases give something in exchange to the consumer, such as a cordon toll accompanied by improved public transportation. In the layer of conceptual scenarios, the online EV case makes use of a dynamic pricing strategy as an action to avoid congestion on its smart grid of power (Sarker et al., 2017). Another aspect that is fundamental to remember is that pricing policies are sensitive measures that require careful planning and compelling deployment to reach public support (Lazarus et al., 2018).
- **Active and green modes**: promote the development of the built environment, business models and incentives for active and low-emission modes, commonly walking and cycling. Studies in this area evaluate enhancements on these networks (Maggioni et al., 2014) and the joint improvement with other modes (e.g. public transport) (Khan et al., 2016). Bike-sharing systems (Li & Kamargianni, 2018) and cargo-bikes for last-mile parcel delivery (Perboli & Rosano, 2019) are also on the rise. In this segment, future work should include recent business models like scooter-sharing systems.
- **Urban sprawl**: in the context of simulation of urban mobility and land-use, Hillier and Iida found a correlation between the spatial configuration of simulation objects where the street network configuration influence the agent's navigational choices, as cited in (Elbanhawy et al., 2013). Modelling spatial behaviours (e.g. trip generation) can be established by behavioural theories (Ettema et al., 2011) where urban sprawl is a determinant factor. Another study evaluates a re-densification land-use policy consisting of changing the distribution between the city and the outside rings to redistribute population, with substantial contributions to the energy, emissions and pollution city

challenges, reducing travel distances and encouraging mobility that relies more on public transit and slow modes (Alonso et al., 2017).

- **Parking**: For administrations, providing sufficient parking for passenger vehicles and urban logistics is often a complex task, especially in high-density urban areas. From the traffic perspective, closing lanes to set up parking lots reduces road capacity significantly. Even more, drivers circling for parking are a menace for the already bad congestion. In the literature, parking is often re-evaluated with new operational configurations in location and schedule (Elahi et al., 2016). Other provide insights to the authorities, as the case of illegal double parking (Chrysostomou et al., 2019).
- **Technological**: certain scenarios demand technological advances for feasibility and to reach goals. For environmental objectives, authors evaluate policies with improvements in energy efficiency (Menezes et al., 2017) or vehicle fleet renewal at different levels (2014). In the latter, results don't show significant effects on fuel consumption and on CO2 emissions, but to a great decrease of the PM10 (fine particles of 10 micrometres or less) emissions. For conceptual scenarios, wireless vehicle communications (Bastani et al., 2014) improve traffic lights and incident detection.
- **Electric Vehicles**: the replacement of the vehicle fleet is the most common case seeking environmental objectives. In (Hofer et al., 2018) findings suggest they are one of the most promising strategies to decrease urban CO2 emissions, particularly if it is combined with private car mode shift and teleworking. For its infrastructure planning, simulation is crucial to support decision-making as found in (Elbanhawy et al., 2013).
- **Urban Logistics**: simulation is widely used in urban logistics. In this paper, emphasis on urban mobility impact is mentioned. Policies such as parcel delivery mixed fleet (e.g. cargo-bikes and drones) (Perboli & Rosano, 2019), resource allocation of service and emergency vehicles (Bhatia et al., 2018) including AVs (Marczuk et al., 2016) and others are expected to modify the mobility dynamics of the city unprecedented. Also, increasing consumer behaviour of private product delivery is inducting variability not studied by the indexed authors.
- **Teleworking**: this measure expects to decrease the annual distance travelled per vehicle/year and reduce public transport load and parking demand, by encouraging

institutional acceptance to let labour work from convenient remote locations (usually home). This policy is found in (Alonso et al., 2017; Batur & Koc, 2017; Hofer et al., 2018; Menezes et al., 2017). Nonetheless, a drawback for urban mobility is that although this measure might reduce routine trips, it may stimulate other travels unrelated to work (Menezes et al., 2017).

- **Quality of Service**: some policies encourage the increase of mode attractiveness (e.g. low waiting time, effective response timing or improve service delivered) and convenience (trip itinerary, mode transfers and coverage). Applications include optimization of resource allocation to reduce response time (Bhatia et al., 2018; Volkov et al., 2012) and investments in urban bicycle infrastructure where end-users are accounted for the decision (Buil et al., 2015).
- **Road configuration**: spots the properties of the street configuration that can lead to an improvement in urban traffic. At the illegal parking case (Chrysostomou et al., 2019), the social behaviour induces a spatial road configuration that constrains flow, increases delays and emissions. In the hurricane scenario (Wang & Taylor, 2016a, 2016b) road arrangements play a decisive role in mobility behaviour during an emergency. At the routing application civic dilemma (Lazarus et al., 2018) the digital platform affects the designed performance and purpose of the local road. From the technological perspective, road experience and safety can be improved with solutions such as the smart bump that hides when detects an approaching vehicle driving at a safe speed and remains only for those infringing this rule (Forbes Staff, 2017). From the vehicle perspective, prior identification of speed bumps can trigger adaptation of the car system suspension (Kwang Ming Lion et al., 2018).

Minor categories

These six categories account for 8.1% usage. Their low frequency mean they are an unconventional scope of simulation: Alternative fuels (Elbanhawy et al., 2013; Menezes et al., 2017; Sarker et al., 2017), Rebalancing & Scheduling (Marczuk et al., 2016; Volkov et al., 2012; Yao & Morikawa, 2015), Data Privacy, (Anda et al., 2018; Lazarus et al., 2018), Population Growth (Feng & Timmermans, 2014) and Accessibility (Feng & Timmermans, 2014)

3.10. Discussion of Literature review

The world's sustainable development agenda pursue prosperity of the lives of human beings and protection of the planet among other goals to transform the planet by 2030. In order to reach “the future we want”, challenges are confronted by different areas, multidisciplinary perspectives and action levels.

This categorical literature review has found consistent this vision among researchers. However, it is considered that besides the solution planning, a transition period must be nimbly surpassed in order to succeed on these goals. Four levels of challenges were identified.

Level 1: Local Maxima

It turned evident that most of the research questions follow a traditional analytic direction. The targeted problems belong to the current congestion and operational problems, where vehicle waiting time and economic loss is regularly sought to reduce. The analysis of isolated historic instances due to data availability, technique used and computational cost, have the possibility of biasing to local maxima and become a short term solution only promising for the selected environment.

Level 2: User preference

The mobility models in metropolitan areas based on the massive use of private cars will soon become unsustainable (Grimaldo et al., 2012, 2011). On the societal layer, some authors have the firm suggestion that a radical behavioural change from the end-user is needed in order to make a substantial impact. The social challenge relies on car culture habits, which are still dominant, limiting decision-makers from implementing alternative solutions other than car-based ones (Musso & Corazza, 2006). From this aggregated improvement perspective, it is commonly recommended that users shift towards a greener and more active multi-mode choices. Some authors have tested transit policies that are more intrusive in the effort to prevent people from using private transportation. There, additional factors such as resistance and service attractiveness were found to generate additional obstacles to the improved scenario. It is not a trivial factor that if a policy is not relevant or disowned by the end-users, then all the effort in identifying the problem, designing a feasible solution and implementing is wasted (Pageaud et al., 2018).

Level 3: Intelligence

It is irrefutable that society is diverging to an unprecedented new construct by the inclusion of disruptive technologies in all aspects of human life. Thus, problem-solving methods (e.g. simulation) are required to evolve as well to sustain resilient planning. Wang and Sun (as cited in Babulak & Ming Wang, 2009) discuss four generations of simulation software as of 1993. It could be assumed that a new generation is emerging under the previous arguments and the new approaches looking for applying AI in all industries, which has the potential to unlock a new era of computing and generation of knowledge.

Level 4: Future

State-of-the-art research contains the most novel advances in technology applied to urban mobility. Some works apply early conceptions of schemes integrating the extensive and exhaustive use of machine-centred systems. The presented simulation models assume a mature, fully deployed and improved system with little attention in the transition period (Bodde & Jianan Sun, 2016). Examples of intersection computer-managers and fully AMoD Systems were disseminated in this paper.

The conception of Human-Machine interactions is gaining more attention as questions of security, operations and social acceptance arise. In recent years, discussions of the future of mobility are dominated by connected driving, automation and alternative drives, with a focus less often on the user (VDA, 2015, p. 8). The current vision allows envisaging a seamless integration to society. Nonetheless, problem-solving techniques and disciplines will derive to solve questions in the future triggered by these environments that yet not exist.

3.11. Research Gap

In section 3.9 the objectives sought in the selected publications are listed in order to categorize the main reason to execute each research question. From my perspective, most of the solutions are vehicle-based, which means they consider each vehicle with equal priority to receive the benefits of every applied measure. They focus on the reduction in environmental impact and improvement of operational efficiency, but little attention is put on aggregated individual benefit. Also, none of the works were related to High-Occupancy Lanes as a measure to decrease traffic. Here, I identify an area for study in this thesis.

Chapter 4

Solution Approach

The city of Montreal is chosen as the city of study for this work. Figure 6 defines the overall methodology of this thesis. A crucial part of this thesis is the modelling of the demand to understand user behaviour across the city at a macro scale. In this chapter, it is presented the framework used for the macro-analysis.

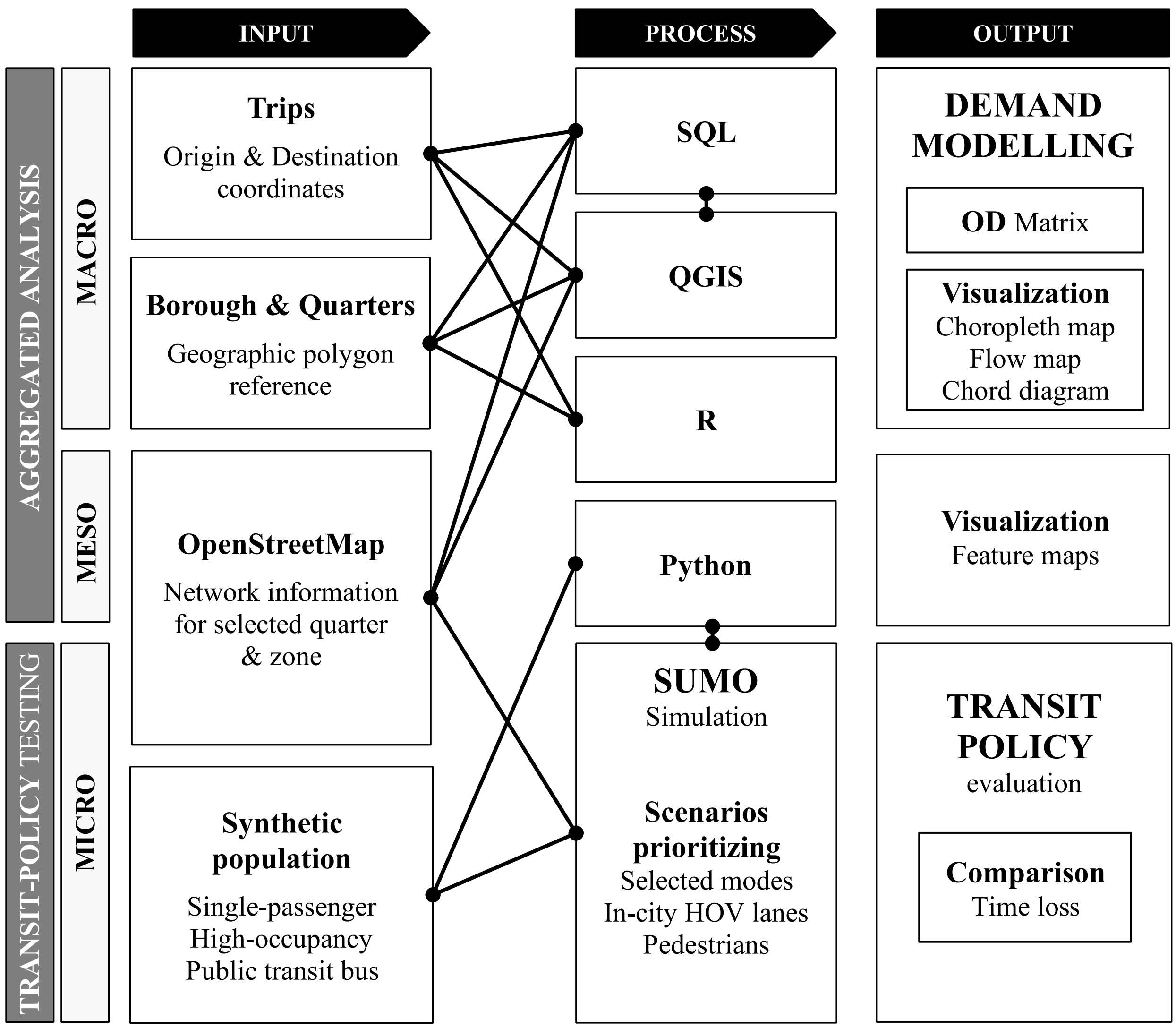


Figure 6: Thesis methodology

Computing resources

For this research project, a Desktop PC property of Concordia University was used, including a sixth-generation, Intel® Core™ i7-6700 CPU clocked at 3.40 GHz with a maximum frequency of 4.00 GHz and supported with 16 GB of RAM and a mechanic 1TB hard drive.

Granularity of analysis

The initial approach of analysis involved using postal codes for cell configuration. However, during the progression, I found this information has a licence, as expressed by *Ville de Montréal*: "postal codes are property of Canada Post and are not available as open data. The City of Montreal holds a license to use postal codes only for internal use. We cannot provide derivative files or allow the downloading of this data" (Ville de Montréal/Service des infrastructures du réseau routier, 2019). Thus, quarters and borough open data was chosen as the resolution, described in the following section.

4.1. Datasets

Datasets are the main source of information to model traffic demand. Three sources are used:

Table 11: Datasets used in the thesis

Dataset	Type	Purpose	Description
MTL Trajet	Coordinate points	Trip origins and destinations	Trajectories of participants composed of multiple coordinates
Housing Reference Quarters	Polygon	Aggregation	Vector data of location, shape, and attributes of geographic features of Montreal
Administrative limits	Polygon	Aggregation	
Traffic lights	Coordinate points	Network customization	Location of red lights managed by the city of Montreal.

4.1.1. *MTL Trajet*

The mobilization of citizens is one of the fundamental aspects every metropolitan area struggles with. In the plan of Montreal, one of the many measures launched is the project "MTL Trajet" (original title: *Déplacements MTL Trajet*, hereafter *"coordinates dataset"*) that serves the purpose of collecting mobility data of users allowing to estimate the repercussions of construction works in the city, calculation of travel times or traffic light management (Ville de Montréal, n.d.).

Itinerum project

The Itinerum platform started as part of a research project conducted by Concordia University's Professor Zachary Patterson, head of the Transportation Research for Integrated Planning Lab (hereafter TRIP Lab). Previously known as DataMobile in 2014, the purpose of the application was to collect travel behaviour data from Concordia University students, faculty and staff (TRIP Lab, 2019). Several studies have used Itinerum for data collection, being MTL Trajet the dataset suitable for this thesis.

Users have to download the application (Itinerum, a project developed by Concordia U), register, answer an initial survey (e.g. home/work locations, preferred modes of transportation) and accept the permissions to let the application record location data in the background and automatically during a fixed period of time (duration of participation). There have been 3 editions of the project, where the latest publicly available is the 2017 edition, collected from 2017-09-18 to 2017-10-18.

Database structure

The dataset is available at Montreal's open data website (Ville de Montréal/Service de l'urbanisme et de la mobilité, 2017). The publication contains two tables (Figure 7):

- **Trips table**: contains 185,285 itineraries executed and recorded voluntarily by its users identified by a unique `id_trip`, where each has a field including the overall `starttime` and `endtime`. Finally, the survey registered the `mode` of transportation used in the trip and the `purpose` of it. Here, these columns displaying contextual information are key for usage in the analysis part.
- **Coordinates table**: each trip is composed of a series of coordinate points recorded through the execution of the itinerary. The overall count of coordinate points of all 185 thousand trips is of 13,015,782. The `id_trip` allows linking the coordinate point to the itinerary on the Trips table. It also includes the `latitute`, `logitude` and `altitude`

for geographical reference, a `timestamp` of the GPS point and supported values (some registered by device's sensors) such as `speed`, `h_accuracy` and `v_accuracy`.

	id_trip	starttime	endtime	mode	purpose
1	1547	2017-09-18T04:16:58	2017-09-18T04:...		
2	308312	2017-09-18T06:17:46	2017-09-18T06:...		
3	384772	2017-09-18T09:30:24	2017-09-18T10:...		
4	150744	2017-09-18T10:02:50	2017-09-18T10:...	Voiture / Moto	Reconduire / alle...
5	199011	2017-09-18T10:18:40	2017-09-18T10:...		
6	421155	2017-09-18T10:42:13	2017-09-18T10:...		
7	29064	2017-09-18T10:47:52	2017-09-18T10:...		
8	203781	2017-09-18T10:53:49	2017-09-18T11:...		
9	273549	2017-09-18T10:54:50	2017-09-18T11:...		
10	314196	2017-09-18T10:57:01	2017-09-18T11:...		

	latitude	longitude	speed	altitude	h_accuracy	v_accuracy	timestamp	id_trip
1	45.545447	-73.653716	-1	35.362567	20	2.510547	2017-09-18T04:...	1547
2	45.545756	-73.653425	0	35.568665	10	4	2017-09-18T04:...	1547
3	45.545652	-73.653715	2.07	31.903748	10	4	2017-09-18T04:...	1547
4	45.54557	-73.654042	3.42	33.553619	10	4	2017-09-18T04:...	1547
5	45.545406	-73.654266	4.35	33.668152	10	3	2017-09-18T04:...	1547
6	45.545499	-73.654612	5.39	32.61618	10	3	2017-09-18T04:...	1547
7	45.545933	-73.65459	3.52	33.113556	10	4	2017-09-18T04:...	1547
8	45.635807	-73.832849	5.650684	30.141936	32	15.678569	2017-09-18T09:...	384772
9	45.636337	-73.799904	18.048561	14.743964	24	175.490845	2017-09-18T09:...	384772
10	45.636086	-73.80015	5.13202	5.375364	16	41.315834	2017-09-18T09:...	384772

Figure 7: Tables of MTL Trajet dataset
Top: Trips. **Bottom**: Coordinates
(Ville de Montréal/Service de l'urbanisme et de la mobilité, 2017)

Structured Query Language (SQL)

The enormous amount of registries stored in Itinerum servers makes it accessible through a relational database management system (RDBMS) that uses Structured Query Language (`SQL`) as the language to query the database. `Microsoft SQL Server Management Studio` was used for this operation. Sample syntax is shown below.

```sql
/* Count of coordinate registries per day */

SELECT ["ID"], RIGHT(LEFT(["timestamp"],11),10) AS FECHA
INTO #Tempt
  FROM [model].[dbo].[coordinates]

  SELECT FECHA, COUNT (["ID"])
  FROM #Tempt
  GROUP BY FECHA
  ORDER BY FECHA
  DROP TABLE #Tempt
```

Data representativeness

Data collection of high quality and resolution (i.e. individual user high-accuracy location in short periods of time) is a task difficult to obtain due to its time consumption, high-cost and privacy concerns. Due to the nature of collection (Ville de Montreal's target audience), the MTL Trajet dataset is not representative of the population. Therefore, results cannot be generalized to the population of Montreal (i.e. children or users with low-literacy in technology are not a target audience).

However, the purpose of this research project is to focus on high occupancy vehicles. Since the occupancy level is not defined in the data, it can be estimated indirectly using aggregated statistics. In simplistic terms, the target audience of MTL Trajet project is also the target audience of this research work: early, early middle and late middle-age adults (ages 22-64) is generally the population with the capacity of changing their mode of transportation. Therefore, some assumptions are made that elevate the representativeness of data.

Mode choice

The dataset contains information on what mode of transportation each trip used. Here, some might contain one or multiple modes. For ease of calculation, all usage of different modes is treated equally. Therefore, percentages in Figure 8 add up a hundred percent.

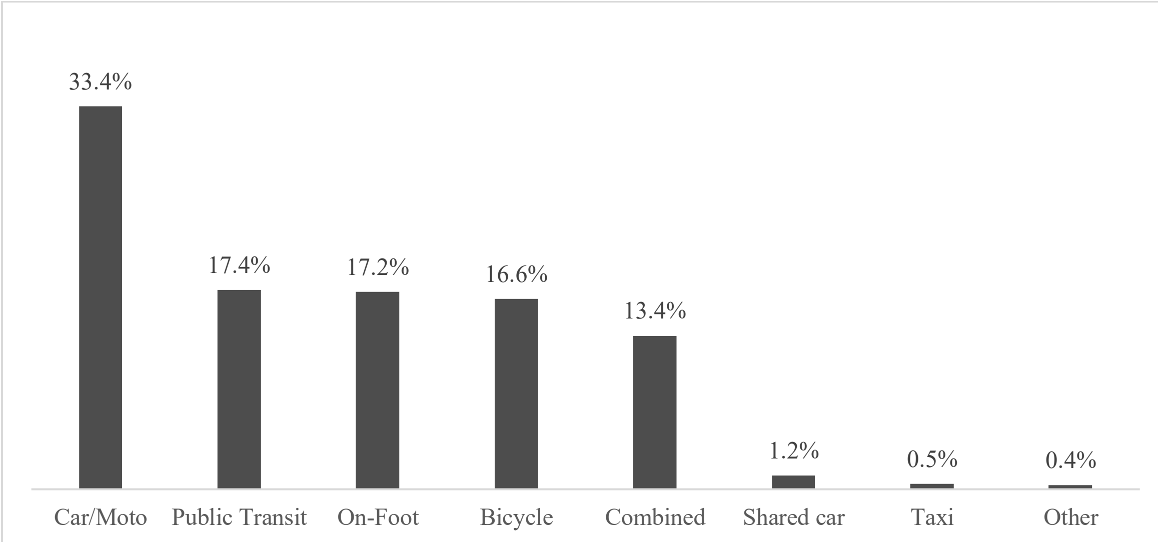


Figure 8: Mode choice of MTL Trajet dataset, trips table

4.1.2. ***Quarters of reference in housing***

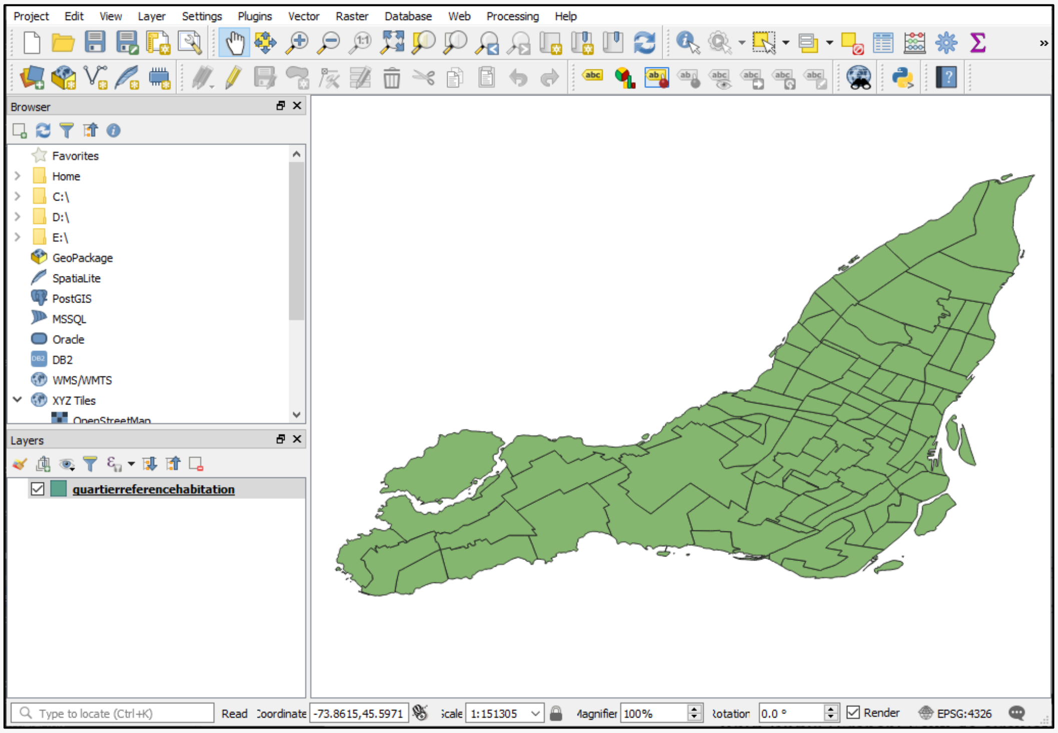
The Quarters of reference in housing dataset (in French: *Quartiers de référence en habitation*, hereafter *"boundaries file"*) contains a geographic layer that divides Montréal into historical and analytical entities, meeting the needs of housing analysis. These neighbourhoods are areas relatively homogeneous socio-economically (Ville de Montréal/Service de l'habitation, 2019).

The information is stored in a `.geojson` shape file whose visualization is displayed in Figure 9a. The Coordinate Reference System is `EPSG: 4326`. The file contains 15 municipalities, 19 boroughs for Montreal and a total of 91 quarters (77 for Montreal) as presented in Figure 10.

4.1.3. ***Administrative limits***

The Administrative limits dataset (original title: *Limite administrative de l'agglomération de Montréal (Arrondissements et Villes liées)*, hereafter *"boroughs file"*) contains a geographic layer that divides Montréal into 19 administrative areas of the city plus the independent municipalities (Ville de Montréal/Service des infrastructures du réseau routier, 2019). The list of boroughs is enlisted in Figure 9b. Figure 11 presents the division of Montreal by borough.

(a)



(b)

Ahuntsic-Cartierville: 6
Anjou: 1
Côte-des-Neiges–Notre-Dame-de-Grâce: 7
Lachine: 2
LaSalle: 2
Le Plateau-Mont-Royal: 6
Le Sud-Ouest: 5
L'Île-Bizard–Sainte-Geneviève: 1
Mercier–Hochelaga-Maisonneuve: 9
Montréal-Nord: 4
Outremont: 1
Pierrefonds-Roxboro: 2
Rivière-des-Prairies–Pointe-aux-Trembles: 3
Rosemont–La Petite-Patrie: 7
Saint-Laurent: 5
Saint-Léonard: 2
Verdun: 3
Ville-Marie: 4
Villeray–Saint-Michel–Parc-Extension: 7

Figure 9: Housing Reference Quarters dataset
(a) Visualization in QGIS (b) Count of quarters per borough of Montreal

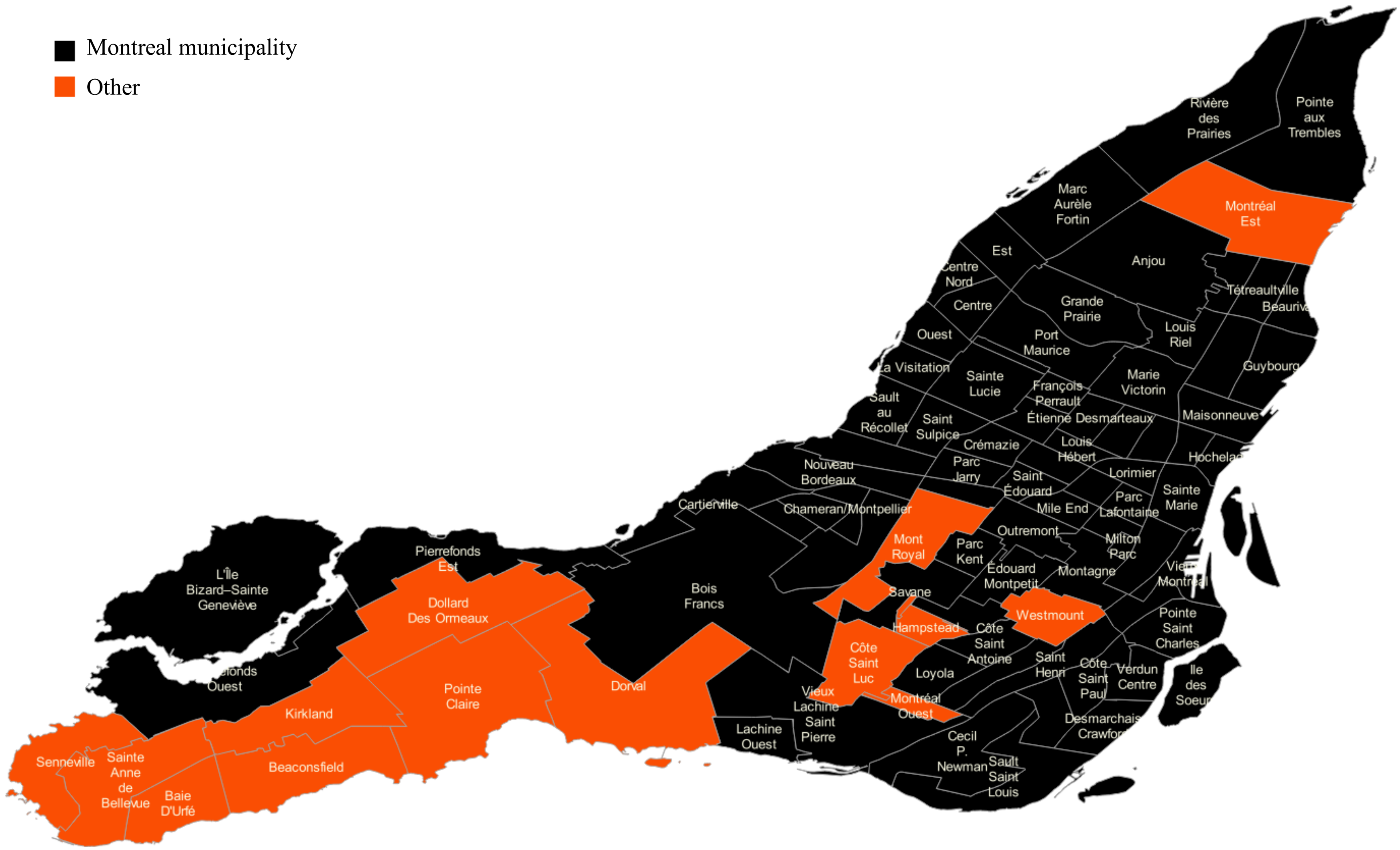


Figure 10: Quarters of reference in housing geographic layer

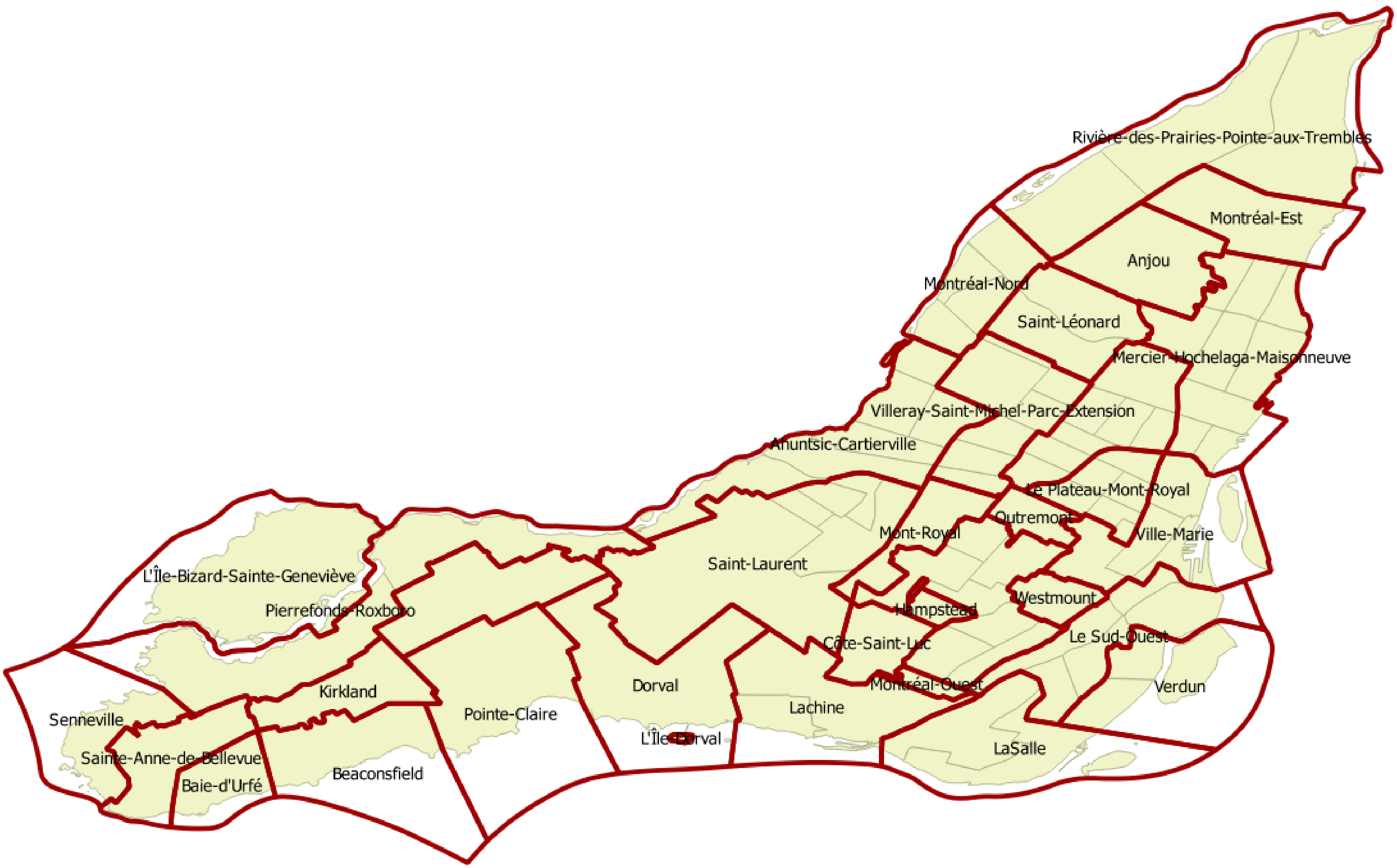


Figure 11: Administrative limits geographic layer overlapped with Quarters of reference in housing

4.2. Customization of data for analysis

To find the most transited zone of Montreal at the macro level, I executed the following workflow:

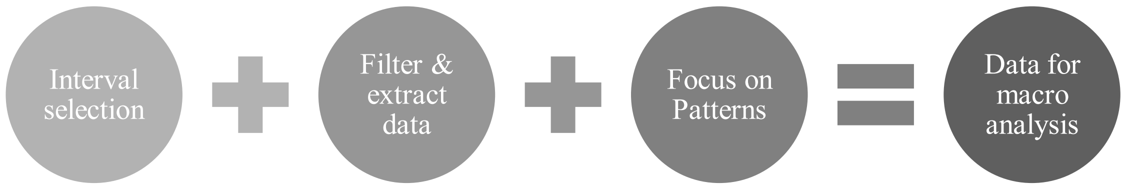


Figure 12: Data funnelling workflow for macro-level

The MTL Trajet dataset contains 185,285 trajectories composed by 13,015,782 coordinate points allocated along with the execution of the *trip*, as exemplified in Figure 13. Data were collected from September 18 to October 18 of 2017 and the GPS records were normally registered every 10 to 20 seconds.

QGIS is a free and open-source cross-platform desktop geographic information system (GIS) application that supports viewing, editing, and analysis of geospatial data (*QGIS*, 2020). For this thesis, I used (mostly) `QGIS` 2.18.28 due to plugin compatibility.

Figure 13: Visualization of sample trip coordinates from MTL Trajet dataset

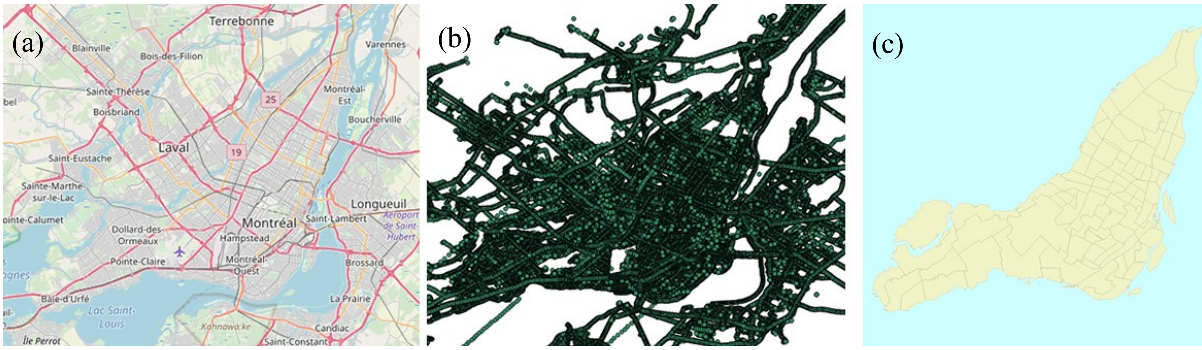


Figure 14: Comparison of Montreal spatial datasets.
(a) OpenStreetMap (b) Coordinates (c) Boundaries file

4.2.1. ***Selection of the interval of analysis***

As participants of the MTL Trajet study decided whether to record their trips for a few times or the total duration of their participation (2 weeks), an inconsistent number of trips per user is registered. In order to select the time frame for the study, the methodology involves selecting a **day-interval** by the higher number of records to generalize travel patterns during weekdays (Figure 15). Friday, October 6 is the day with the greatest number of trips (10,379) followed by Thursday, October 5 (9,740). Thursdays are assumed to show a more regular travel pattern than Fridays (the afternoon is socially conceived as the beginning of the weekend), so **October 5, 2017**, is chosen as the day of analysis. As the auxiliary time frame for analysis, a **week-interval** following the same rationale is chosen from **Saturday, September 30 to Friday, October 6, 2017**.

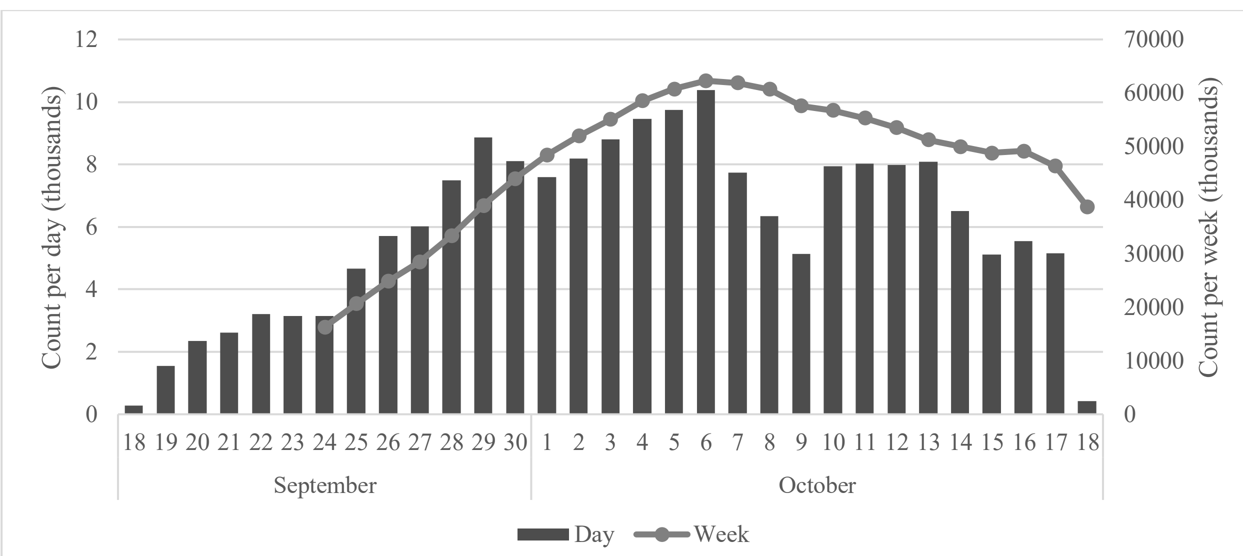


Figure 15: Aggregated count of trips from MTL Trajet dataset

4.2.2. *Build the data table for analysis*

The complete dataset contains registries of more than 13 million coordinates and 185 thousand of trips, an amount of information complex to process, analyze and compute. As a reference, `Microsoft Excel` supports a maximum of 1,048,576 rows. Therefore, extraction techniques must be applied in order to manage the data. In order to excerpt a total of **9,525 trips suitable for analysis**, steps from Figure 16 were accomplished.

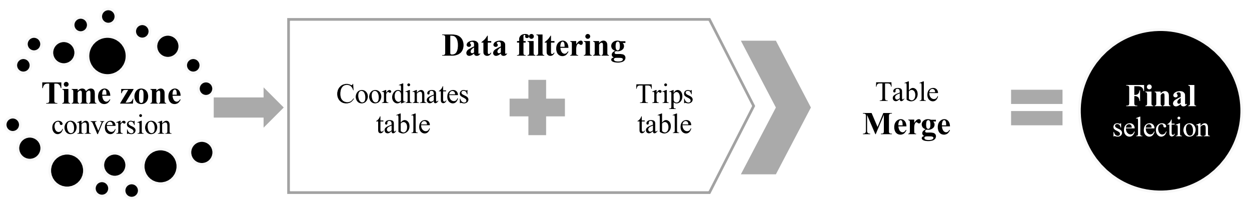


Figure 16: Data extraction workflow

Time zone conversion

Registries in both trips and points table have a timestamp using the Coordinated Universal Time (UTC) format, which is the primary time standard by which the world regulates clocks and time. For the calculations, placing the analysis in the Eastern Standard Time (EST) was essential (a registry from October 6 at 3 a.m. (UTC) belongs to October 5, 10 p.m (EST). This time zone is 5 hours behind UTC and is in use during standard time in the east of North America (thus, Montreal), the Caribbean and Central America. However, during the observed day, it was 4 hours of difference due to summer/winter time gaps as seen in Figure 17.

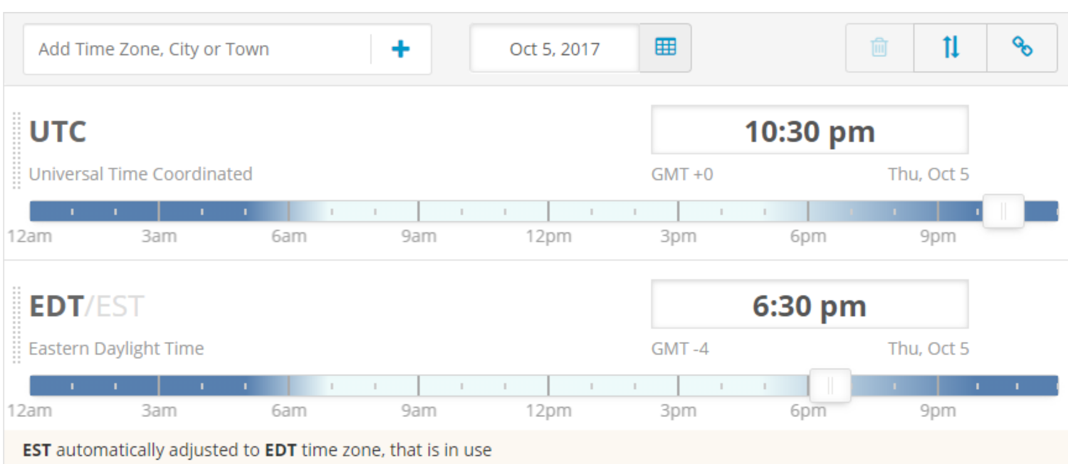


Figure 17: Conversion of timezone for October 5, 2017
(UTC to EST Converter, 2020)

Data filtering

The trips table (185K rows) is manageable in `Microsoft Excel`. Here, I converted `starttime` field from UTC to EST and selected the records from October 5.

The coordinates table is only accessible via `SQL`. I queried records from October 5 and 6 since some of the targets fall in the 6th due to the timestamps being skewed 4 hours later. The scope of this research was set to focus on the origin and destination of itineraries, not the route itself. Thus, for the instructions I used two functions to obtain the Origin (`MIN` function) and Destination (`MAX` function) coordinates for each `id_trip` using the `timestamp` as the argument and the `LIKE '2017-10-05%' or '2017-10-06%'` restraining statement.

Table merge

After I extracted registries from both tables, I modifying the time zone from `UTC` to `EST`. After, I merged the two extracts relating their `id_trip` and using `VLOOKUP` function in `Excel`. The resulting pre-final table is shown in Figure 18.

						origin		destination		
id_trip	useful	mode	purpose	starttime	endtime	latitudeO	longitudeO	latitudeD	longitudeD	hour_bin
66938	YES	Voiture / Moto	Travail / Rendez-vous d'affaires	2017-10-05 10:59:55UTC	2017-10-05 12:33:23UTC	45.23588900	-74.28696300	45.54156100	-73.56561400	6h - 7h
356894	NO	Voiture / Moto	Magasinage / emplettes	2017-10-05 01:44:38UTC	2017-10-05 01:48:48UTC	45.24624190	-73.64108591	45.25898886	-73.61981168	
98588	NO	Voiture / Moto	Retourner à mon domicile	2017-10-05 01:55:38UTC	2017-10-05 02:21:09UTC	45.26337420	-73.61473800	45.42855090	-73.65847360	
344733	YES	Voiture / Moto	Travail / Rendez-vous d'affaires	2017-10-05 15:51:23UTC	2017-10-05 16:18:34UTC	45.26978099	-73.46860808	45.47104057	-73.46661119	11h - 12h
127132	YES	Voiture / Moto	Travail / Rendez-vous d'affaires	2017-10-05 12:19:01UTC	2017-10-05 13:12:37UTC	45.30188212	-73.26682413	45.24376160	-73.25553060	8h - 9h
375141	NO	À pied, Transport collec	Retourner à mon domicile	2017-10-05 00:19:59UTC	2017-10-05 01:09:24UTC	45.30986800	-73.74590300	45.44952300	-73.57696200	
12454	YES	À pied, Transport collec	Éducation	2017-10-05 15:39:03UTC	2017-10-05 16:38:50UTC	45.34573364	-73.73330498	45.48980220	-73.58664110	11h - 12h
184055	YES	Transport collectif	Travail / Rendez-vous d'affaires	2017-10-05 10:38:34UTC	2017-10-05 11:31:11UTC	45.35030200	-73.75375300	45.44704400	-73.60802400	6h - 7h
404254	YES	Voiture / Moto	Retourner à mon domicile	2017-10-05 04:49:36UTC	2017-10-05 05:29:01UTC	45.35216900	-73.69057500	45.49624800	-73.83866600	0h - 1h
268230	NO	Transport collectif, Voit	Retourner à mon domicile	2017-10-05 02:46:36UTC	2017-10-05 03:31:47UTC	45.35940591	-73.74673062	45.47071775	-73.56584377	
475772	YES	Voiture / Moto	Loisir	2017-10-06 01:56:45UTC	2017-10-06 02:48:59UTC	45.36522302	-72.94244381	45.59626844	-73.55106254	21h - 22h
205141	YES	Voiture / Moto	Loisir	2017-10-05 18:49:44UTC	2017-10-05 19:38:51UTC	45.36529919	-72.94263944	45.46248452	-73.59012254	14h - 15h
414285	YES	À pied, Transport collec	Retourner à mon domicile	2017-10-05 23:02:37UTC	2017-10-05 23:06:28UTC	45.37742200	-73.51585400	45.37929300	-73.51417800	19h - 20h
283121	YES	Voiture / Moto	Loisir	2017-10-05 21:26:15UTC	2017-10-05 21:45:13UTC	45.38090400	-73.53542600	45.40094300	-73.54697000	17h - 18h
145670	YES	Voiture / Moto	Loisir	2017-10-05 22:34:54UTC	2017-10-05 22:47:31UTC	45.38092200	-73.53542900	45.40092500	-73.54711000	18h - 19h
427	YES	Transport collectif, Voit	Travail / Rendez-vous d'affaires	2017-10-05 11:33:24UTC	2017-10-05 12:50:12UTC	45.38450000	-73.52443900	45.50892400	-73.55614700	7h - 8h
404054	YES	Transport collectif, Voit	Retourner à mon domicile	2017-10-05 19:33:38UTC	2017-10-05 20:11:56UTC	45.38602700	-74.00839200	45.51027100	-73.71518300	15h - 16h
374482	YES	Transport collectif, Voit	Travail / Rendez-vous d'affaires	2017-10-05 10:12:23UTC	2017-10-05 11:37:44UTC	45.38665224	-73.53259590	45.51556510	-73.56076960	6h - 7h
407014	NO	Voiture / Moto	Retourner à mon domicile	2017-10-05 02:02:19UTC	2017-10-05 02:47:04UTC	45.38976700	-74.01576900	45.54717700	-73.63135700	
181768	YES	Voiture / Moto	Repas / collation / café	2017-10-05 18:46:53UTC	2017-10-05 19:07:27UTC	45.39237221	-73.96711058	45.47194379	-73.82655021	14h - 15h
208821	YES	Voiture / Moto	Travail / Rendez-vous d'affaires	2017-10-05 11:12:10UTC	2017-10-05 12:23:25UTC	45.39445200	-73.95724900	45.52045400	-73.58438200	7h - 8h
444529	YES	Voiture / Moto	Retourner à mon domicile	2017-10-05 21:43:15UTC	2017-10-05 22:02:06UTC	45.39568509	-73.61014210	45.42058530	-73.63156850	17h - 18h
167824	NO	Voiture / Moto	Retourner à mon domicile	2017-10-05 00:47:54UTC	2017-10-05 01:54:18UTC	45.39810270	-73.95931796	45.46473230	-73.57228940	
201104	YES	Voiture / Moto	Loisir	2017-10-05 22:01:09UTC	2017-10-05 22:11:14UTC	45.40055700	-73.54470400	45.37884400	-73.53555400	18h - 19h
391720	YES	Transport collectif, Voit	Travail / Rendez-vous d'affaires	2017-10-05 10:06:28UTC	2017-10-05 11:49:45UTC	45.40599740	-74.02670410	45.50600330	-73.56015610	6h - 7h
336013	YES	Transport collectif, Voit	Retourner à mon domicile	2017-10-05 19:54:51UTC	2017-10-05 20:51:01UTC	45.40717820	-73.93990300	45.48932474	-73.84635771	15h - 16h
426410	YES	À pied	Loisir	2017-10-05 16:44:39UTC	2017-10-05 16:50:12UTC	45.40780600	-73.94011900	45.40736700	-73.94030500	12h - 13h
89357	YES	Voiture / Moto	Retourner à mon domicile	2017-10-05 11:47:45UTC	2017-10-05 13:09:47UTC	45.40876100	-73.47273700	45.50213000	-73.56458500	7h - 8h
387156	YES	Transport collectif, Voit	Travail / Rendez-vous d'affaires	2017-10-05 11:25:39UTC	2017-10-05 13:09:07UTC	45.40994240	-74.06418860	45.50497420	-73.55721660	7h - 8h
59822	YES	Voiture / Moto	Retourner à mon domicile	2017-10-05 20:33:48UTC	2017-10-05 22:00:58UTC	45.41034771	-74.04157976	45.42307920	-73.62199464	16h - 17h
51844	YES	À pied, Transport collec	Retourner à mon domicile	2017-10-05 20:06:48UTC	2017-10-05 21:39:57UTC	45.41589140	-73.90700110	45.52753920	-73.59198460	16h - 17h
134090	YES	À pied, Voiture / Moto	Reconduire / aller chercher une pers	2017-10-05 22:22:45UTC	2017-10-05 22:57:03UTC	45.41676040	-73.62479160	45.41732320	-73.61963520	18h - 19h
126887	YES	Voiture / Moto	Magasinage / emplettes	2017-10-05 20:35:30UTC	2017-10-05 20:42:14UTC	45.41703700	-73.63259200	45.42438600	-73.62489100	16h - 17h
312080	YES	Voiture / Moto	Travail / Rendez-vous d'affaires	2017-10-05 12:03:14UTC	2017-10-05 12:23:57UTC	45.41819215	-73.63235446	45.36395677	-73.57002185	8h - 9h
96034	YES	Voiture / Moto	Travail / Rendez-vous d'affaires	2017-10-05 12:04:41UTC	2017-10-05 12:17:25UTC	45.41832898	-73.61369199	45.43238880	-73.64039060	8h - 9h
299367	YES	Voiture / Moto	Travail / Rendez-vous d'affaires	2017-10-05 10:09:38UTC	2017-10-05 10:58:21UTC	45.41893100	-73.62358090	45.51842840	-73.66369660	6h - 7h
47406	YES	Autopartage	Retourner à mon domicile	2017-10-05 21:45:52UTC	2017-10-05 22:47:52UTC	45.41985100	-73.91408700	45.52328700	-73.59707600	17h - 18h
471609	YES	Voiture / Moto	Reconduire / aller chercher une pers	2017-10-05 20:15:57UTC	2017-10-05 20:23:14UTC	45.42001247	-73.64113212	45.42118460	-73.63044690	16h - 17h
408612	YES	Transport collectif	Travail / Rendez-vous d'affaires	2017-10-05 14:35:30UTC	2017-10-05 14:56:01UTC	45.42020100	-73.64299800	45.44751900	-73.60931400	10h - 11h
296784	YES	Transport collectif	Travail / Rendez-vous d'affaires	2017-10-05 19:08:18UTC	2017-10-05 19:45:45UTC	45.42167300	-73.62136887	45.44649310	-73.60216170	15h - 16h
108315	YES	Voiture / Moto	Magasinage / emplettes	2017-10-05 23:08:07UTC	2017-10-05 23:13:07UTC	45.42239800	-73.64196100	45.42991500	-73.63644300	19h - 20h
20679	YES	Transport collectif	Éducation	2017-10-05 11:47:43UTC	2017-10-05 12:36:12UTC	45.42311860	-73.64130830	45.49462942	-73.57841199	7h - 8h
407555	YES	Transport collectif	Retourner à mon domicile	2017-10-05 20:26:55UTC	2017-10-05 21:43:55UTC	45.42334400	-73.64098030	45.47331587	-73.58251742	16h - 17h
418471	YES	Transport collectif	Travail / Rendez-vous d'affaires	2017-10-05 16:59:17UTC	2017-10-05 17:43:38UTC	45.42386900	-73.61084140	45.44579153	-73.64458471	12h - 13h

origins_week destinations_week hour_distro trajets

Figure 18: Merge of trips and coordinate tables for the selected period

Final selection

Due to the nature of the query, some unwanted records were filtered and others did not find an equivalent `id_trip`. An auxiliary column `useful` states the final filtering. The final selection of records contains 9,525 trips suitable for analysis in this research study (hereafter: *customized dataset*), where each trip includes its start/end timestamps, origin/destination coordinates, mode and purpose of the trips.

4.2.3. *Selection of focus periods*

A second auxiliary column `hour_bin` allows allocating each trip according to its start time in an hour (EST) interval (Figure 19). From this graph two congested traffic patterns are identified: 7h to 9h: 1,503 trips; 16h to 19h: 2,658 trips. The time intervals of both groups can be interpreted as the entry and exit of routine activities of the users for the weekdays.

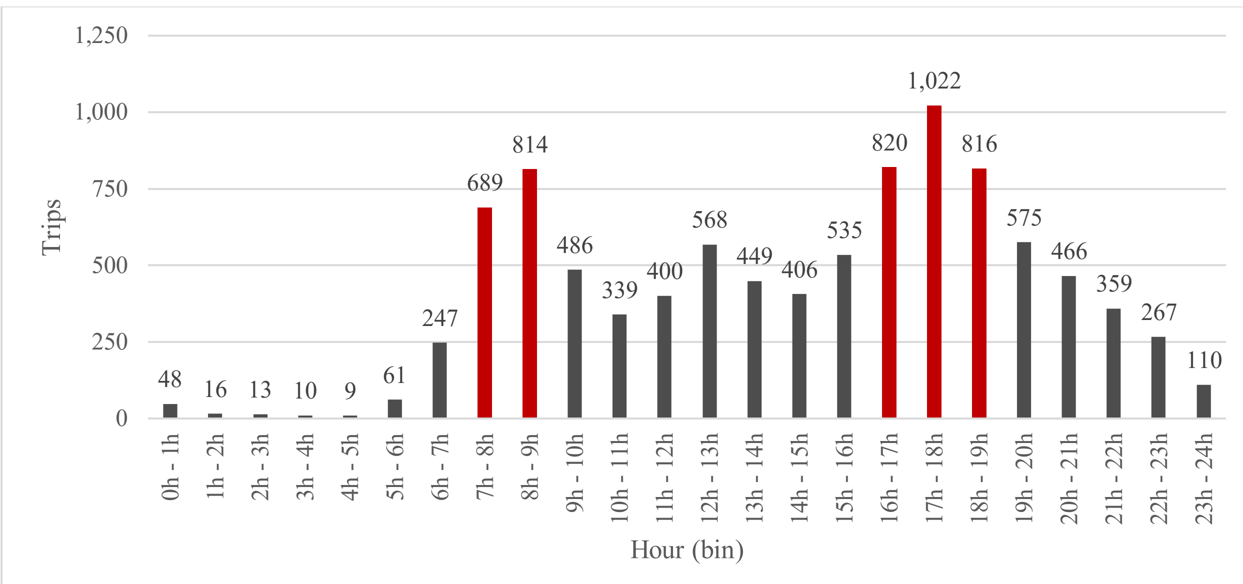


Figure 19: Count of trips per hour, October 5, 2017 (EST)
Source: MTL Trajet dataset. **Total count**: 9,525

Trip duration

From *the best week,* it was found that 70% of the trips have a duration of 30 minutes or less, where 93.57% achieve the one-hour threshold. As a reference, the 2016 Census of Population average car commuting duration in 2016 was 24.1 minutes (Government of Canada, 2017).

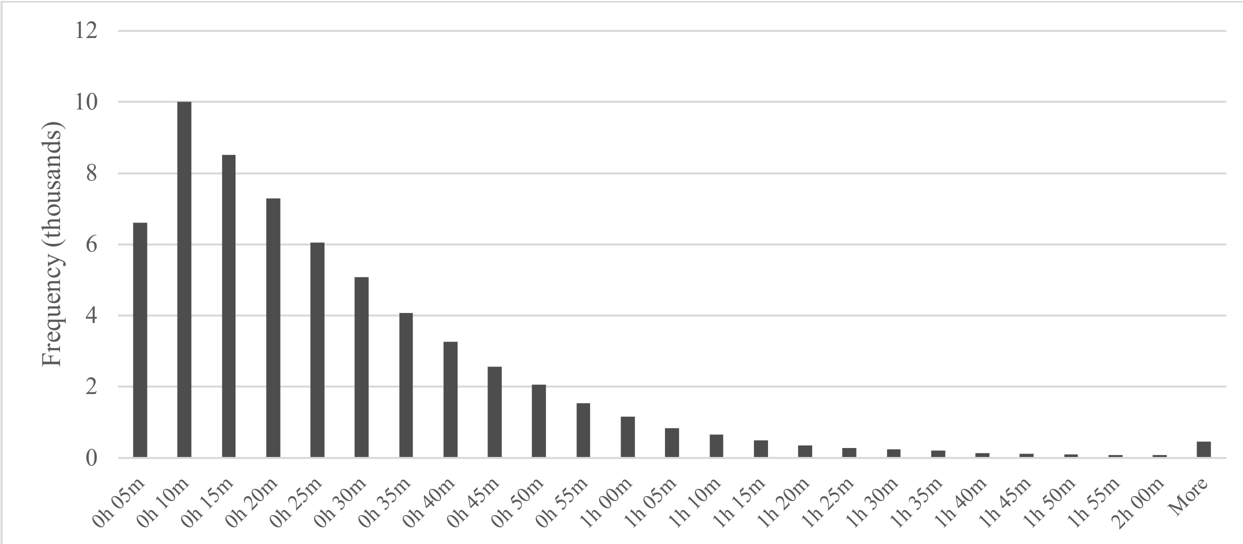


Figure 20: Average trip duration of week interval
Period: 9/30 to 10/6. **Source**: MTL Trajet dataset

4.3. Choropleth maps

Choropleth maps are used to visualize statistical data through various shading patterns or symbols on predetermined geographic areas (i.e. boundaries), easily representing the variability of the desired measurement, across multiple areas (DeLorenzo & Dugger, n.d.).

In order to visualize the mobility behaviour of the city of Montreal at the macro scale, several tools are described. The first task involves visualizing the most transited areas for origins and destinations. The customized table obtained from the MTL Trajet dataset in section 4.2 and the boundaries geometry dataset have to be joint to allocate the coordinate points into *boxes* defined by the polygons.

Limitations

Due to the amount of data stored in the dataset, the PC crashed a considerable amount of times (see Computing resources) during the initial iterations, making it a challenging task. The customized dataset eased data processing.

Procedures

The boundaries file was used as the frame for the Choropleth map. There was an issue with the geometries on the original file at it was fixed by the feature `Processing Toolbox > Vector Geometry > Fix geometries` in QGIS 3.2.3 (the latest version). To create the diagram, a

CSV file layer containing `id_trip`, `longitude` and `latitude` is required. Using the QGIS feature `Vector > Analysis Tools > Count points in polygon`, I joined the fixed boundaries file with the origin and destination coordinates. Each coordinate was allocated inside a geometry from the boundaries file (that represents a quarter) to obtain a new vector layer including a column `NUMPOINTS` where adds up the number of points falling inside the polygon as shown in Figure 22. The choropleth map uses a gradient colouring of the geometries according to the field to display. I used `NUMPOINTS` magnitude to create 10 classes for the diagram graduation.

Results

Figure 21 summarizes the most frequent neighbourhoods for origins and destinations of the trips for the *best week*. Resulting Choropleth map from the analyzed period from 7 to 9 am is shown in Figure 23 that gives a clearer insight into the behaviour of users during morning peak hours. As seen in the figure, the origins of trips during congested hours are mostly located in the majority of quarters in the **central-south part of the city**. When it comes to the quarter trip distribution, it decreases progressively. The destinations of trips are highly concentrated in downtown and old port of Montreal, making the slope of their distribution graph falling quickly.

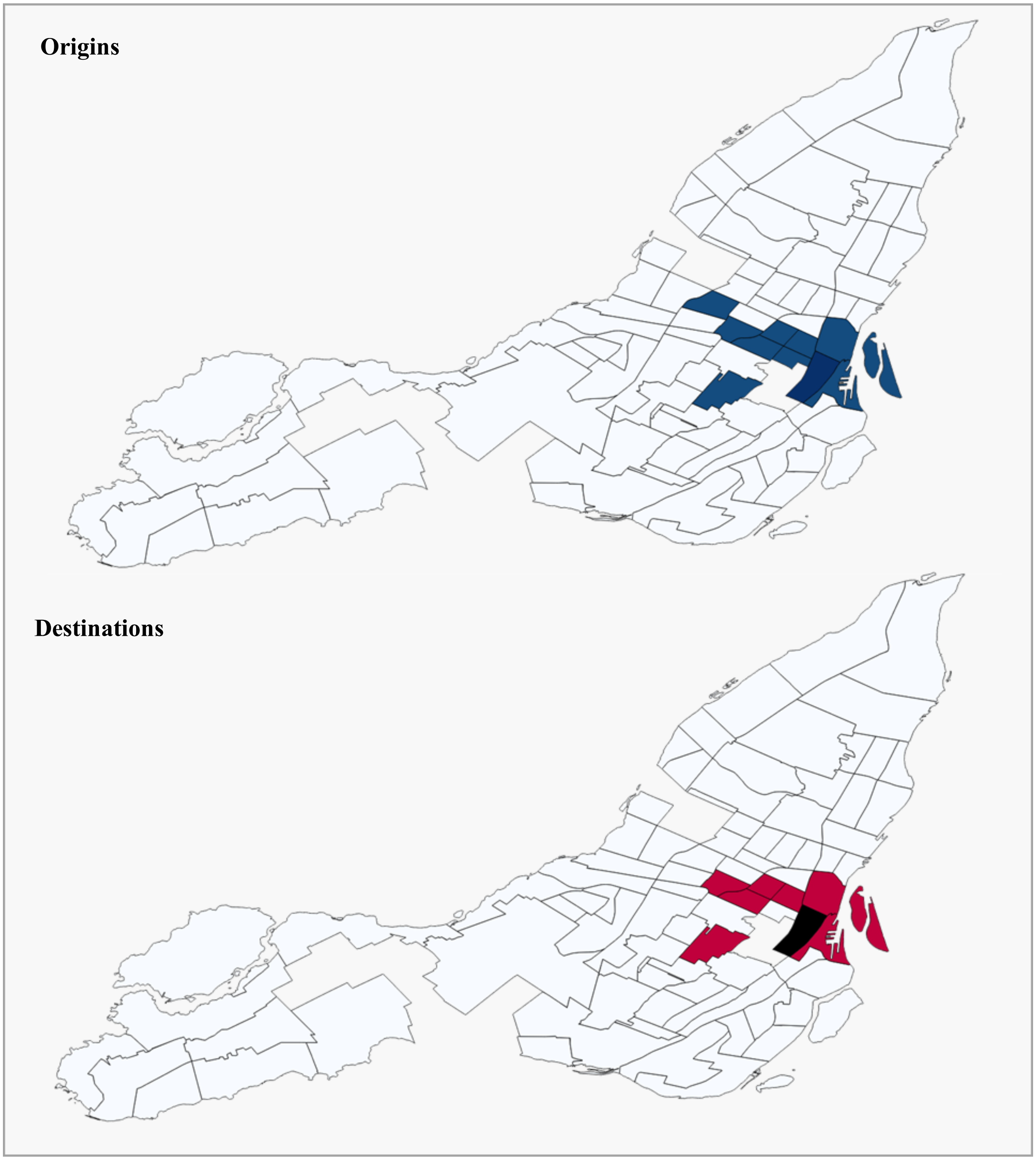
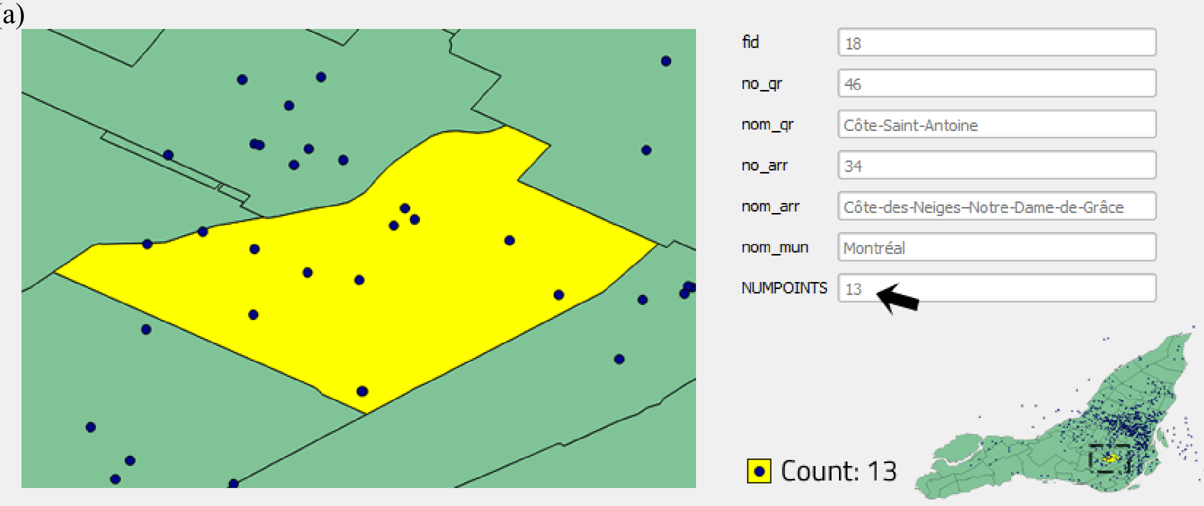


Figure 21: Choropleth map, week selection

(a)



(b)

fid	no_qr	nom_qr	no_arr	nom_arr	nom_mun	NUMPOINTS
25	38	René-Lévesque	19	Ville-Marie	Montréal	287
48	37	Vieux-Montréal	19	Ville-Marie	Montréal	131
26	41	Édouard-Montpetit	34	Côte-des-Neiges...	Montréal	62
29	30	Sainte-Marie	19	Ville-Marie	Montréal	53
39	34	Mile End	21	Le Plateau-Mont-...	Montréal	37
42	14	Saint-Édouard	24	Rosemont–La Pe...	Montréal	35
20	50	Saint-Henri	20	Le Sud-Ouest	Montréal	26
59	58	Bois-Francs	15	Saint-Laurent	Montréal	25
23	51	Petite-Bourgogne	20	Le Sud-Ouest	Montréal	23
24	39	Montagne	19	Ville-Marie	Montréal	21
79	86	Pointe-Claire			Pointe-Claire	20

Figure 22: Count of coordinate points inside polygons
(a) Custom coordinates overlapped with boundaries polygons
(b) Boundaries file including the count of points inside geometry

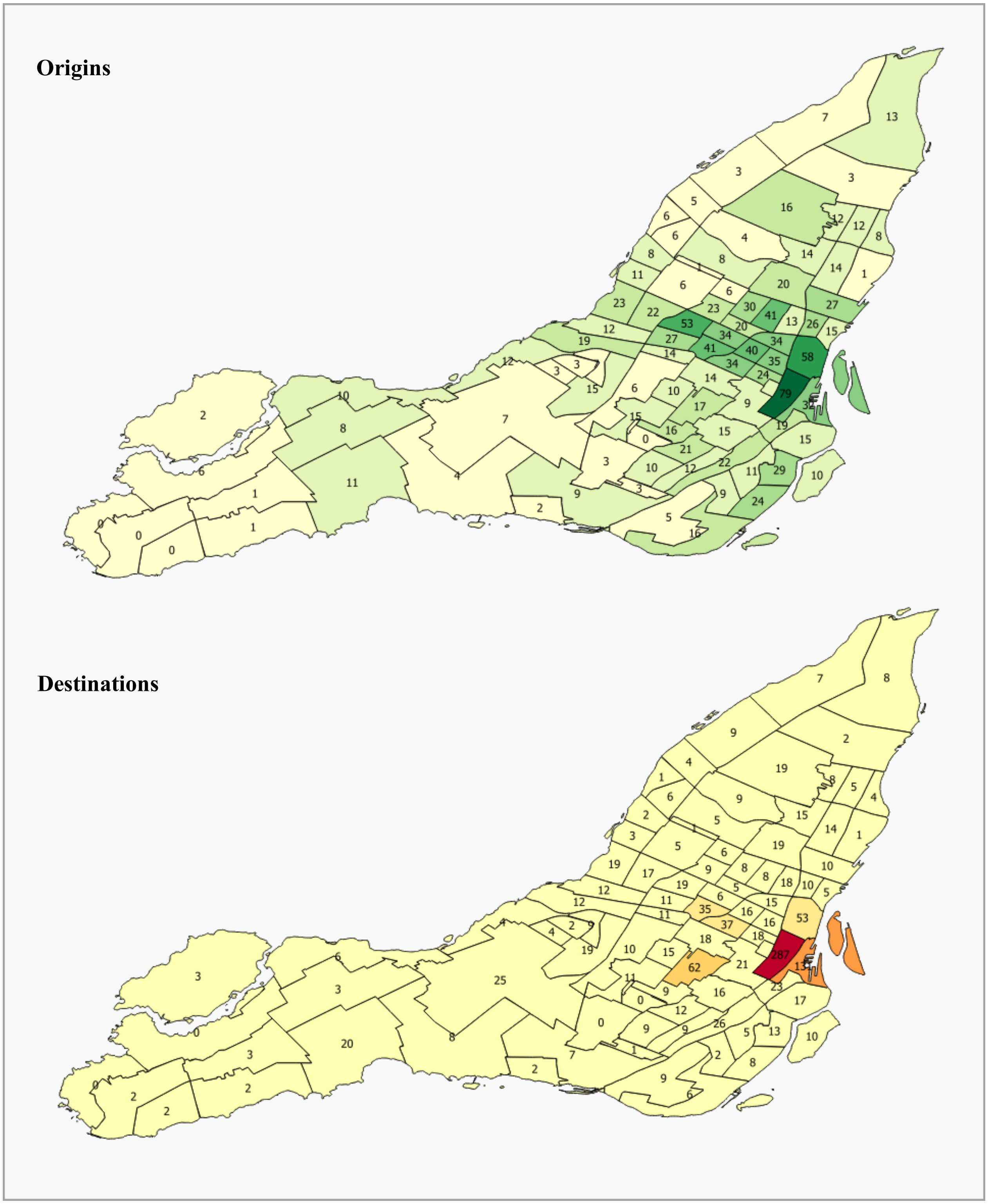
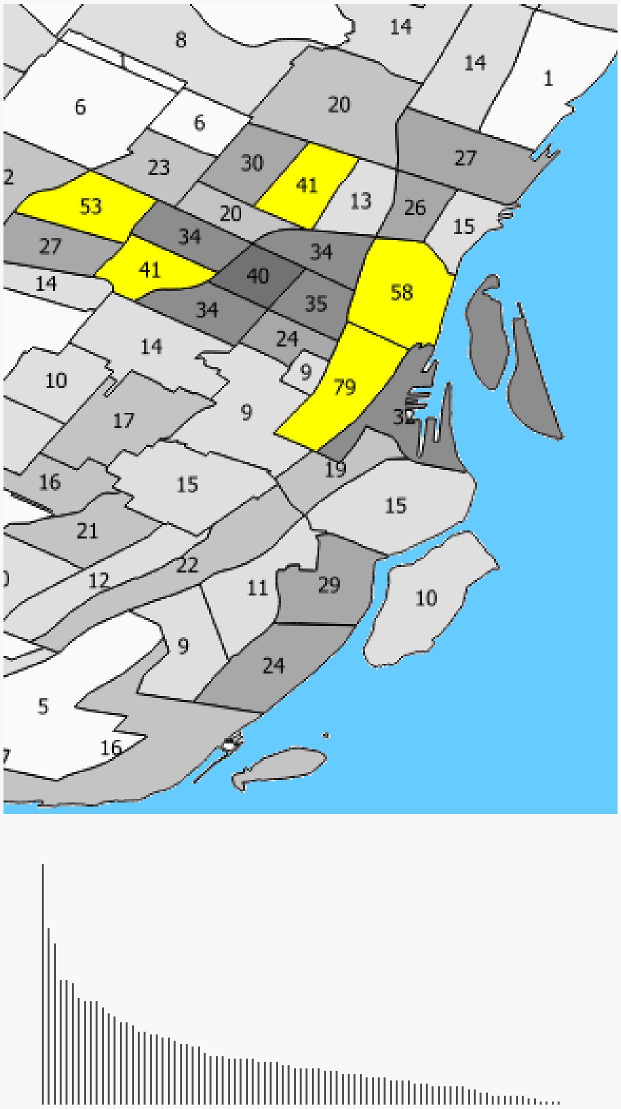
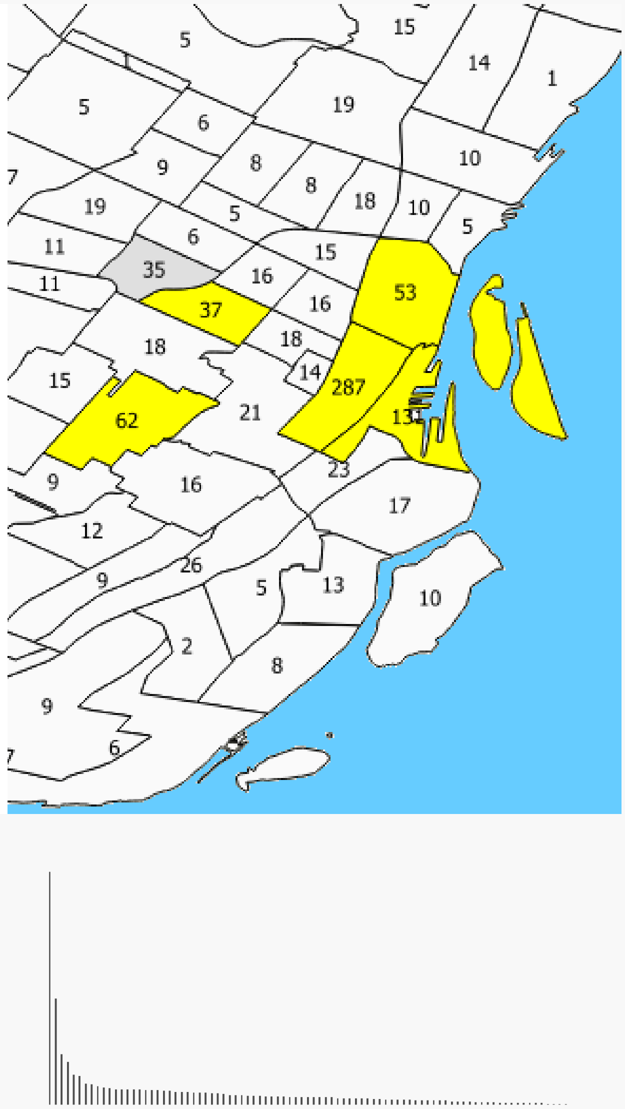


Figure 23: Choropleth map. October 5, 2017, 7 to 9 am.
Source: MTL Trajet custom table

Origins **Destinations**



1. René-Lévesque (Ville-Marie): 79 trips
2. Sainte-Marie (Ville-Marie): 58 trips
3. Crémazie (Villeray–Saint-Michel–Parc-Extension): 53 trips
4. Vieux-Rosemont (Rosemont–La Petite-Patrie): 41 trips
5. Saint-Édouard (Rosemont–La Petite-Patrie): 41 trips



1. René-Lévesque (Ville-Marie): 287 trips
2. Vieux-Montréal (Ville-Marie): 131 trips
3. Édouard-Montpetit (Côte-des-Neiges–Notre-Dame-de-Grâce): 62 trips
4. Sainte-Marie (Ville-Marie): 53 trips
5. Mile End (Le Plateau-Mont-Royal): 37 trips

Figure 24: Most transited quarters, October 5, 2017, 7 to 9 am.
Top: Choropleth map highlighted with the top 5 quarters. **Middle**: Quarter trip distribution.
Bottom: List of top 5 quarters. **Source**: MTL Trajet custom table

4.4. Flow maps

The usage of Flow maps is also found in the literature as Spider Diagrams (Desire lines), Force-directed graphs and edge bundling, which have very similar features for the purpose of this investigation. They are visualization tools that show which clients visit which stores, linking the information through a ray and “making it easy to see the actual area of influence of each store” (ArcGIS, n.d.). In the context of this work, the user and store are represented as the origin and destination respectively.

Limitations

Flow maps have the ability to display vectors with magnitude and directions between areas of the graph. By the nature of the dataset used in this thesis, it outputs a visually congested graph. Because of this, only relevant vectors are sought (Figure 25).

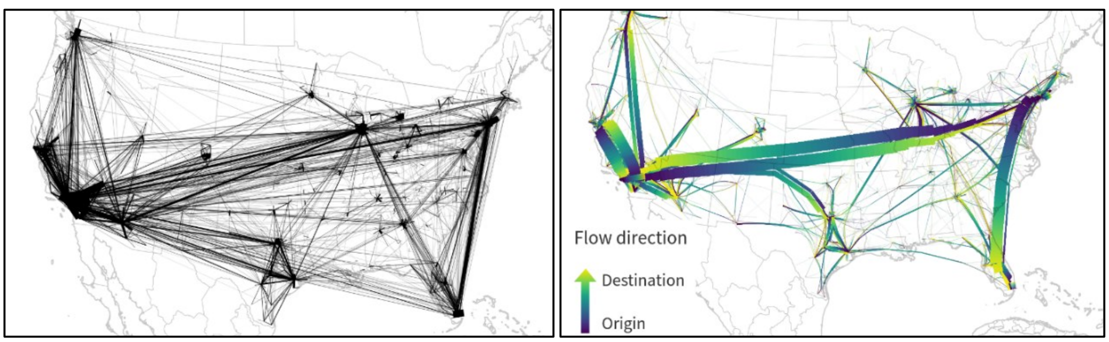


Figure 25: Flow map (edge bundling) example
Left: unbundled. **Right**: bundled. **Source**: (Dynamic Transportation Systems, 2017/2019)

Procedure

In order to generate a visually conclusive flow map, the following workflow was executed:

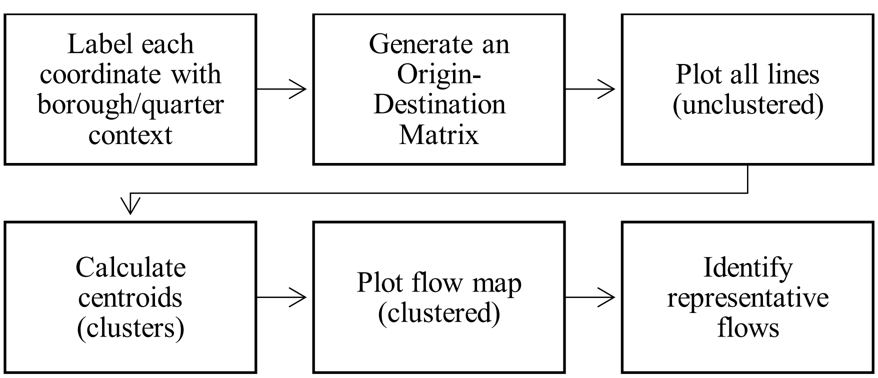


Figure 26: Flow map workflow

4.4.1. *Reverse geocoding*

The functions used to create the Origin and Destination choropleth map count the number of points falling inside a polygon. However, it does not add the polygon information back to the coordinate. A reverse geocoding is “the process of finding a place name from a given latitude and longitude” (Schneider, n.d.), information that is required to generate an OD matrix based on borough cell configuration.

The code used was narrowed from *Data Scietifique* workshop by Yara Abu Awad. The libraries used are `sf`, `sp` and `magrittr`.

The Coordinate Reference Systems used is `WGS84`, defined by:

```
CRS.new <- CRS("+init=epsg:4326 +proj=longlat +ellps=WGS84 +datum=WGS84
+no_defs +towgs84=0,0,0")
```

The coordinates are loaded with:

```
points <- read.csv('trips.csv', header = T, stringsAsFactors = FALSE)
```

Then, coordinates loaded must be converted to a compatible object for the libraries features:

```
coordinates(points)<-~longitude+latitude
proj4string(points) = CRS("+proj=longlat +ellps=WGS84 +datum=WGS84 +no_defs")
points2 = st_as_sf(points) #Convert foreign object to an sf object
```

The boundaries file is loaded:

```
boundaries = st_read('boundaries.gpkg')
st_crs(boundaries) #check the coordinate system
summary(boundaries) #look at attribute table
```

And then both coordinates and boundaries are plotted as displayed in Figure 28.

```
plot(boundaries %>% st_geometry) #plot polygons
plot(points2 %>% st_geometry,add=TRUE,pch=20,col=34) #add points
```

The coordinates are combined with the attributes of the boundaries layer:

```
boundariesp = st_transform(boundaries, '+proj=utm +zone=19 +ellps=GRS80
+towgs84=0,0,0,0,0,0,0 +units=m +no_defs')
pointsp = st_transform(points2, '+proj=utm +zone=19 +ellps=GRS80
+towgs84=0,0,0,0,0,0,0 +units=m +no_defs')
combination <- st_join(pointsp, boundariesp)
```

And the output is written on a file:

```
write.csv(combination,"output.csv")
```

The output is shown in Figure 27, where an `NA` means that the coordinate point did not fall inside any geometry. This table value relies on the `id_trip` linked to a quarter by `no_qr` and `nom_qr` columns.

id_trip	type	no_qr	nom_qr	no_arr	nom_arr	nom_mun	geometry
341542	origin7to9	NA	NA	NA	NA	NA	c(128327.358790795, 5056095.02840515)
165670	origin7to9	NA	NA	NA	NA	NA	c(147374.861112171, 5050156.50306835)
224993	origin7to9	30	Sainte-Marie	19	Ville-Marie	Montréal	c(144676.598819731, 5051429.9847859)
131141	origin7to9	30	Sainte-Marie	19	Ville-Marie	Montréal	c(144082.769086304, 5052542.42303802)
447830	origin7to9	81	Westmount	NA	NA	Westmount	c(141736.720579697, 5046838.25028618)
213391	origin7to9	23	Tétreaultville	22	Mercier–Hochelaga-Maisonneuve	Montréal	c(147513.178999919, 5060095.3944378)
242230	origin7to9	32	Parc-Lafontaine	21	Le Plateau-Mont-Royal	Montréal	c(142480.386962863, 5051522.73604783)
127294	origin7to9	15	Père-Marquette	24	Rosemont–La Petite-Patrie	Montréal	c(140525.456400652, 5053247.45531251)
161506	origin7to9	68	Sault-Saint-Louis	17	LaSalle	Montréal	c(136773.561079886, 5040173.50084738)
57581	origin7to9	45	Loyola	34	Côte-des-Neiges–Notre-Dame-de-Grâce	Montréal	c(136545.51961318, 5044558.60799142)
447220	origin7to9	85	Dorval	NA	NA	Dorval	c(128495.207242295, 5043761.41919492)
169184	origin7to9	60A	Ouest	16	Montréal-Nord	Montréal	c(138320.418233261, 5058963.89911368)
464702	origin7to9	60A	Ouest	16	Montréal-Nord	Montréal	c(137981.378775444, 5057637.94947547)
328839	origin7to9	NA	NA	NA	NA	NA	c(160143.426204074, 5049867.07537032)
354426	origin7to9	67	Cecil-P.-Newman	17	LaSalle	Montréal	c(137875.788787441, 5041417.59890936)
114865	origin7to9	20	Marie-Victorin	24	Rosemont–La Petite-Patrie	Montréal	c(142971.681683986, 5056175.49515141)

Figure 27: Output from reverse geocoding (top lines)
Software: R

4.4.2. *Origin-Destination Matrix*

I labelled the coordinate points with the borough and quarter they belonged to. With this, some trips are discarded if the origin and/or destination coordinate falls in a polygon from other municipalities than Montreal (Figure 28).

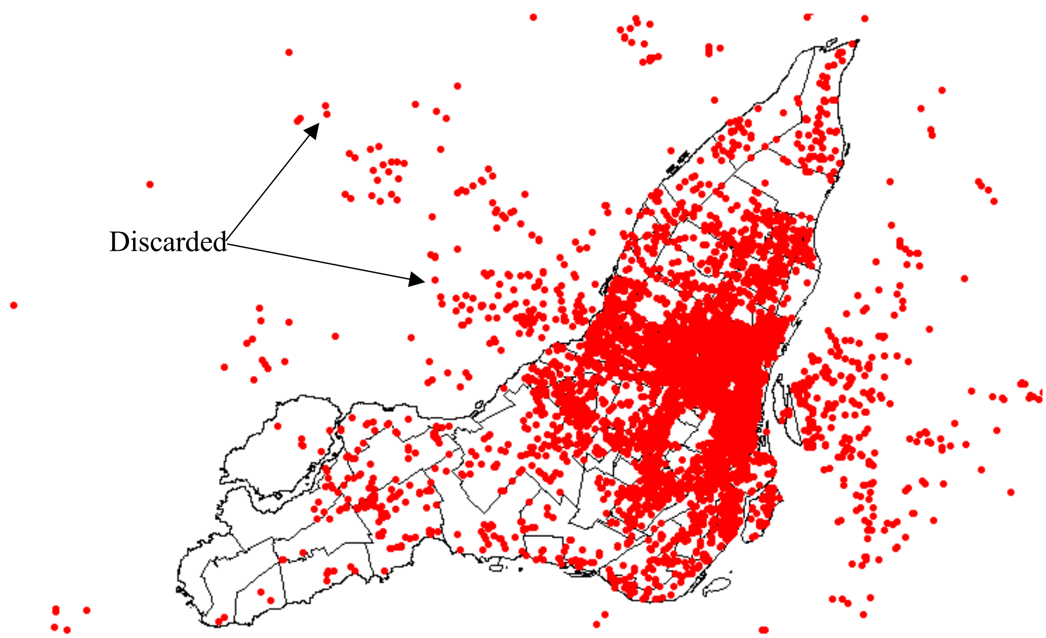


Figure 28: Origin-Destination coordinates inside and outside Montreal boroughs
Software: R

With the output of section 4.4.1 a second custom table was composed (Figure 29) where each row contains the origin and destination information for the quarter (`no_qr`, `nom_qr`) and borough (`no_arr`, `nom_arr`) they belong to. This set up allows getting a square matrix using the `Pivot table` feature by crossing two fields (Figure 30).

	ORIGINS				DESTINATIONS			
id_trip	no_q	nom_qr_orig	no_ar	nom_arr_orig	no_q	nom_qr_dest	no_ar	nom_arr_dest
116	37	Vieux-Montréal	19	Ville-Marie	37	Vieux-Montréal	19	Ville-Marie
181	67	Cecil-P.-Newman	17	LaSalle	67	Cecil-P.-Newman	17	LaSalle
421	36	Milton-Parc	21	Le Plateau-Mont-Royal	35	Saint-Louis	21	Le Plateau-Mont-Royal
582	13	Crémazie	25	Villeray–Saint-Michel–Pa	13	Crémazie	25	Villeray–Saint-Michel–Pa
640	38	René-Lévesque	19	Ville-Marie	26	Longue-Pointe	22	Mercier–Hochelaga-Mais
700	27	Hochelaga	22	Mercier–Hochelaga-Mais	27	Hochelaga	22	Mercier–Hochelaga-Mais
710	15	Père-Marquette	24	Rosemont–La Petite-Patı	38	René-Lévesque	19	Ville-Marie
730	16	Louis-Hébert	24	Rosemont–La Petite-Patı	51	Petite-Bourgogne	20	Le Sud-Ouest
852	34	Mile End	21	Le Plateau-Mont-Royal	39	Montagne	19	Ville-Marie
903	39	Montagne	19	Ville-Marie	15	Père-Marquette	24	Rosemont–La Petite-Patr
963	65	Ile-des-Soeurs	12	Verdun	65	Ile-des-Soeurs	12	Verdun
1031	50	Saint-Henri	20	Le Sud-Ouest	38	René-Lévesque	19	Ville-Marie
1061	37	Vieux-Montréal	19	Ville-Marie	49	Ville-Émard	20	Le Sud-Ouest
1064	38	René-Lévesque	19	Ville-Marie	28	Maisonneuve	22	Mercier–Hochelaga-Mais
1125	33	Parc-Laurier	21	Le Plateau-Mont-Royal	34	Mile End	21	Le Plateau-Mont-Royal
1210	32	Parc-Lafontaine	21	Le Plateau-Mont-Royal	3	Nicolas-Viel	23	Ahuntsic-Cartierville

Figure 29: Second custom table for OD-Matrix input

useful	YES
type_orig	origin7to9

R	5	9	12	14	15	16	17	19	20	21	22	23	24	25	27	31	32	33	34
5	4							4			1								5
9		6		1	1			1			4	1	2						
12		1	16		1		1	16	9	5			1	2	1				6
14				3				2			1	1	1	3					
15	1				17			3	2	2			1	1					2
16		1		1	1	8		2		1	1	4		3					1
17							7	5	2			1			2				1
19	1		3		1			136	11	10	1	1	1					1	4
20		1	5		2		2	26	19	4	1		2	1				1	5
21	1	2	1	1	2			61	7	48	4	3	11	4				1	17
22		1	2	1		1		40	5	4	42	1	10	1				6	6
23	1				9	2		20	3	2	2	33	4	4			1	2	4
24	1	1	1	5	3			58	6	24	6	6	53	14	2			2	8
25	2	2		1	6	1	1	36	4	8	2	11	7	24				2	13
27							2	3							4				1
31					1			2								5	1		2
32							1										1		
33		3				1		3			4		1	2				7	
34	3		3		9		1	27	3	3	2	1	2	1					39

FILTERS: useful, type_orig
COLUMNS: no_arr_dest
ROWS: no_arr_orig
Σ VALUES: Count of id_trip

Figure 30: Pivot table (summary view) composing an OD-Matrix for Boroughs, October 5, 7 to 9 am. **Vertical axis**: origins. **Horizontal axis**: destinations. **Software**: Excel

4.4.3. ***Desire lines***

A table including the `trip ID`, `origin` coordinate and `destination` coordinate was composed to plot the desire lines. Figure 31 shows an unweighted map, where each user is represented individually. Due to the amount of data being plotted, it is difficult to read the resulting map. Thus, a weighted map (where the weight depends on variables such as frequency) is sought in the following steps.

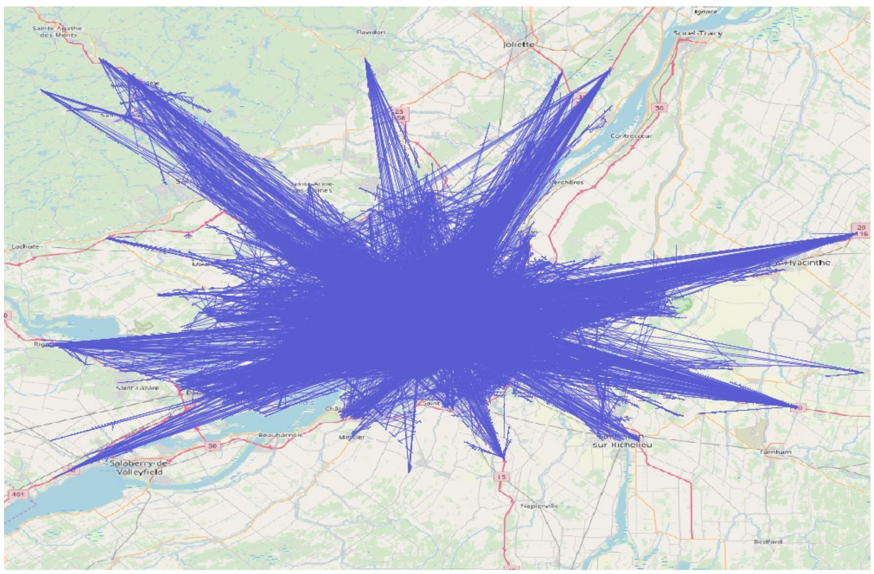


Figure 31: Spider map-desire lines of the *best week* (ungrouped, unfiltered)

4.4.4. ***Centroids***

In order to get a cleaner diagram, a weighted spider map is sought. Using centroids of each polygon will allow grouping desire lines according to their quarter or borough. A centroid layer is created through the feature `Vector > Geometry Tools > Centroids` in QGIS 3.2.3. Since the output is a geometry file, the Option `Vector > Geometry Tools > Add Geometry Attributes` allows one to export the polygon layer with a column including the *x* and *y* coordinates of the centroids. A text file containing the *x* and *y* coordinates is required.

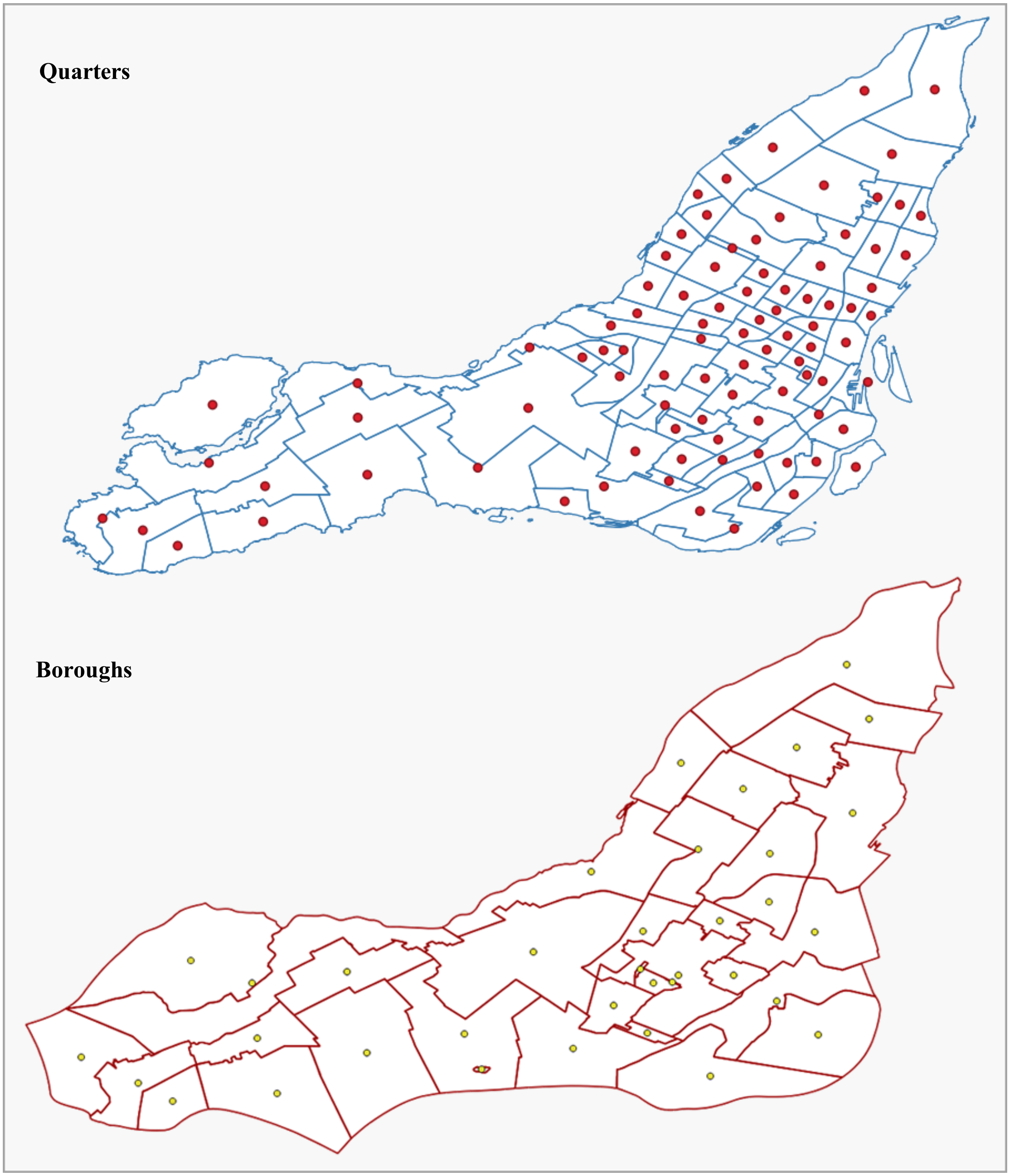


Figure 32: Centroids in polygons

4.4.5. *Plotting*

`FlowMapper` 0.4.1 is used along with `QGIS` 2.18.28. As of today, this plugin is not compatible with recent versions of the software.

For the flow aggregation, it was used a representation type of `Standard Deviation`, as it is considered that visually it is more relevant the amount of dispersion of the given magnitudes of the OD matrix.

The output diagram is presented in Figure 33d. Here, the output measure is represented through an arrow of increasing width and changing colour. Although it is visually cleaner than its early version, I proceeded to filter representative vectors.

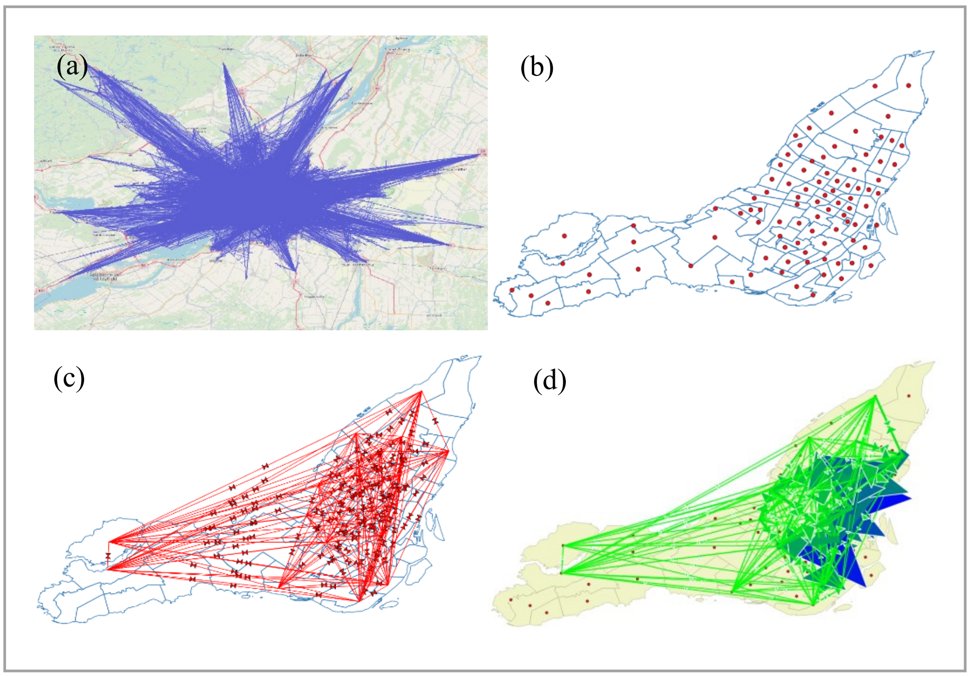


Figure 33: Creation process of Flow map
(a) Desire lines (ungrouped, unfiltered) (b) Boundaries polygons and its centroids
(c) Flow lines between quarter centroids (unweighted, unfiltered)
(d) Flow lines between quarter centroids (weighted, both directions, unfiltered)

4.4.6. *Representative vectors*

The final part of the diagram process was to filter the lines with the strongest force (magnitude) to look for outstanding trends. As seen in the Choropleth maps, reaching downtown is the principal destination for the participants of MTL Trajet, as well the most representative vector for adjacent boroughs, being Le Plateau-Mont-Royal and Rosemont-La Petite-Patrie the areas that host the greatest amount of users travelling to downtown in the morning.

Please note that the geometries used in Boroughs dataset contain land and water, thus, geometries are different than the quarters dataset.

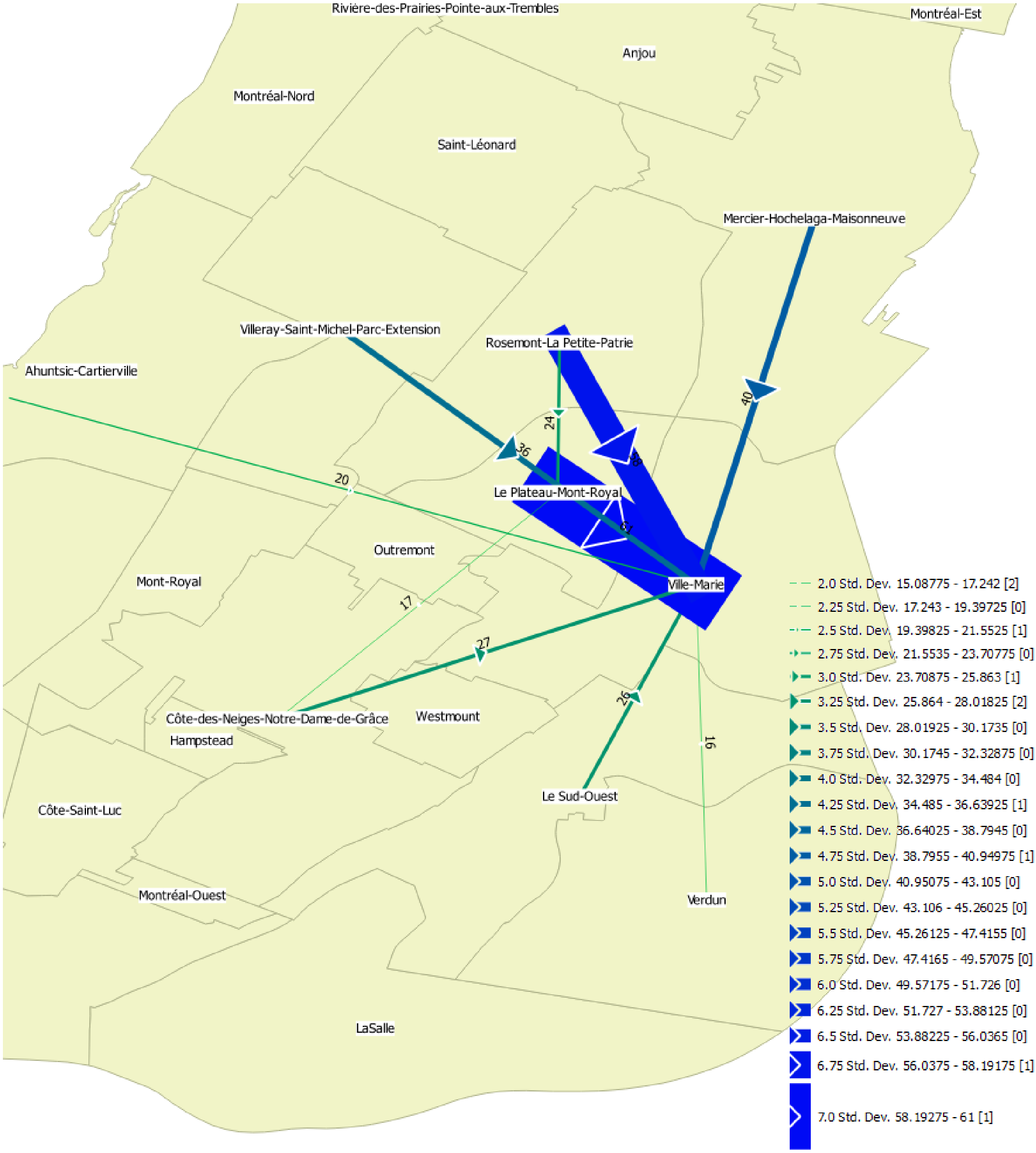


Figure 34: Force-directed diagram based on Boroughs, October 5, 2017, 7 to 9 am.

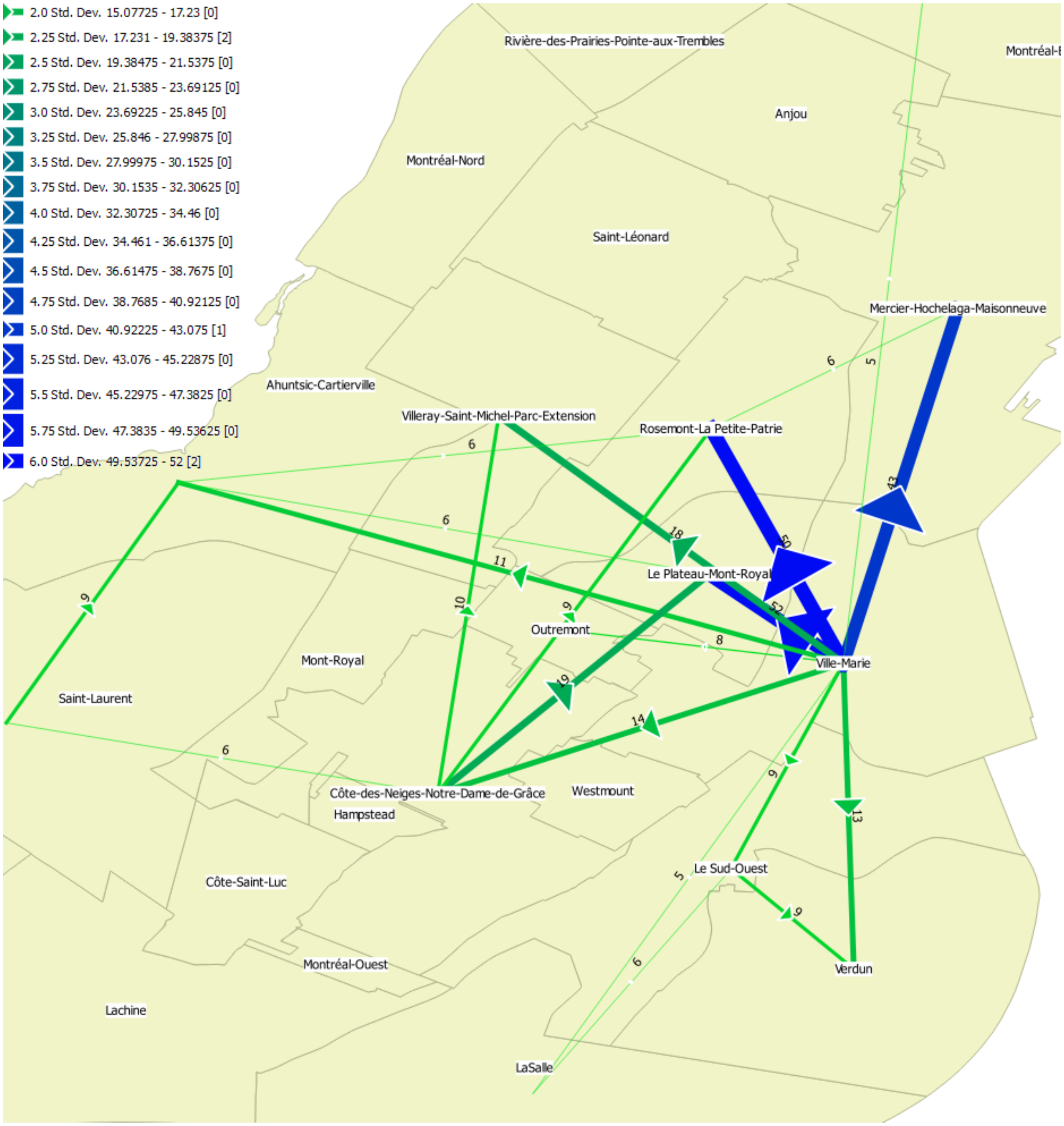


Figure 35: Force-directed diagram based on Boroughs, October 5, 2017, 4 to 7 pm.

4.5. Chord diagram

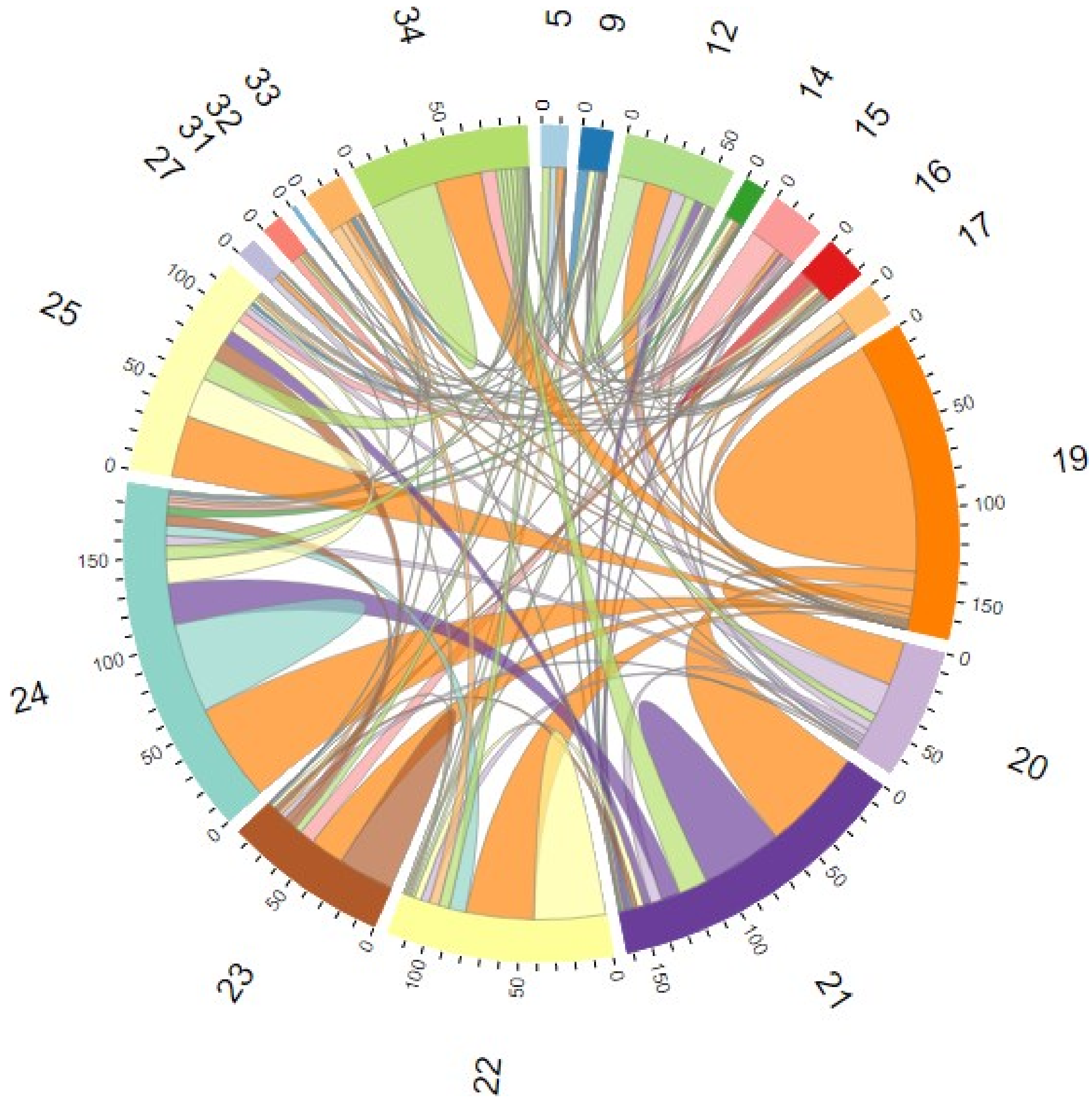
A chord diagram show flows between several nodes (e.g. centroids) represented in a circular layout, after which arcs are drawn between each features allowing to visualize a weighted relationship (Holtz, n.d.).

For this task, I used the Origin-Destination Matrix built-in section 4.4.2. The R package used for this task was `chorddiag` through the following code:

```
library(chorddiag)

m <- matrix(c(<Origin-Destination Matrix goes here>), # Must be square matrix
            byrow = TRUE,
            nrow = 19, ncol = 19)

# A vector of 19 colors for 19 groups
boroughs <- c("5", "9", "12", "14", "15", "16", "17", "19", "20", "21", "22",
"23", "24", "25", "27", "31", "32", "33", "34")
dimnames(m) <- list(have = boroughs,
                    prefer = boroughs)
groupColors <-
c('#a6cee3','#1f78b4','#b2df8a','#33a02c','#fb9a99','#e31a1c','#fdbf6f','#ff7f
00','#cab2d6','#6a3d9a','#ffff99','#b15928','#8dd3c7','#ffffb3','#bebada','#fb
8072','#80b1d3','#fdb462','#b3de69')

p <- chorddiag(m, groupColors = groupColors, groupnamePadding = 50)
p # Displays the diagram
```

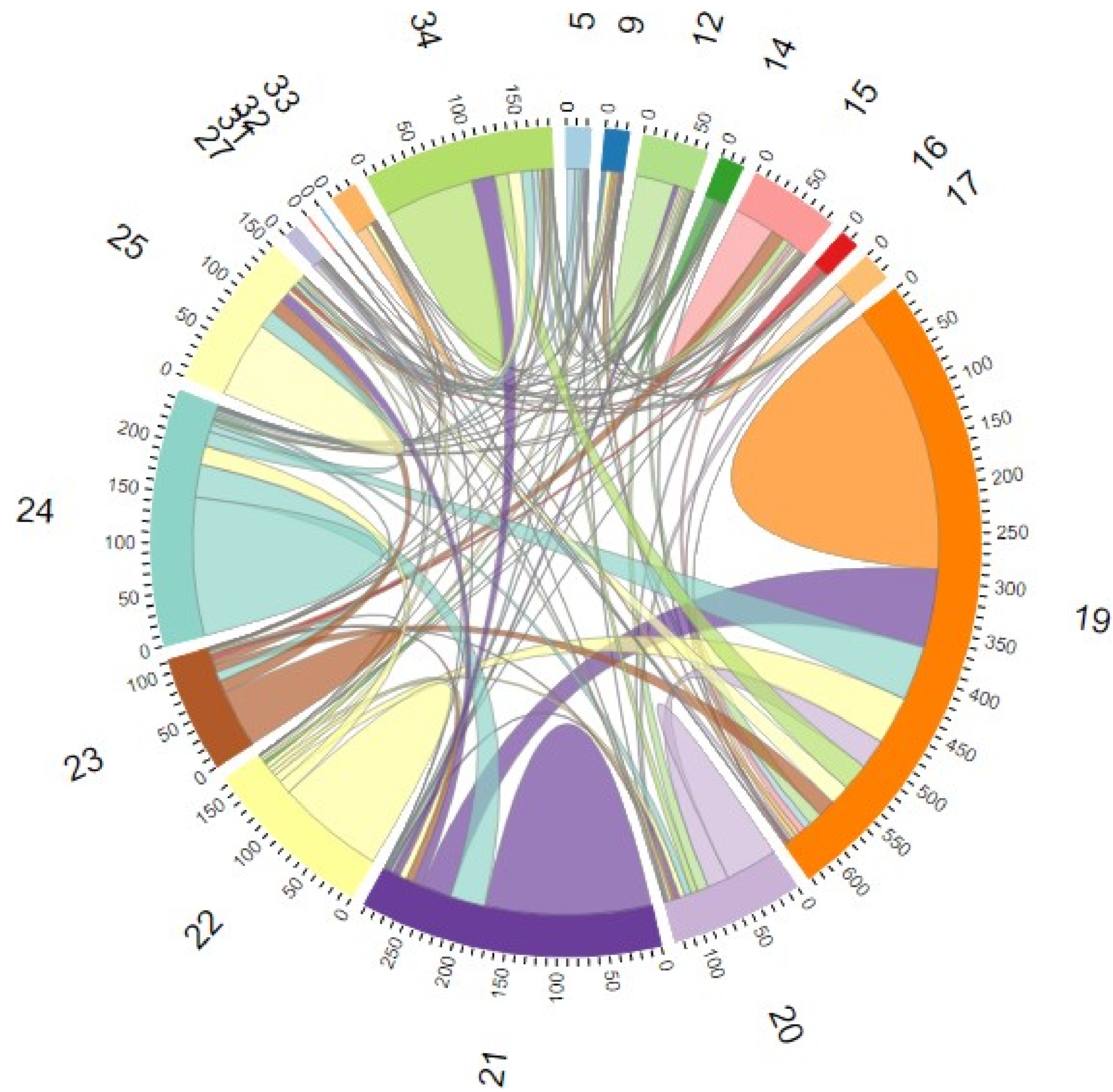
Figure 36 and Figure 37 show the resulting diagrams. Their lecture is as exemplified: from borough 24 in the 7 to 9 am version, 58 users traveled to borough 19 (orange arc) as confirmed with the OD matrix. Also, 53 stayed in the same borough. We can reconfirm the relevance of borough 19, as visually it is attracting more arcs than the others.

Figure 38 shows the distribution accounting only the users that stayed inside the same borough, meaning they live close to their destination (work/school). Under this basis, most of the participants live close from downtown.



5 Outremont · **9** Anjou · **12** Verdun · **14** Saint-Léonard · **15** Saint-Laurent · **16** Montréal-Nord · **17** LaSalle **19** Ville-Marie · **20** Le Sud-Ouest · **21** Le Plateau-Mont-Royal · **22** Mercier–Hochelaga-Maisonneuve **23** Ahuntsic-Cartierville · **24** Rosemont–La Petite-Patrie · **25** Villeray–Saint-Michel–Parc-Extension · **27** Lachine **31** Pierrefonds-Roxboro · **32** L'Île-Bizard–Sainte-Geneviève · **33** Rivière-des-Prairies–Pointe-aux-Trembles **34** Côte-des-Neiges–Notre-Dame-de-Grâce

Figure 36: Chord diagram based on Boroughs, October 5, 2017, 7 to 9 am.



5 Outremont · **9** Anjou · **12** Verdun · **14** Saint-Léonard · **15** Saint-Laurent · **16** Montréal-Nord · **17** LaSalle **19** Ville-Marie · **20** Le Sud-Ouest · **21** Le Plateau-Mont-Royal · **22** Mercier–Hochelaga-Maisonneuve **23** Ahuntsic-Cartierville · **24** Rosemont–La Petite-Patrie · **25** Villeray–Saint-Michel–Parc-Extension · **27** Lachine **31** Pierrefonds-Roxboro · **32** L'Île-Bizard–Sainte-Geneviève · **33** Rivière-des-Prairies–Pointe-aux-Trembles **34** Côte-des-Neiges–Notre-Dame-de-Grâce

Figure 37: Chord diagram based on Boroughs, October 5, 2017, 4 to 7 pm

5 Outremont
9 Anjou
12 Verdun
14 Saint-Léonard
15 Saint-Laurent
16 Montréal-Nord
17 LaSalle
19 Ville-Marie
20 Le Sud-Ouest
21 Le Plateau-Mont-Royal
22 Mercier–Hochelaga-Maisonneuve
23 Ahuntsic-Cartierville
24 Rosemont–La Petite-Patrie
25 Villeray–Saint-Michel–Parc-Extension
27 Lachine
31 Pierrefonds-Roxboro
32 L'Île-Bizard–Sainte-Geneviève
33 Rivière-des-Prairies–Pointe-aux-Trembles
34 Côte-des-Neiges–Notre-Dame-de-Grâce

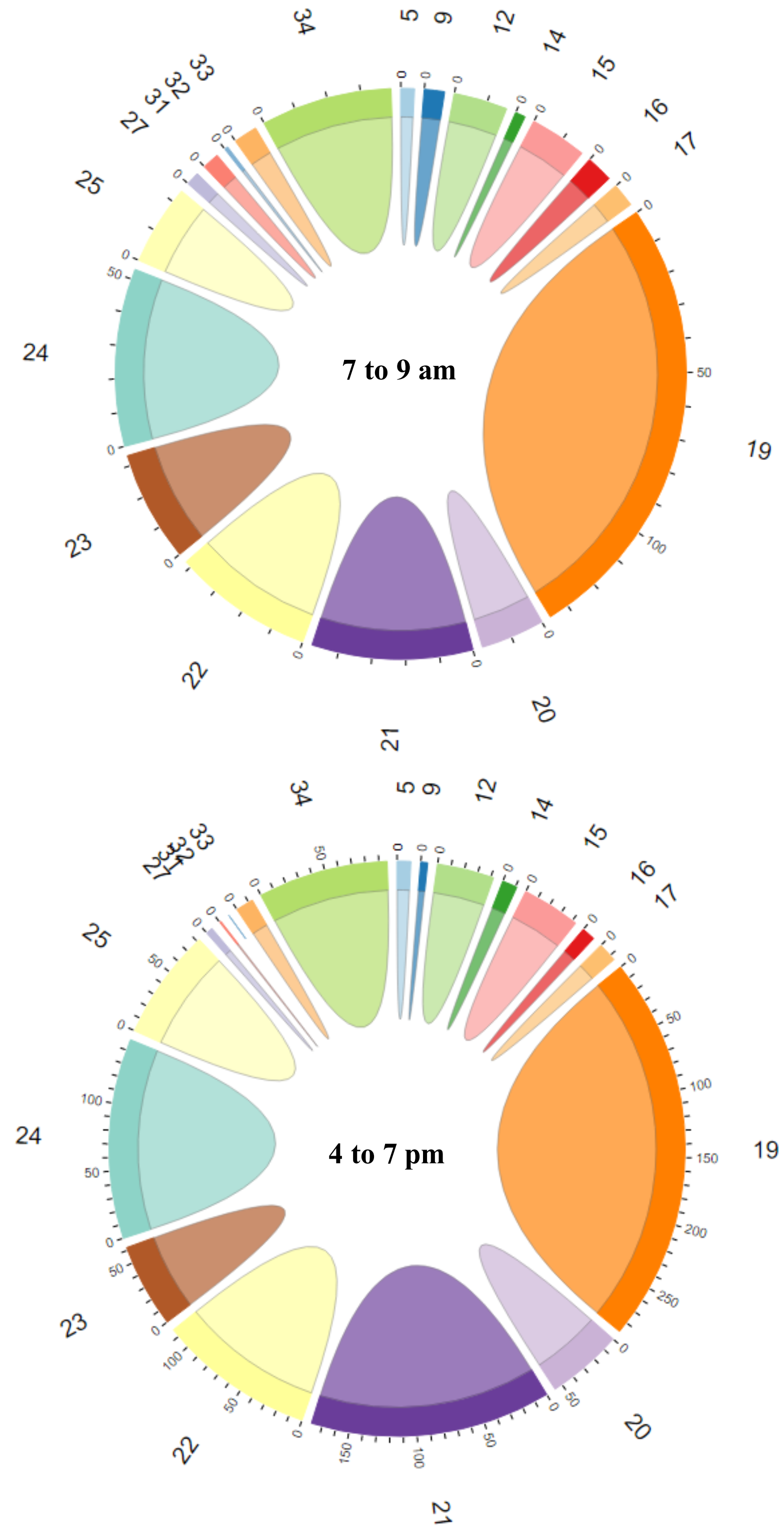


Figure 38: Chord diagram showing users travelling inside the borough

Chapter 5

Application Results

In the previous chapter, a macro focus on the boundaries of the territory of Montreal was sought for visualization and analysis, where the 19 boroughs along with their 77 quarters were targeted for spatial analysis through three data visualization tasks. Macro-scale demand was reconstructed for October 5, 2019, for the congested periods of 7 to 9 am and 4 to 7 pm.

In this chapter, **meso and micro-scale analyses** are presented. A meso-analysis is performed for the observed most transited territory found in the macro analysis. Meso-scale maps aid to visualize relations among elements of the area in order to find hints to improve urban mobility. At micro-scale, findings of meso-analysis can be converted to hypothetical scenarios to experiment with changes in the system at a micro-scale to improve urban mobility. The use of new transit-policies in these curated scenarios are simulated. The process and selected results are presented. Since the data is not representative of the population of Montreal, general assumptions cannot be made from this work. However, it gives useful insight into urban mobility behaviour for workers and students with a routine place of travel.

5.1. Meso-scale analysis of René-Lévesque quarter

As found in the previous chapter, the quarter of René-Lévesque (hereafter: “RLQ” or “top quarter”) in the borough of Ville-Marie is the most transited quarter for both origins and destination. This aligns with the perception of downtown Montreal as the main economic area. In order to perform mesoscale analyses of this quarter, I followed the workflow shown in Figure 39.

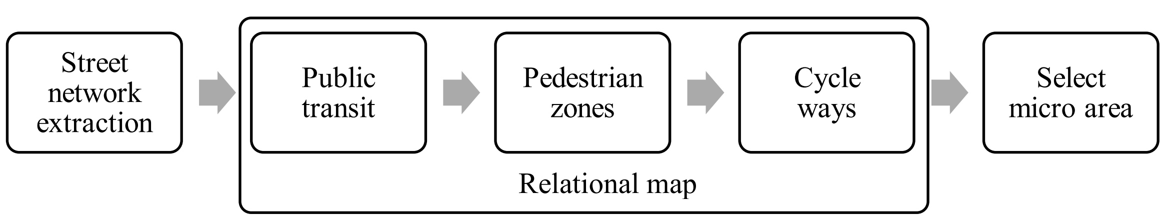


Figure 39: Meso-scale analysis workflow for René-Lévesque quarter

5.1.1. *Extraction of the street network elements*

I used two OpenStreetMap tools to extract micro-scale information from the chosen zone: `OSMInfo` and `OSM` built-in features in `QGIS`. The mesoscale analysis is approached by the extent of information used for the maps.

`OSMInfo` is a `QGIS` plugin that pulls all information for a particular point in the canvas and shows details about objects from `OpenStreetMap` (NextGIS, 2015/2019). When selecting a spot, it shows nearby objects (streets, buildings or parks represented by polygons etc.) and the hierarchy of where the point is located (Country > Time zone > Province > City > Borough > Quarter > Area) as shown in Figure 40. With this tool, I extracted the geometry of the René-Lévesque quarter for further steps.

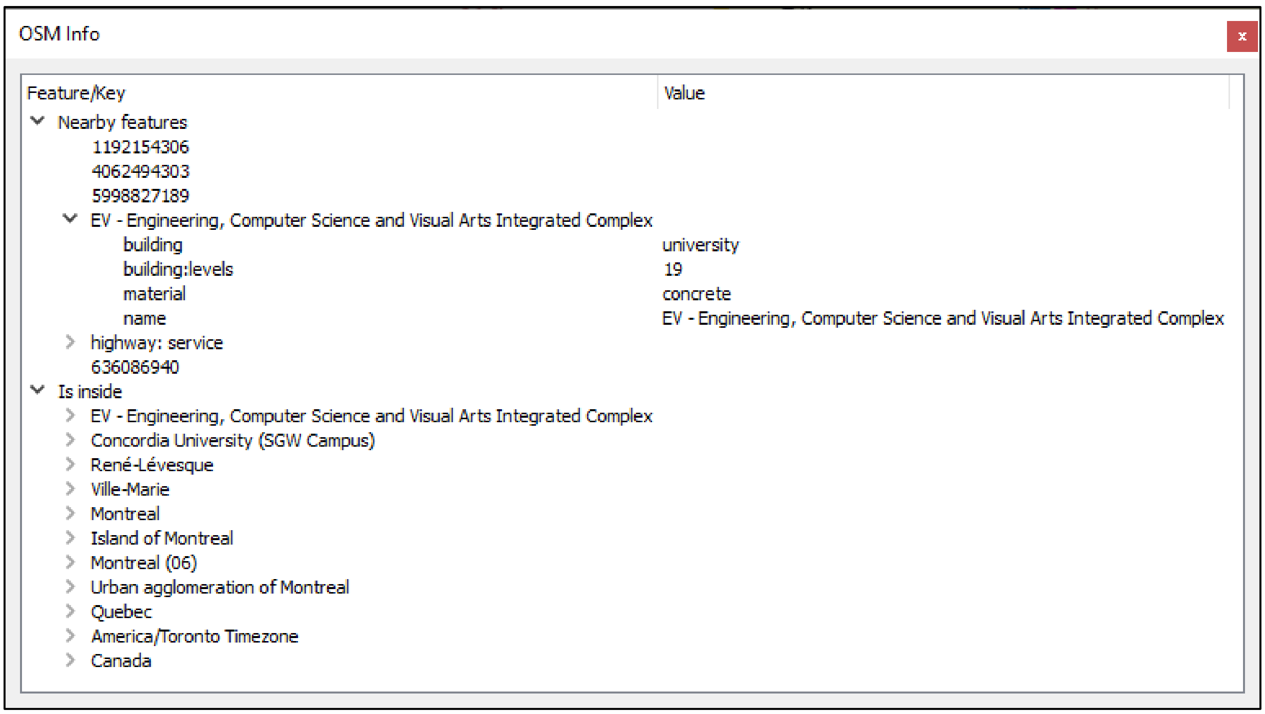


Figure 40: OSMInfo search function

`QGIS` has integrated `OSM` functionalities. The instruction `Vector > OpenStreetMap > Download Data` allows to request `OSM` data from its server. In my case, I extracted the `OSM` network using the RLQ Polygon as the frame, obtaining a file with extension `*.osm` and file size fewer than 10 megabytes.

The downloaded file stores several inner tables (Figure 41), where the relevant for this task were the ones displaying **polygons** (e.g., buildings, areas, parks), **lines** (e.g., metro, streets, pathways) and **points** (e.g., metro exits, stores). Conjointly, these objects compose a map in the social conception we understand (e.g. OpenStreetMap, Google Maps, Apple Maps, Here Maps).

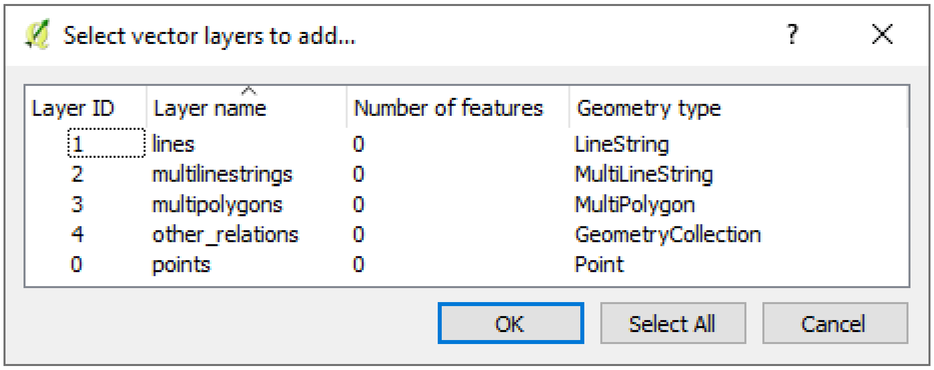


Figure 41: Importation of OpenStreetMap data to a QGIS project.

Besides their geometric and geographic attributes, each feature contains information about its hierarchy or element type. For this project, the attribute `highway` was relevant, which targeted objects may be of the categories enlisted in Table 12.

Table 12: Highway tag from OpenStreetMap data
Source: (OpenStreetMap Wiki, 2020)

Property	Description
`primary`	The next most important roads in a country's system (link larger towns.)
`secondary`	The next most important roads in a country's system (link towns.)
`tertiary`	The next most important roads in a country's system (link small towns and villages)
`pedestrian`	For roads used mainly/exclusively for pedestrians in shopping and some residential areas which may allow access by motorized vehicles only for very limited periods of the day.
`footway`	For designated footpaths; i.e., mainly/exclusively for pedestrians. This includes walking tracks and gravel paths. If bicycles are allowed as well, you can indicate this by adding a tag. It should not be used for paths where the primary or intended usage is unknown.
`cycleway`	For designated cycleways.

In pursuance of filtering only relevant elements, a `Search by expression` query in `QGIS` is executed. The language is similar to the one used in `SQL`. To search among the thousands of records of each table, the expression used is `"highway" ILIKE '%tag%'` where `tag` can be substituted by `'pedestrian'`, `'footway'`, `'tertiary'` or any of interest of the available options.

The quarter maps

Each of these queries was exported to a new file, and after several iterations of filtering, they were accommodated in different layers. Several maps were composed for analysis. The selected area analysis is shown in Figure 42. This figure is achieved by turning On/Off the filtered layers in previous steps in order to visualize specific relations of the network.

5.1.2. *Analysis of Public transit accessibility*

Access to buildings and areas by metro/large capacity public transit is essential for crowded areas such as schools, government services and hospitals. In Montreal, the public transit system is powered by *la Société de transport de Montréal* (STM). Insights of the relation between universities inside/close to René-Lévesque quarter and the transit system is shown in Figure 43 for the metro and Figure 44 for buses. We can see that McGill University (tangent to Metro line and RLQ) has relatively the minimum accessibility requirement for both metro and bus despite its size. Full connectivity to main campuses of *l'Université du Québec à Montréal* (UQÀM) and Concordia University is achieved, and sufficient for the second campus of UQÀM. Finally, public transit access for *l'École de technologie supérieure* (ÉTS) is inexistent for the metro and seems highly limited by bus mode.

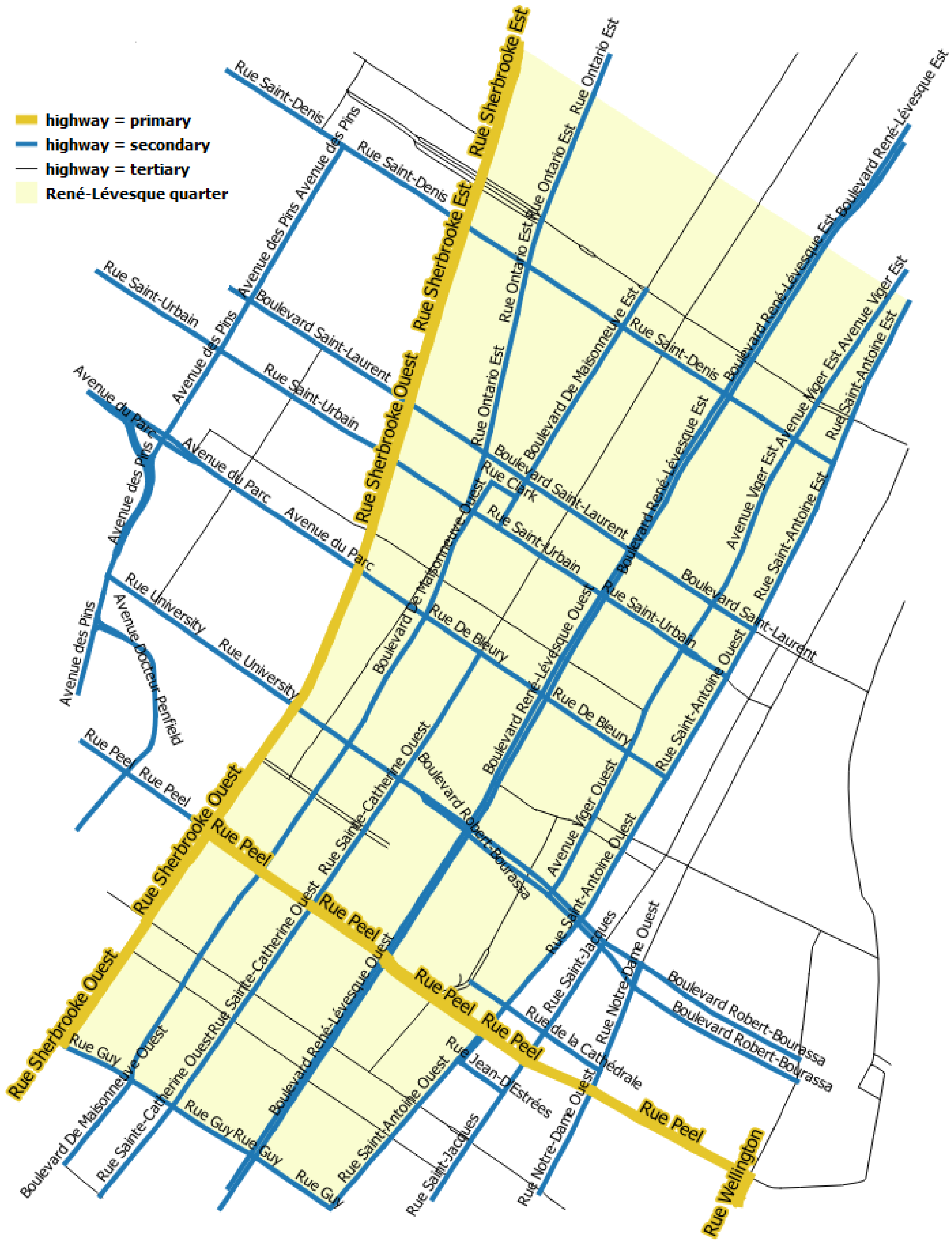


Figure 42: Main network of René-Lévesque quarter
Data: OpenStreetMap. **Software**: QGIS.

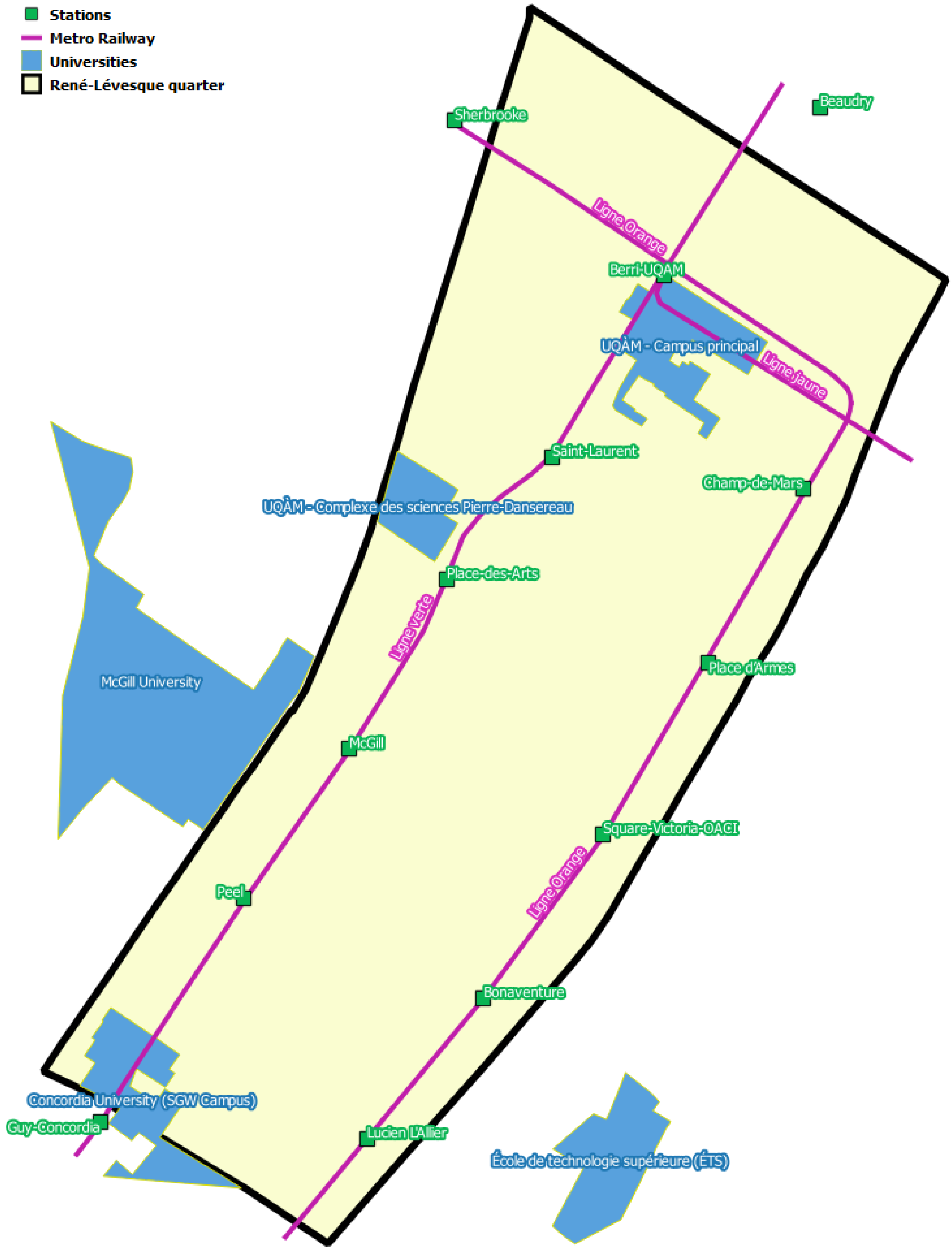


Figure 43: Public transit connectivity by metro for universities in/close to René-Lévesque quarter
Data: OpenStreetMap. **Software**: QGIS.

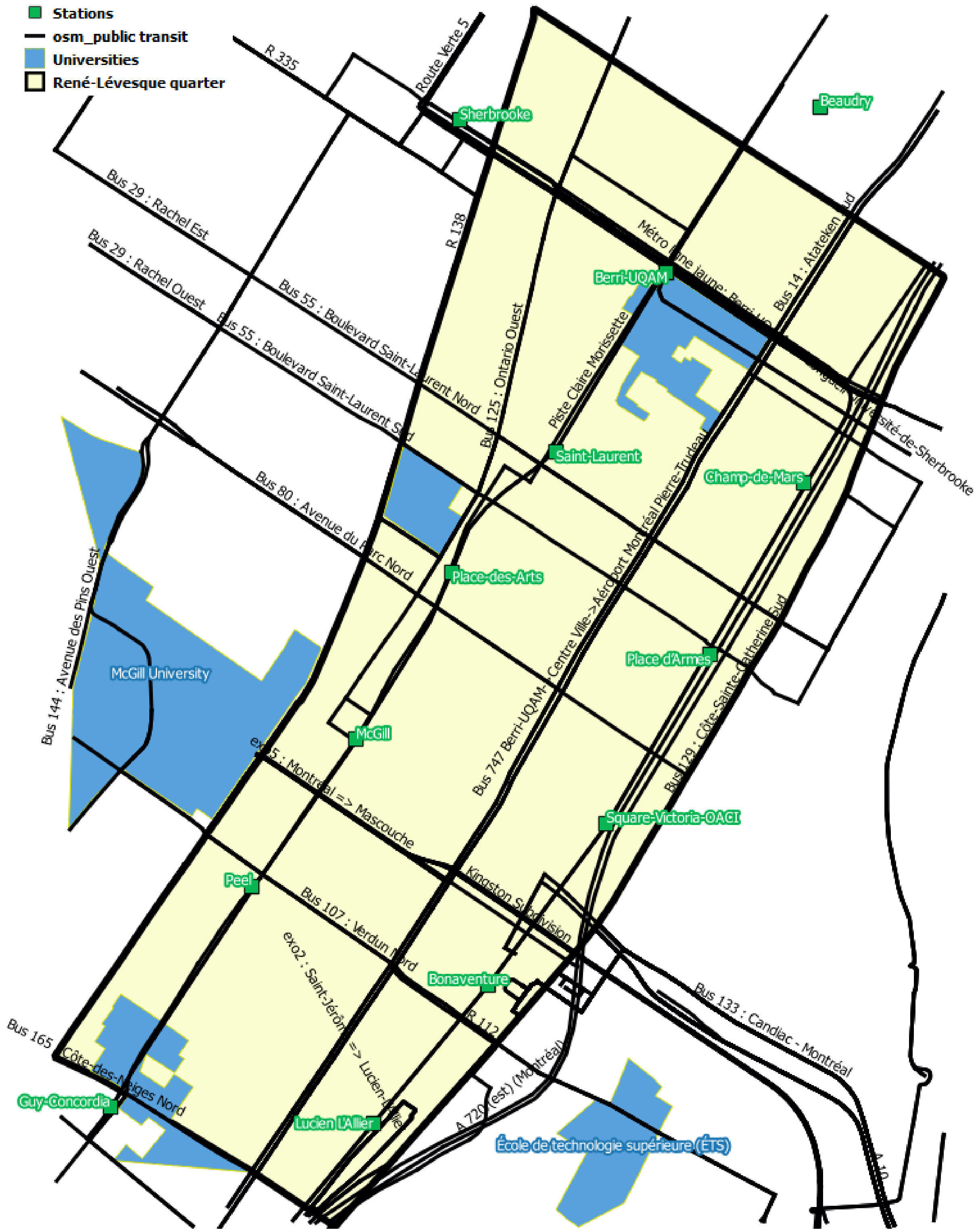


Figure 44: Public transit connectivity by bus for universities in/close to René-Lévesque quarter
Data: OpenStreetMap. **Software**: QGIS.

5.1.3. *Analysis of pedestrian zones*

Pedestrian public spaces bring people together, make them get out of isolation and meet their neighbours, agrees Sue Montgomery, Mayor of the Côte-des-Neiges–Notre-Dame-de-Grâce borough. She says that with climate change in mind, it is time to rethink the cityscape (Isaac Olson/CBC News, 2019b). The main benefits found for pedestrian zone developments (Ebru, 2013): low atmospheric emissions, low road accident rates, better-built environment conditions, discouragement of the private car and other motorized vehicles (a measure of travel demand management) and encouragement of active modes.

There are eight kilometres of pedestrian zones in Montreal, and new projects are being deployed during 2020. The pedestrian area located at *Rue De la Gauchetière Est* (Figure 45) is one of the most popular zones in Montreal. It serves as a space for commercial development, recreation and the sense of community discussed by Montgomery.

Figure 45: Pedestrian zone in Montreal's Chinatown.
Photo by © Eva Blue downloaded from mtl.org

A pilot project in Jean-Brillant Street was started during 2019, where a sidewalk daily serving 15,000 people and connecting Côte-des-Neiges Metro station and the University of Montréal got an extension of a wider walking area and reduced its roadway to a single, one-way lane for cars (Isaac Olson/CBC News, 2019b). Pedestrian areas inside/close to the René-Lévesque quarter are shown in Figure 46. Only McGill University has access to one, the main campus of UQÀM has marginally one area close and the Concordia University has none. "There's just so much foot traffic in that area that it was a no-brainer to make it safer and more pleasant to walk," said borough Mayor Sue Montgomery about Jean-Brillant pilot, which relates to these other examples.

Figure 46: Pedestrian zones close to René-Lévesque quarter
Data: OpenStreetMap. **Software**: QGIS.

5.1.4. *Analysis of cycleways*

The figure below shows the bike paths in Montreal as registered by `OSM`. Although bicycles are permitted at mostly all over the city, only UQÀM has access to a long path according to `OSM` data.

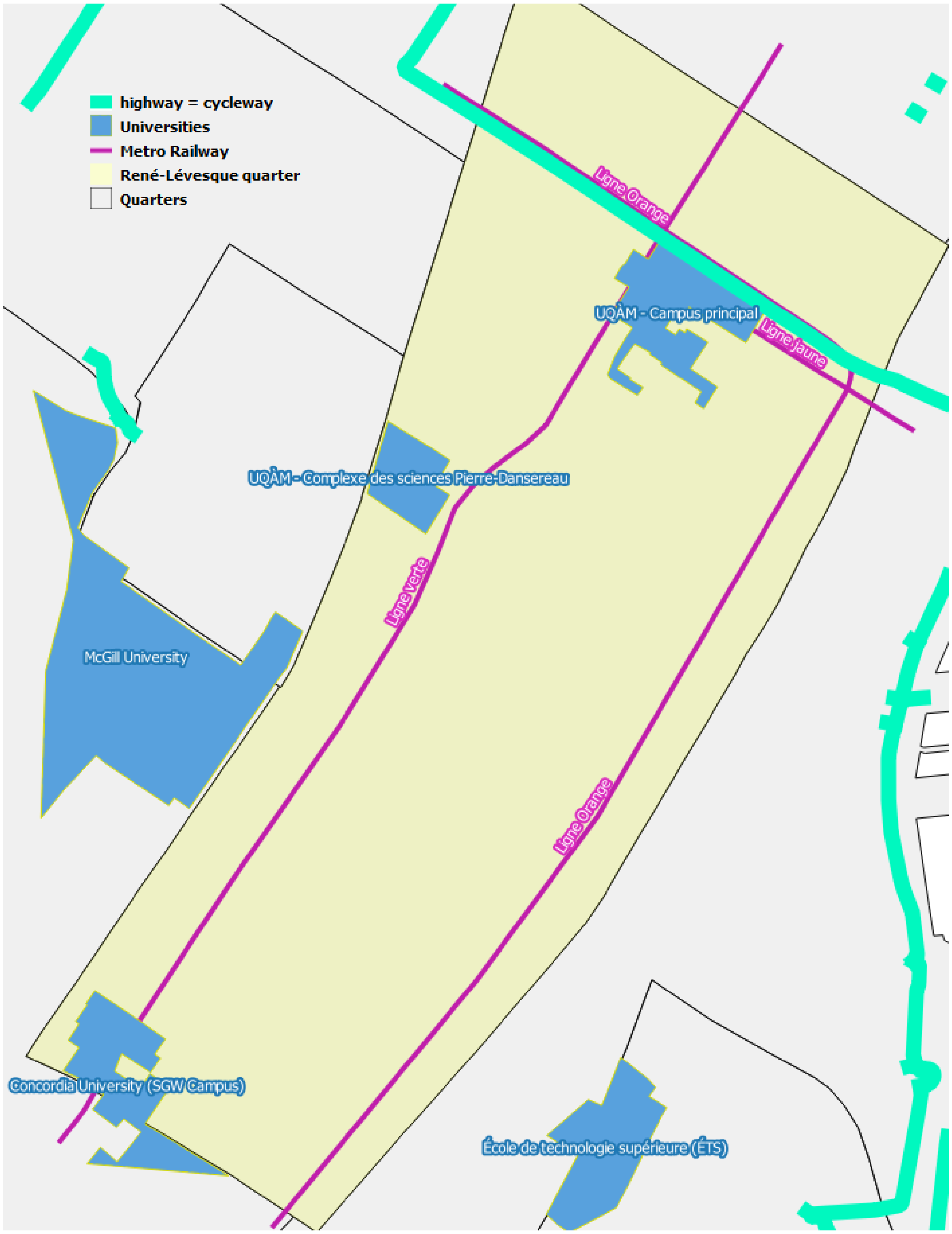


Figure 47: Cycleways in/close to René-Lévesque quarter
Data: OpenStreetMap. **Software**: QGIS.

5.2. Micro-scale analysis using simulation

In the literature review, I conclude microsimulation as the most used solution to tackle urban mobility systems. Although there is not a clear-widely used leading package in this segment of the study, `SUMO` (Simulation of Urban Mobility) accounted for the most popular as measured in Section 3.7. Thus, for this work microsimulation technique in `SUMO` for transit policy testing is the methodology for the analysis.

In `SUMO`, the relation between the vehicle and the driver or other vehicles are formulated via differential equations where the individual behaviour can be represented with longitudinal (car-following) or lateral (lane-changing) modelling behaviours, being the former where car speed is conditioned to the vehicles ahead (Behrisch et al., 2011, Tang et al., 2014, as cited in Zambom Santana et al., 2018). Microsimulation is more detailed yet with high computational cost and are not recommended for metropolitan-size areas with millions of agents (Zambom Santana et al., 2018).

`SUMO` is a free and open traffic simulation suite available since 2001 that allows modelling of intermodal traffic systems with a wealth of supporting tools that handle tasks such as route finding, visualization, network import and emission calculation (German Aerospace Center (DLR), n.d.). `SUMO` is robust, flexible and offers ease of usage with the advantage of simulating different vehicle types (Kristensen & Ezeora, 2017).

I took this path to generate a simulation to test transit-policies at the microscale:

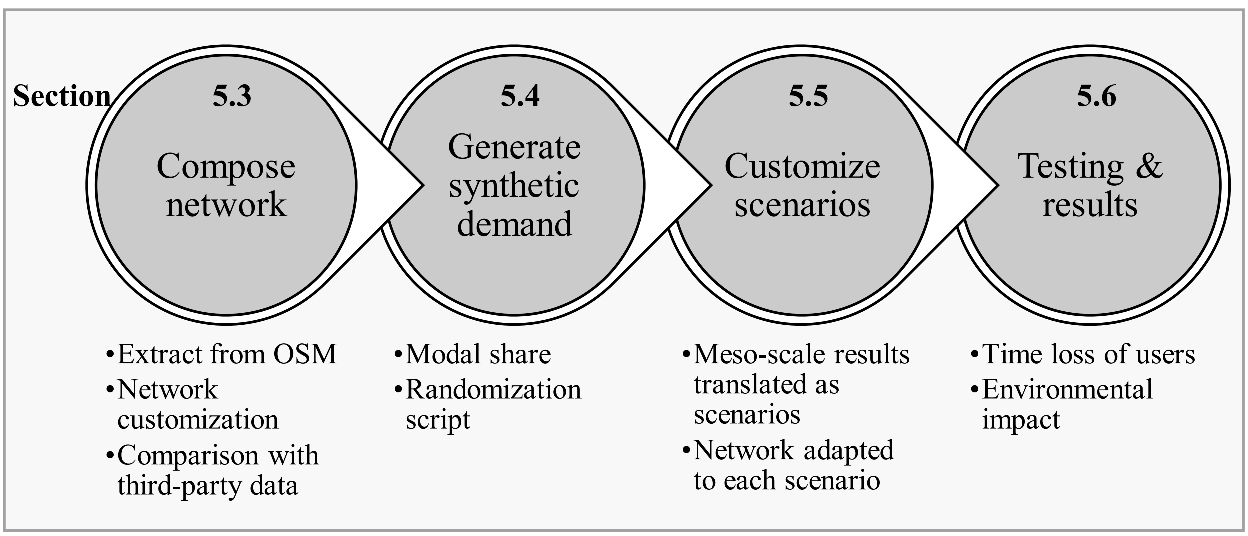


Figure 48: Microsimulation composition

The simulation model is composed of multiple files that contain information of the model such as seen in Figure 49. A detailed list of input and output files and processing instructions can be found in (German Aerospace Center (DLR), 2020c).

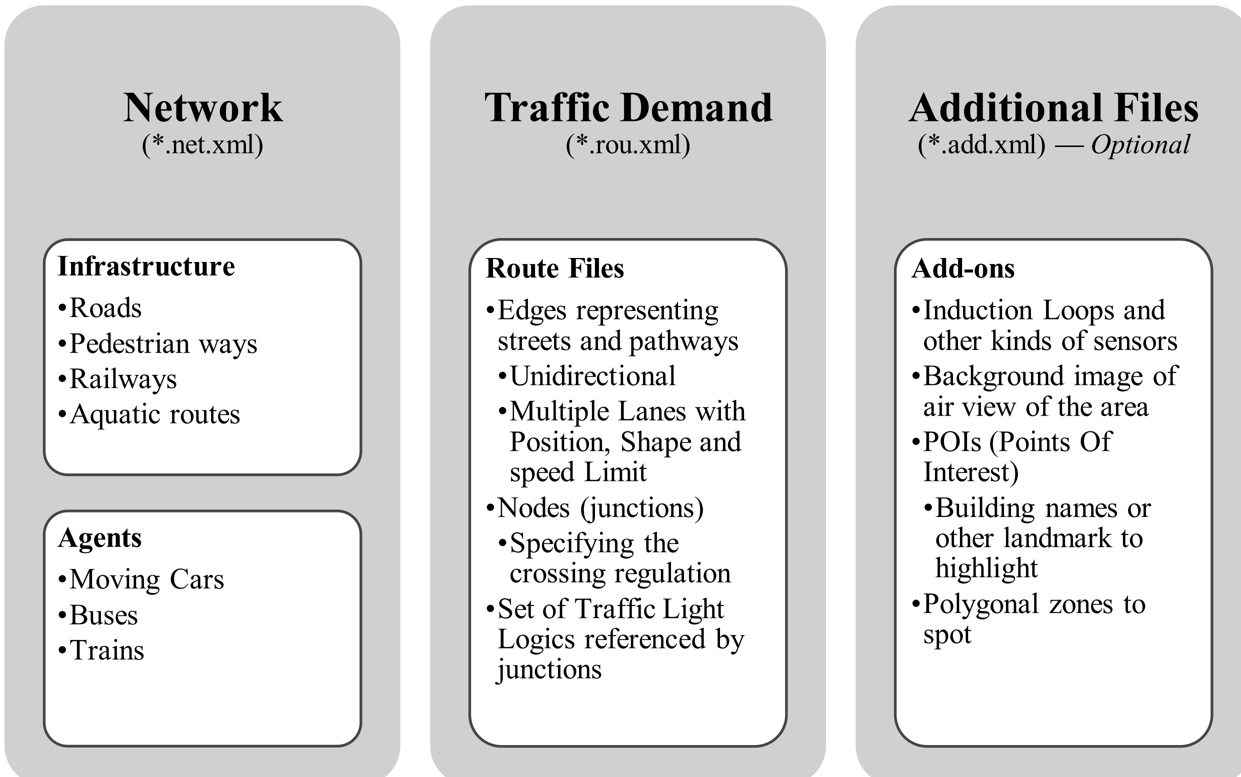


Figure 49: SUMO core file requirements and content examples
Source: (Gudwin, 2016)

5.3. Network composition for the microsimulation

A SUMO network file describes the traffic-related part of a map, the roads and intersections where the simulated vehicles run along or across. The core elements are the "*edges*" that represent roads or streets, and nodes joining edges that are called "*junctions*" in SUMO-jargon and represent intersections. Edges are unidirectional.

The SUMO network contains the following further information:

- every street (edge) is a collection of lanes that includes the position, shape and speed limit of every lane,
- traffic light logics are referenced by junctions,

- junctions, including their right of way regulation,
- connections between lanes at junctions (nodes) that state how crossing is allowed to which directions

5.3.1. *Selected micro-scale simulation area*

In section 5.1 several maps revealing mesoscale quarter elements and its relation with universities were bounded to focus on key urban mobility wellbeing aspects such as public transit, pedestrian areas and cycleways. Among the universities inside/close to the selected quarter, Concordia University resulted distant from convenient locations of this nature. Thus, its surrounding area is chosen as the area for the microsimulation study.

Concordia University is one of the top universities in Quebec. During its 2018/2019 period, it held 37,154 Undergraduate and 9,675 Graduate enrolled students. The 20.6% of its population account for international students and the Arts & Science faculty and Gina Cody School of Engineering and Computer Science have the highest share of students (Concordia University, 2020).

The surrounding area is shown in Figure 50. It is enclosed by one road of primary class and four secondaries, followed by mostly residential streets. Metro transit connectivity is fully accessible through the station Guy-Concordia. The **micro-scale area selected** for the simulation in `SUMO` resides inside the inner polygon formed by Sherbrooke St., Peel St., René-Lévesque Blvd. and Guy St. as signalized in Figure 51: Figure 51.

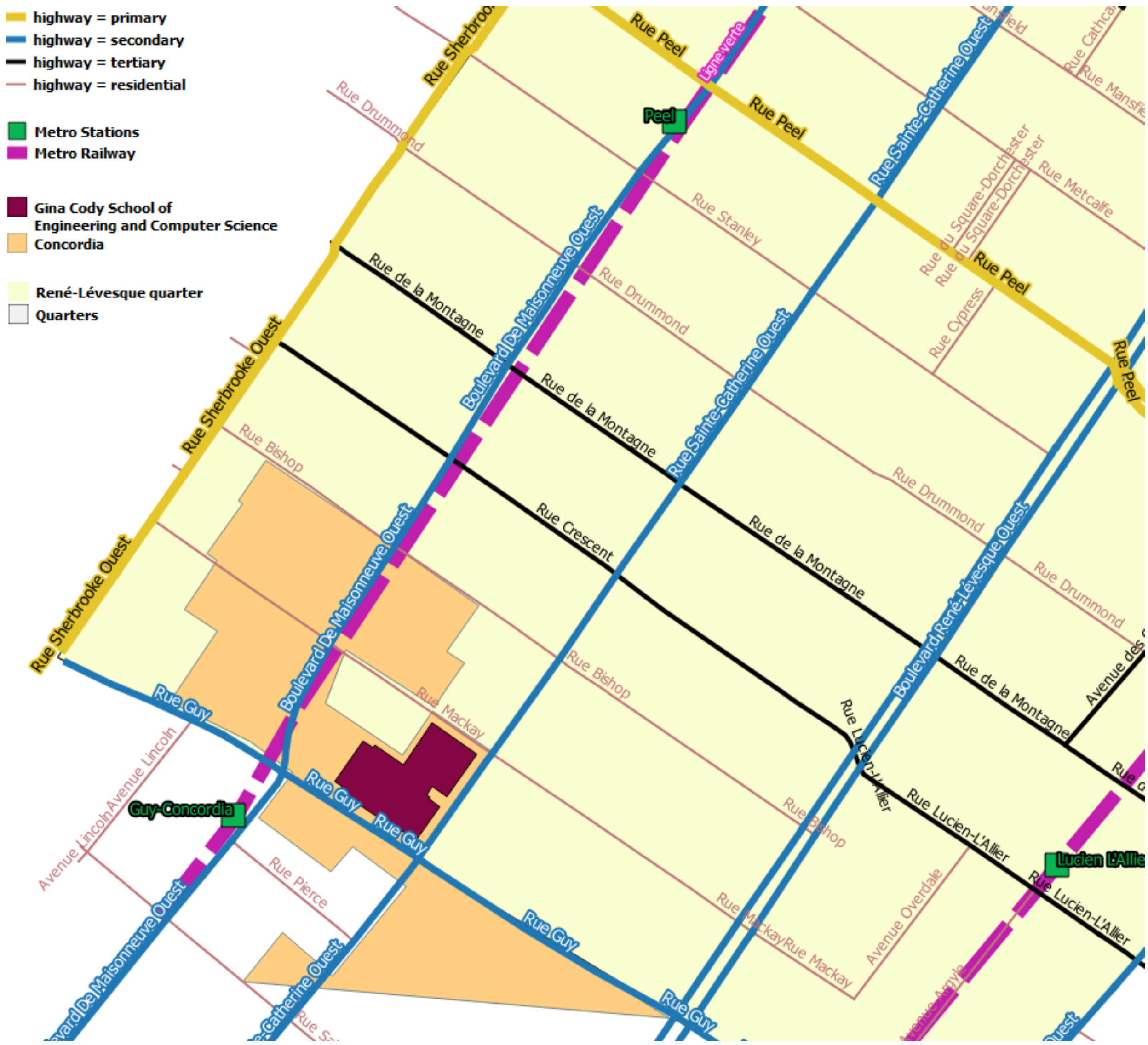


Figure 50: Concordia University neighbourhood
Data: OpenStreetMap. **Software**: QGIS.

5.3.2. *Converting OpenStreetMap to SUMO network*

`SUMO` is loaded with supporting `Python` tools such as `OSMWebWizard.py` in `<SUMO_HOME>/tools` directory, that "based on a selection of an `OSM` map excerpt, you will be able to configure a randomized traffic demand and run and visualize the scenario in the `SUMO-GUI`" (German Aerospace Center (DLR), 2020e) (Figure 51).

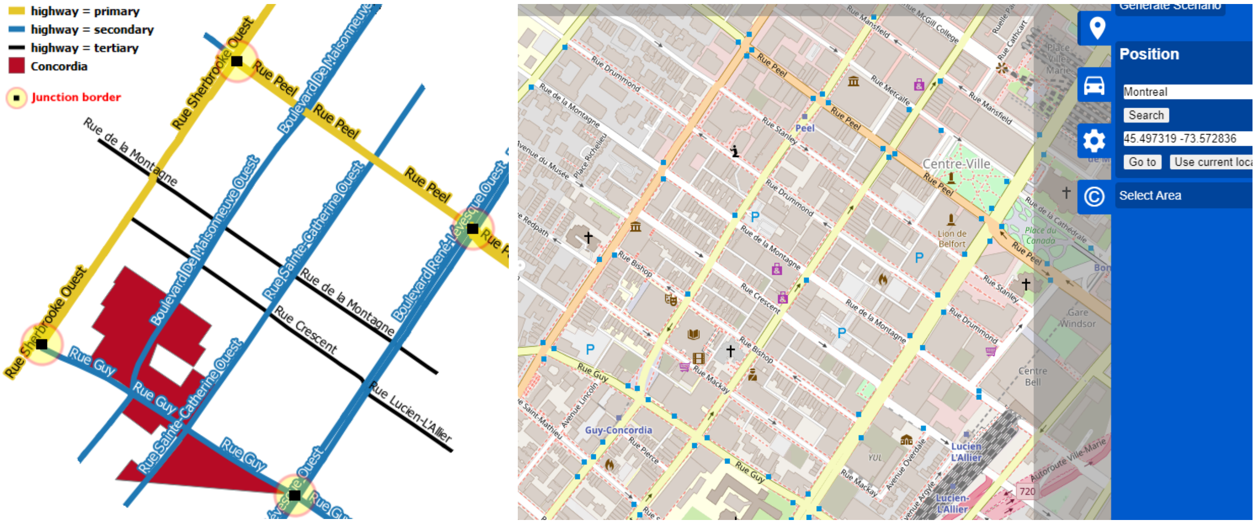


Figure 51: Microsimulation area
Left: map. **Right**: OSMWebWizard.py GUI.
Data: OpenStreetMap. **Software**: QGIS.

5.3.3. *Customization of the network*

The resulting output from `OSMWebWizard.py` is rendered in Figure 52a using `SUMO`'s module `NETEDIT` 1.2.0. The parsed fragment from `OSM` to `SUMO` network contains all elements available including unwanted geometries, roads and elements that might require a re-work in most cases in order to ensure a reliable connected network for the simulation (P. Wagner, personal communication, July 2019). Resulting customized network is shown in Figure 52b. I proceeded to delete edges outside of the defined area, unfocused paths for the simulation such as railway, footways, or service roads and simplified edges connections.

Since `OpenStreetMap` is crowdsourced, it faces a lack of updates and reliability issues as exemplified in Figure 53. Parking lanes were translated as regular lanes, so I did manual modifications in `NETEDIT`. Another source of error was the highway importance definitions, working lanes, current traffic light locations and speed limits that diverged from the real-world, explained with more detail in further sections.

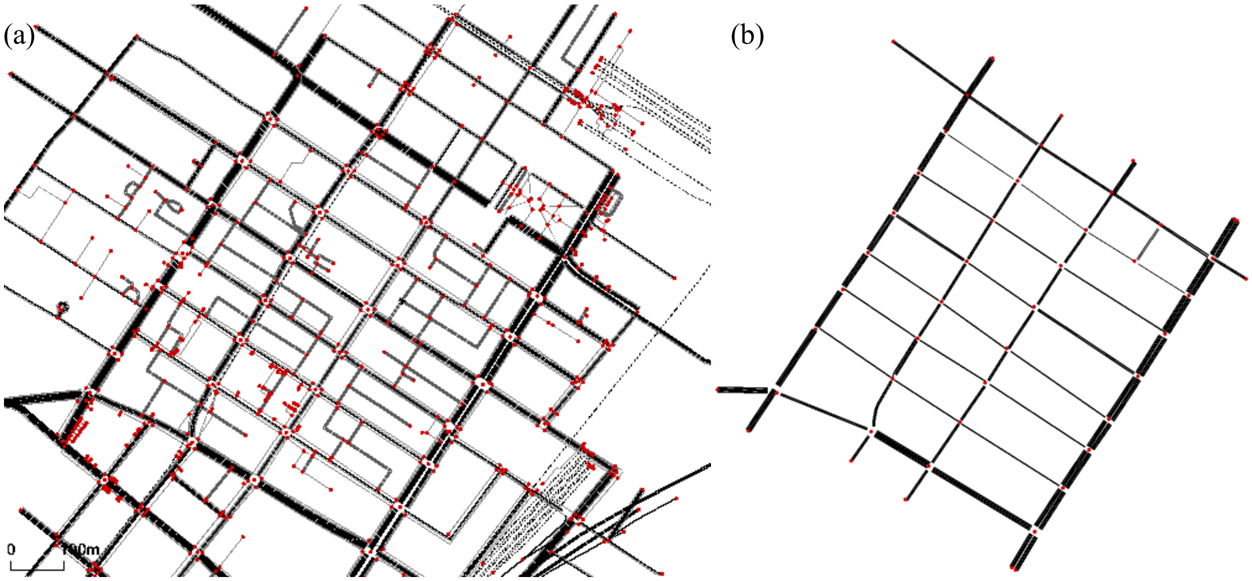


Figure 52: Selected micro-scale area in SUMO/NETEDIT
(a) Original (b) Customized

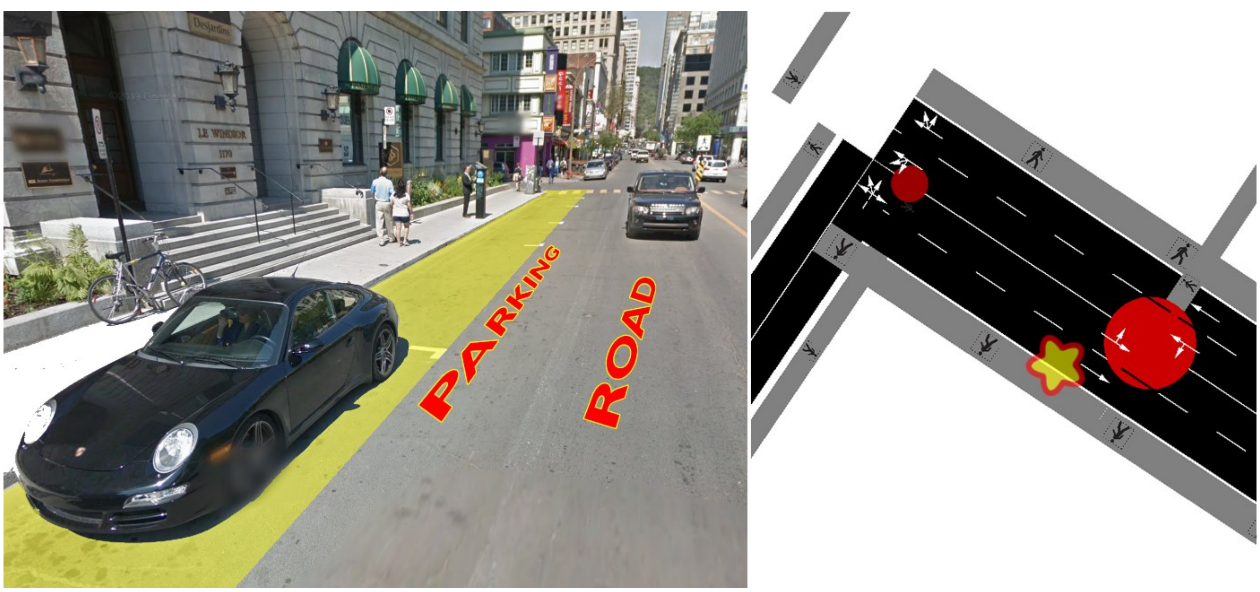


Figure 53: Parsed network error example close to Peel St. and Cypress St.
Left: Google Maps. **Right**: OpenStreetMap/NETEDIT. **Credit**: Author

Speed limits

The extract of `OSM` was revised after parsed to `SUMO`. I noticed the speed limits of most streets were set to 13.89 km/h, which is different from the real-world application. Then, I proceeded to change the speed of all streets in the network through the edge attribute `speed`. In Montreal, the limit of main streets is set to 40 km/h and residential to 30 km/h as part of Vision Zero plan to provide safety for pedestrians and cyclists (Isaac Olson/CBC News, 2019a).

Another aspect to consider when building a network in sumo is the edge attribute `priority` that states the importance of the edge to be chosen for the routing. In practice, drivers tend to go mostly through main avenues which is translated to a higher `priority` index.

Using the built-in `Python` script `plot_net_speeds.py` it is possible to visualize the maximum allowed speeds of the given network (Figure 54) for original and edited versions.

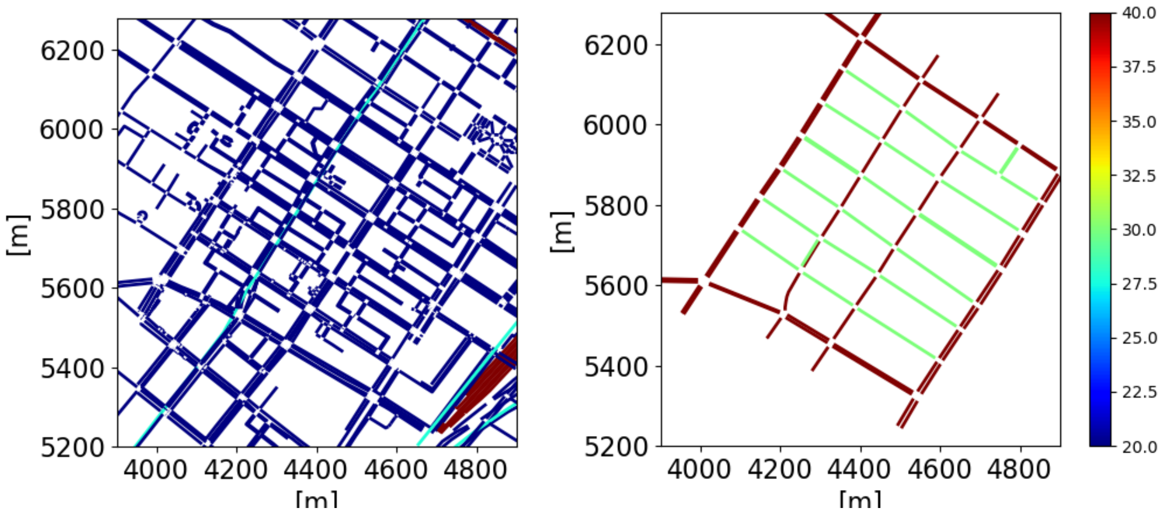


Figure 54: Maximum allowed speeds of the network
Left: Original, OpenStreetMap. **Right**: Corrected, (Isaac Olson/CBC News, 2019a)
Software: Python

Traffic Lights

Following the corrections of the network, there were a few elements of the traffic lights that were misplaced. I used the dataset published in Montreal's open data portal "Traffic lights - pedestrian lights" (original title: *Feux de circulation – feux pour piétons*). This file contains the location of all traffic lights managed by the City of Montreal, at least one of which is equipped with a pedestrian light (Ville de Montréal/Son-Thu Le, 2020).

I loaded the shapefile in a `QGIS` project used in previous sections. By comparing it with `NETEDIT` rendering, I identified the points to correct in the simulation network. I fixed the spots using `NETEDIT`'s feature `Edit > Traffic light mode`. Figure 55 compares both outputs.

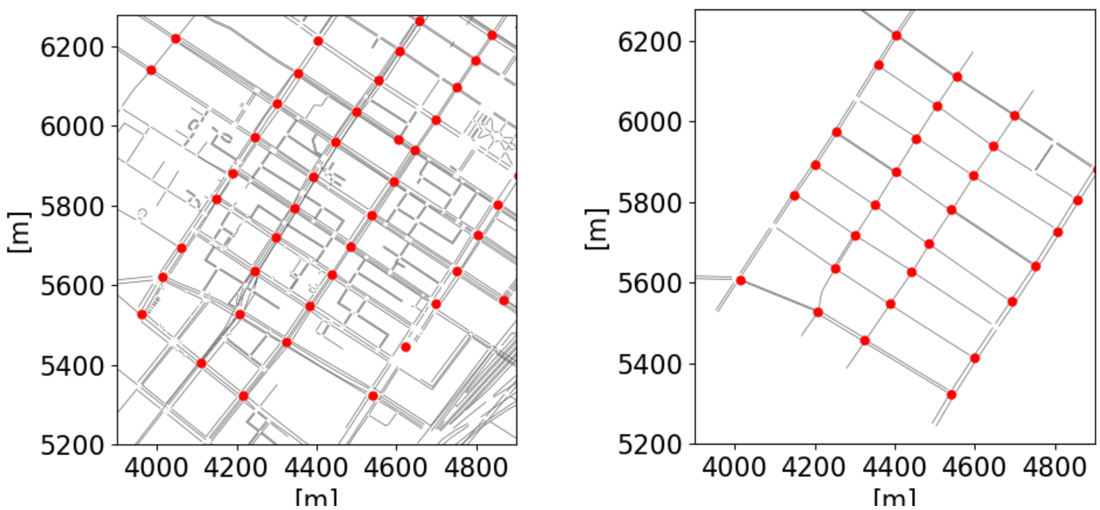


Figure 55: Traffic lights of the simulation network
Left: Original, OpenStreetMap. **Right**: Corrected, (Ville de Montréal/Son-Thu Le, 2020)
Software: Python

5.4. Demand modelling for the simulation

After having generated a network, one still needs some kind of description about the vehicles, a requirement named the traffic demand (German Aerospace Center (DLR), 2019b), which `SUMO`'s nomenclature is as follows:

Table 13: Elements of Traffic Demand
Source: (German Aerospace Center (DLR), 2019b; Gudwin, 2016)

File type	Description
Trip	Agent movement from one place to another defined by the starting edge (street), the destination edge, and the departure time.
Route	An expanded trip that contains not only the first and the last edge but all edges where the vehicle will pass through, from its origin up to its final destination.

5.4.1. *Iterations of demand modelling methodology*

Modelled demand from the MTL Trajet dataset was originally intended to be inputted in the simulation model. However, after unsuccessfully trying two methods, I decided to not load real-world demand in the simulation.

SUMOpy

The first trial was using the OD matrix as `SUMO` input using `SUMOPy`. `SUMOPy` is intended to expand the capabilities of `SUMO` by providing a user-friendly simulation suite to manage the huge amount of data necessary to run complex multi-modal simulations including different demand generation methods such as support for OD matrices, turn flows and synthetic populations (German Aerospace Center (DLR), 2019a).

However, after understood how this package was conceived, there were the following limitations that made using it unachievable: `SUMOpy` uses `Python` as its engine with `NumPy` and `Matplotlib` libraries, the Python Imaging Library (`PIL/Pillow`) and `PyOpenGL`, a `Python` binding to OpenGL. It also uses `Basemap` that allows transforming coordinates to one of 25 different map projections and `wxPython`, a wrapper for the cross-platform GUI API `wxWidgets` for `Python`.

The installation of `SUMOpy` was attempted first in `Windows` 10 and then on `Linux` distribution `Ubuntu` 18.04.3 LTS. Several errors and obstacles were encountered during failed installation, as it was found that the different components are heavily dependent on specific versions of the other modules, some of them inexistent in software repositories or currently unsupported by developers. That was the case of `wxPython`, a module that despite been tested and installed through external sources in both `Windows` and `Linux`, its connection with `Python` and `SUMOpy` failed.

Coordinate transformation to SUMO network object

The second option was the coordinate conversion of trips' origin and destinations to the closest lane in `SUMO` network using a script based on `traci.simulation.convertGeo()` function. However, as a regular user of `SUMO` with no strong background in programming, my current programming skills were an obstacle to executing this task, as my understanding of code and file composition is not beyond the data visualization and `SQL` used in this thesis, which was already a challenge for my master degree. Here, there is an area of opportunity for future work.

5.4.2. *Modal share*

Due to the reasons discussed in the previous section, synthetic data is used for the simulation. Even though the aim of demand modelling is approached by artificial values, a certain sense of veracity is sought through modal share.

A modal share (also found as mode split, mode-share, or modal split) is the percentage of travellers using a particular type of transportation or number of trips using said type (Engineering Services - Transportation, City of Vancouver, 2006). To extract this from the MTL Trajet dataset, I used an Excel Pivot table to group all ID's in *trajets* table by `mode` field and count the number of trips that used an expression. 27 groups resulted in some combinations such as "*À pied, Autopartage*", "*Autopartage, Transport collectif, Voiture / Moto, Vélo*" or "*Voiture / Moto*". Several values inside an expression mean multiple modes of transportation were used in the journey.

In order to create a sufficient-realistic mode-share, records from peak hours of October 5 (7 to 9 am and 4 to 7 pm) were filtered in the Pivot table to focus on **congested periods**. Auxiliary columns were placed in Excel to look for expressions of the modes of interest using the formula: `FIND("value",cell)`. The pivot table is shown in Figure 56.

Analysis bin	YES

Mode	Count	Taxi	Partage	Voiture	Collectif	< search
À pied	234	0	0	0	0	0
À pied, Autopartage	1	0	1	0	0	1
À pied, Autopartage, Vélo	1	0	1	0	0	1
À pied, Autre, Transport collectif	1	0	0	0	1	1
À pied, Taxi, Vélo	1	1	0	0	0	1
À pied, Transport collectif	234	0	0	0	234	234
À pied, Transport collectif, Vélo	3	0	0	0	3	3
À pied, Transport collectif, Voiture / Moto	16	0	0	16	16	32
À pied, Vélo	22	0	0	0	0	0
À pied, Voiture / Moto	11	0	0	11	0	11
À pied, Voiture / Moto, Vélo	2	0	0	2	0	2
Autopartage	14	0	14	0	0	14
Autopartage, Transport collectif	1	0	1	0	1	2
Autopartage, Transport collectif, Voiture / M	1	0	1	1	1	3
Autopartage, Vélo	1	0	1	0	0	1
Autopartage, Voiture / Moto	4	0	4	4	0	8
Autre	4	0	0	0	0	0
ND	4	0	0	0	0	0
Taxi	6	6	0	0	0	6
Taxi, Vélo	2	2	0	0	0	2
Transport collectif	448	0	0	0	448	448
Transport collectif, Vélo	9	0	0	0	9	9
Transport collectif, Voiture / Moto	23	0	0	23	23	46
Vélo	478	0	0	0	0	0
Voiture / Moto	514	0	0	514	0	514
Voiture / Moto, Vélo	6	0	0	6	0	6
(blank)	2,120	0	0	0	0	0
Grand Total	**4,161**	**9**	**23**	**577**	**736**	**1,345**
Total		0.67%	1.71%	42.90%	54.72%	

Figure 56: Calculation of user modal share using a pivot table

The resulting modal share is calculated by isolating counts of interest.

Table 14: User share by mode of transportation
Source: MTL Trajet, October 5 (7 to 9 am and 4 to 7 pm)

Mode	Percentage	Nomenclature
Passenger vehicle	42.90%	`auto`
Public transit	54.72%	`transit`
Shared vehicle	2.38%	`shared`

5.4.3. *Randomization*

In order to generate artificial demand, I used the Python SUMO tool randomTrips.py. It generates a set of random trips for a given network by choosing source and destination edge either uniformly at random or with a modified distribution (German Aerospace Center (DLR), 2020d).

When downloading a network from OSMWebWizard.py as explained in section 5.3.2, it uses randomTrips.py to generate artificial demand according to the specifications collected in the browser GUI. I edited the included sample script build.bat in the output to generate demand based on the arguments useful for my model available in Table 15.

Table 15: randomTrips.py arguments
(German Aerospace Center (DLR), 2010, 2020a, 2020b, 2020c, 2020d)

Command	Definition
-n NETFILE	Define the net file (mandatory)
-o TRIPFILE	Define the output trip filename
-p PERIOD --period <FLOAT>	Time distance distribution for each arrival (see next section)
-b BEGIN	Begin time
-e END	End time (default 3600)
--seed <INT>	The random number generation algorithm is initialized with a seed value. It can be used to get repeatable pseudo-randomness.
--fringe-factor <FLOAT>	Increases the probability that trips will start/end at the fringe (border) edges of the network. If the value 10 is given, edges that have no successor or no predecessor will be 10 times more likely to be chosen as start- or endpoint of a trip. This is useful when modelling through-traffic which starts and ends at the outside of the simulated area.
--fringe-start-attributes=FRINGEATTRS	Additional trip attributes when starting on a fringe.
--allow-fringe.min-length	Allow departing on edges that leave the network and arriving on edges that enter the network, if they have at least the given length.
departSpeed	Determines the speed of the vehicle at the insertion
--vehicle-class=VEHICLE_CLASS	The vehicle class assigned to the generated trips (adds a standard vType definition to the output file).
-c VCLASS --vclass=VCLASS --edge-permission=VCLASS	only from and to edges which permit the given vehicle class
--min-distance=MIN_DISTANCE	require start and end edges for each trip to be at least <FLOAT> m apart
--prefix=TRIPPREFIX	prefix for the trip ids
--validate	Whether to produce trip output that is already checked for connectivity

Period argument

One of the key arguments to generate random demand in `randomTrips.py` is to declare the `period` value. By default, the script inserts vehicles with equidistant departure times and `period=FLOAT` (default 1.0). By using values below 1, multiple arrivals per second can be achieved. If option `--binomial` is used, the expected arrival rate is set to 1/period. To exemplify, a value of 3.4 means that one vehicle is generated every 3.4 seconds and the second one at 6.8 seconds by following a uniform distribution known as **"equidistant departure time"**. This **distribution is chosen for the synthetic population generation**.

In order to generate the period desired for my simulation model, I composed the following formula with the factors I had involved:

$$period = \frac{t}{\frac{x \cdot \alpha}{\beta}} = \frac{t \cdot \beta}{x \cdot A}$$

Where:

- The simulation time to distribute all agents arriving at an equidistant time is 3,600 seconds (1 hour) which is the value for t.
- Given that I have the share percentage of trips in Table 14, the α parameter exists.
- x is the total number of agents existing in the simulation (my independent variable).
- Given that the vehicle can be treated as a container, a constant β is assigned per mode type given a trivial assumption.

Script

I proceeded to construct an Excel arrangement that aided me to calculate the value of `period` given the above formula. Finally, by adjusting parameters (Table 15) in `build.bat`, I created synthetic population files for each mode (three). The following is a sample call:

```
python randomTrips.py \
-n input_network.net.xml --seed 42 --fringe-factor 7 \
-p <-calculated-coefficient-Excel-> \
-o output_file.trips.xml -e 3600 --vehicle-class <-mode-> \
--vclass <-mode-> --prefix <-mode-prefix-> --min-distance 100 \
--trip-attributes "departLane=\"best\"" \
--fringe-start-attributes "departSpeed=\"max\"" \
--allow-fringe.min-length 50 --lanes -validate
```

5.5. Simulated Scenarios

The final part of this research is to simulate transit policies over the studied area. In pursuance of this goal, four scenarios have been assembled.

A key concept applied to the simulation is the **transit policy**. This concept overlaps with *public policy*: the former represents "the application of a set of actions on the environment for a given time horizon to satisfy specified objectives" (Pageaud et al., 2018), while the latter is "a policy for the public interest applied to urban mobility (commercial or passenger) to regulate endeavours seeking to influence the performance of transit systems". The effectiveness of transit policies is susceptible to trials and errors where improvement theories are exposed to reality (Pageaud et al., 2018). Here, simulation tools have the potential of mitigating risks and improving the planning process.

The **utilitarianism** is an ethical theory that **supports the design argument of this section**. It advocates actions that maximize happiness and well-being for the affected individuals. The classical approach was developed by four British philosophers and it considers that rightness or wrongness on decision-making relies upon the consequences to society of the decision (McKay, 2000). Utilitarianism seeks the "rightness" as the consequence of decision-making. In this work, this concept is applied to whether system users can be benefited (therefore, satisfied) at spending less time in commuting.

Overall, the procedure to customize and evaluate the simulation scenarios using curated transit-policies from a utilitarian philosophy is described as follows:

Figure 57: Workflow for Simulation Scenario fabrication

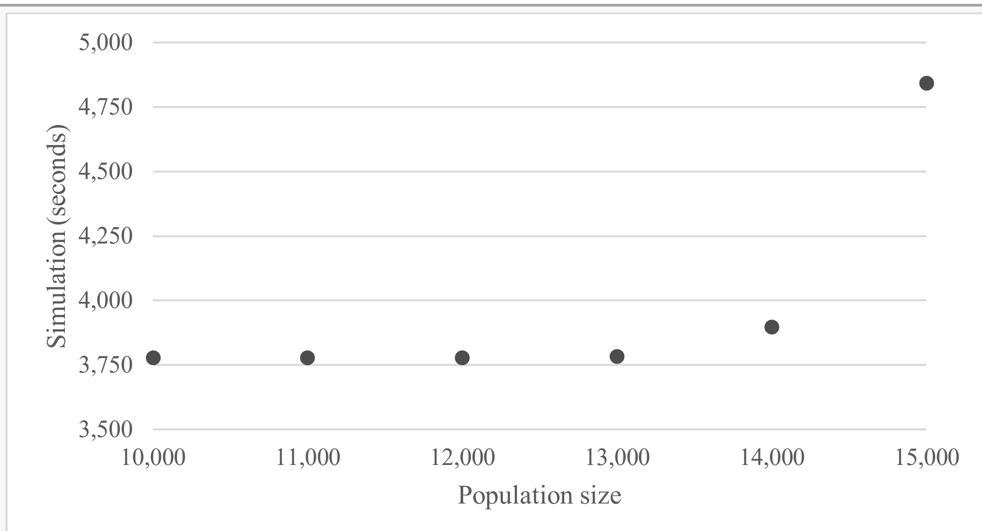
5.5.1. *Simulation of baseline scenario (Scenario-A)*

The first scenario to simulate is the “As-is” state, known as the baseline scenario.

Adjusting the synthetic population

Generating a synthetic population for the simulation is the output from the demand generation. Since I am looking to evaluate the improvement in congested states, I have to ensure the population reflects this in each scenario. Figure 58a shows the number of inserted population (x) and the time it took the simulation to complete. Notice that between 14,000 and 15,000 individuals the simulation loses stability, where a great number of vehicles were teleported either by “the vehicle stood too long in front of an intersection” or “the vehicle has collided with his leader”. This is **interpreted as the congested state**, therefore a simulation population of 14,000 is chosen for the baseline scenario. Resulting coefficients for `period` and calculations are found in Figure 58b.

(a)



(b)

Mode	Share	Population	Vehicles	Capacity	Period
Auto	42.90%	6,006	6,006	1.00	0.5994
Transit	54.72%	7,661	152	50.4	23.6837
Shared	2.38%	333	133	2.50	27.0201
Total	100.00%	14,000	6,291		

Figure 58: Calculations for the synthetic population, baseline scenario
(a)) Total simulation duration of different population sizes where stability is lost after 14,000
(b) Calculations for values to use in the random trip generation script

Customization of Network

The network remains without changes as is the “As-is” state.

5.5.2. *Simulation for bus-only reserved lanes (Scenario-B)*

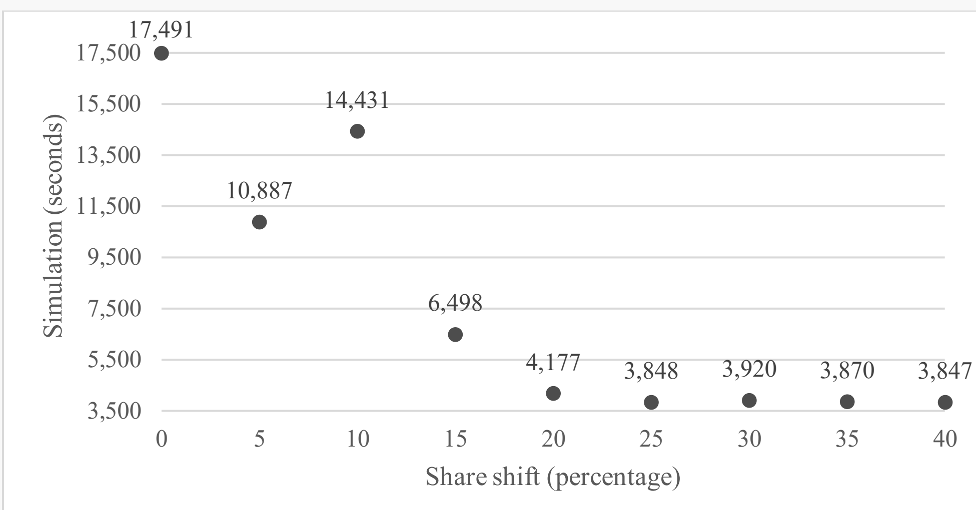
In the literature review, it was found that road arrangement is not regularly addressed to improve urban mobility when compared to other measures described. Reserved lanes for certain modes of transportation are widely used in highways. However, application in the city street network does not appear in the literature, the reason of why I am testing this transit-policy. In Scenario-B, selected lanes in curated streets are restrained for the usage of public transit only.

Adjusting the synthetic population

User shift to another mode of transportation and the modal share is simplified for calculations. The objective is to serve the same number of users as in Scenario-A (14,000) by recalculating `period` values.

The procedure is repeated to find stability in the duration of the simulation. This time is not to find population size, but optimal user shift from personal private vehicle to public transit. Figure 59a shows the results of fixed quantity-interval iterations. It is observed a stable trend starting 20% of modal share shift, meaning that 1 out of every 5 persons has to cooperate with this transit-policy.

(a)



(b)

Mode	Share	Agents	Vehicles	Capacity	Period
Auto	34.32%	4,805	4,805	1.00	0.7493
Transit	63.30%	8,862	176	50.4	20.4736
Shared	2.38%	333	133	2.50	27.0201
Total	100.00%	14,000	5,114		

Figure 59: Calculations for the synthetic population, Scenario-B
(a)) Total simulation duration of different modal shift ratios where stability appears at 20%
(b) Calculations for values to use in the random trip generation script

Customization of Network

I changed the properties of the baseline network in `NETEDIT` to add bus-only reserved lanes around Concordia University. Using the information from the mesoscale map of public transit connectivity by bus for universities (Section 5.1.2, Figure 44), I selected Guy St., Sainte-Catherine St. and De Maisonneuve Blvd. as the pilots for the restrained lanes (Figure 60). The simulation is graphically running in Figure 61.

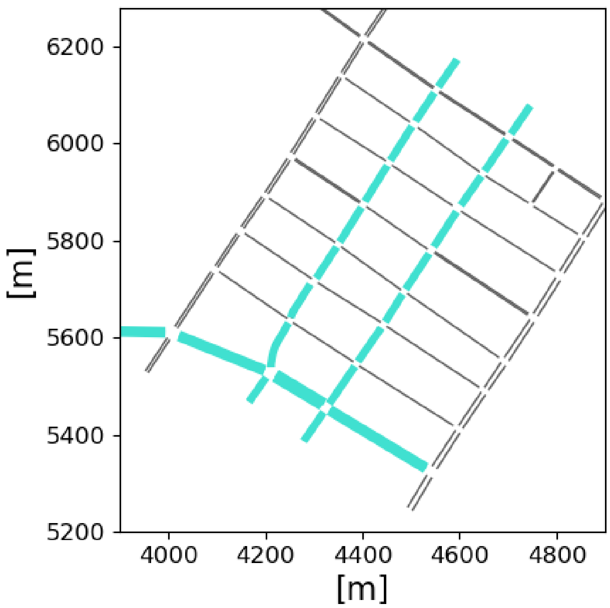


Figure 60: Affected edges of the network according to transit policy of Scenario-B
Software: Python

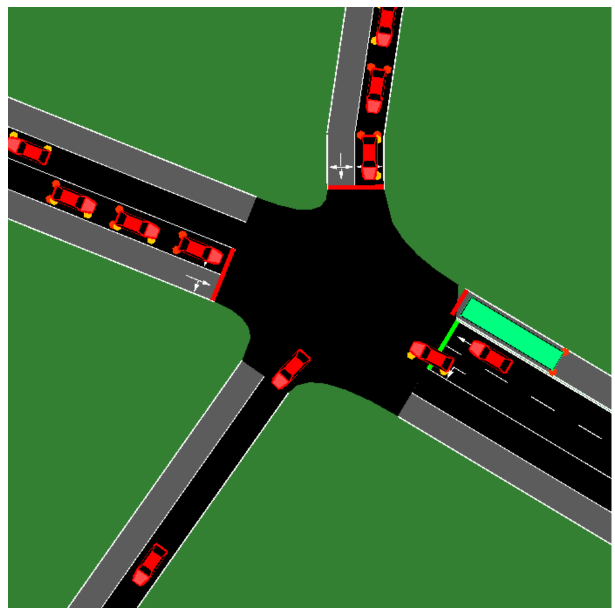


Figure 61: Simulated intersection at De Maisonneuve/Guy showcasing reserved bus lanes
Gray lanes represent the paths reserved for buses, and green figure symbolizes a public transit bus
Software: SUMO-GUI

5.5.3. *Simulation of a new pedestrian area in Rue Crescent (Scenario-C)*

As concluded in the mesoscale analysis for pedestrian zones, there is no one close to Concordia University (Section 5.1.3, Figure 46). Crescent Street is chosen as the testing pilot. It is a famous and popular attraction for both tourists and locals in the "heart and soul of the city" (L'Association des marchands de la rue Crescent, 2018). Figure 62 show some highlights of this area.

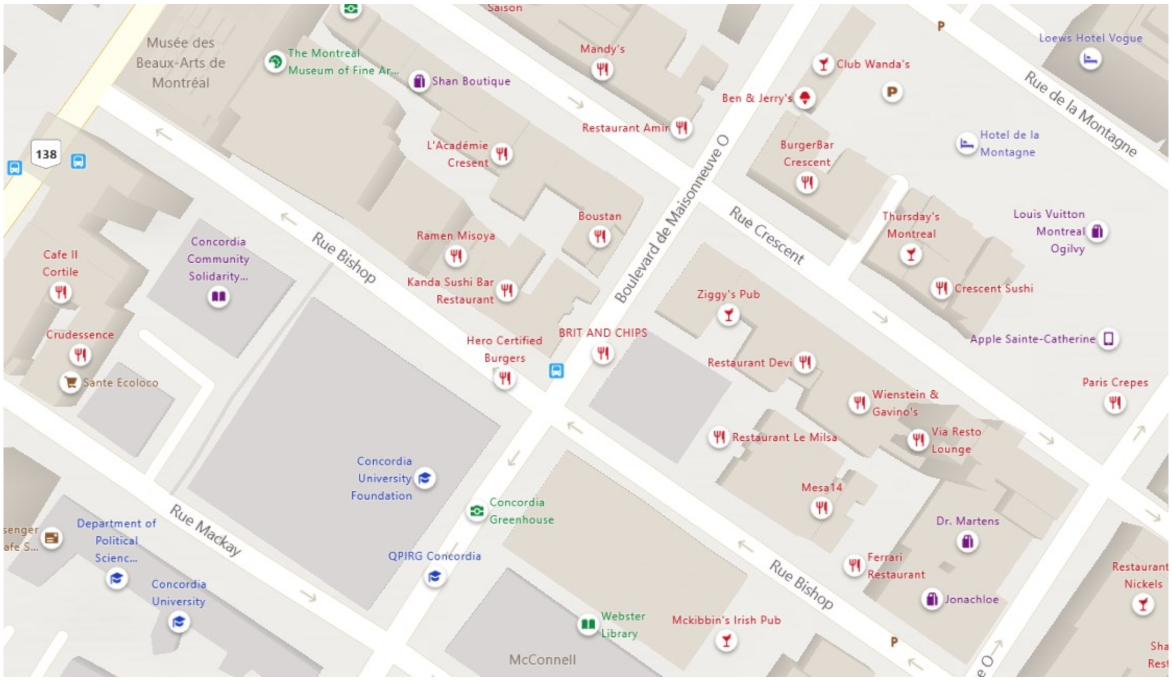


Figure 62: Highlights of Crescent Street
Top: Amenities close to Concordia University and Crescent St. (© 2020 Microsoft Corporation, © 2019 HERE). **Bottom left**: Mural in homage to Leonard Cohen located in the building at 1420 Rue Crescent created by artists El Mac and Gene Pendon, as well as 13 assistant artists from the MU team. The portrait of Leonard Cohen was created from a photo of his daughter, Lorca Cohen. Photo by Pascal Bernardon on Unsplash. **Bottom right**: 2019 Crescent Street Grand Prix Festival by BBF Promotions, January 15, 2018. Photo downloaded from crescentgrandprix.com

Adjusting the synthetic population

The population used is the produced for Scenario-A since no shift in modal share is stated.

Customization of Network

In this scenario, testing the effects on urban mobility of the closure of Crescent Street for the segment between Sherbrooke Street and René-Lévesque Boulevard for pedestrian usage only is the target (Figure 63). When editing the network for this objective, the simulation last 3,929 seconds, compared to 3,898 of the regular network. This means a minor negative impact of 0.80% in the exchange of a pedestrian zone. Results per mode are presented in the next section. The simulation is graphically running in `SUMO-GUI` in Figure 61.

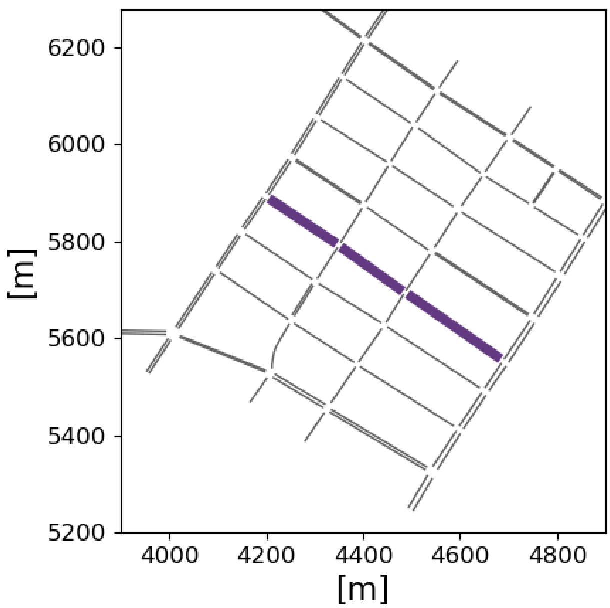


Figure 63: Affected edges of the network according to transit policy of Scenario-C
Software: Python

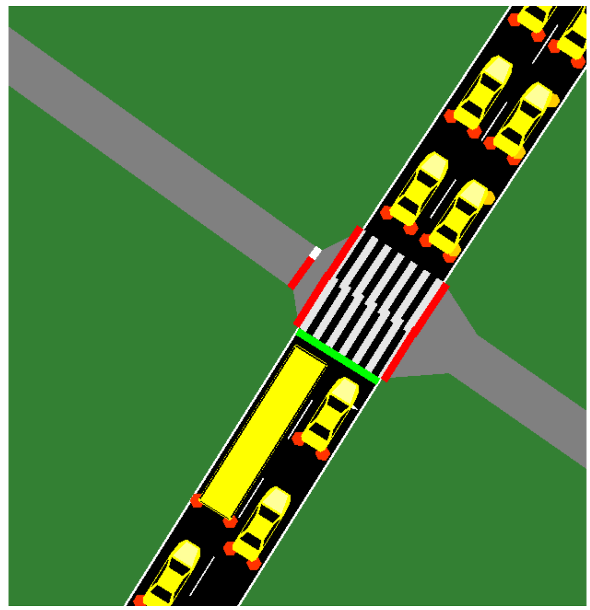


Figure 64: Simulated intersection at Sainte-Catherine/Crescent showcasing pedestrian zone The gray area represents the Crescent Street allowing pedestrian circulation only.
Software: SUMO-GUI

5.5.4. *Simulation of modal shift to High-Occupancy vehicles (Scenario-D)*

According to Statistics Canada, carpooling to work was least common in Quebec compared to the rest of the country, where decisions to carpool, or not, could be affected by the distance of the commute and availability of high occupancy vehicle lanes (Government of Canada, 2017).

To simplify this segment in this scenario, High-Occupancy vehicles (*hereafter*: HOV) are described as passenger vehicles transporting more than one commuter (sharing or not). Hence, a transit-policy involving reserved lanes for high-occupancy vehicles is analyzed. After several trials

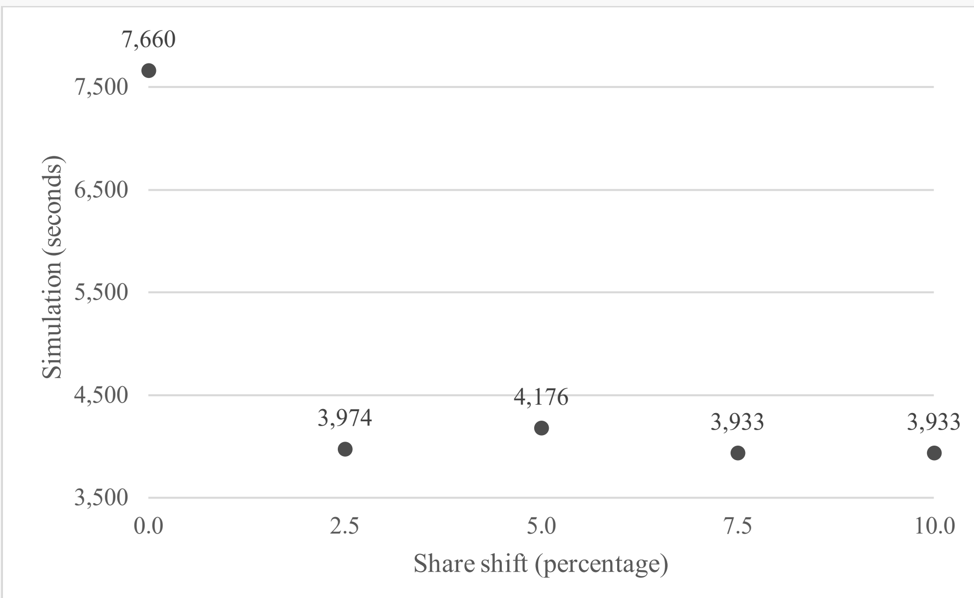
I decided to mix this policy with Scenario-B, meaning a combined scenario with reserved lanes for both buses and high-occupancy shared vehicles and a pedestrian zone in Crescent st.

Adjusting the synthetic population

The modal share created in 5.4.2 counted modes showing "*autopartage*" and "*taxi*" labels. For this general segment, a simplified vehicle capacity of 2.5 passengers is used for population calculations.

After the initial 20% of user share shift from single-passenger vehicle to public transit, the user modal shift is calculated from single-passenger vehicle to HOV. Using the same method previously executed, stability was found starting 7.5 percent of share shift from single-passenger vehicle to HOV, meaning a total of 27.5% of user modal shift for this scenario.

(a)



(b)

Mode	Share	Agents	Vehicles	Capacity	Period
Auto	31.10%	4,354	4,354	1.00	0.8268
Transit	63.30%	8,862	176	50.4	20.4736
Shared	5.60%	784	313	2.50	11.4865
Total	100.00%	14,000	4,844		

Figure 65: Calculations for the synthetic population, Scenario-D
(a)) Total simulation duration of different modal shift ratios where stability appears at 7.5%
(b) Calculations for values to use in the random trip generation script

Customization of Network

Figure 66 schematizes the affected edges of the network, representing the combined measures in two colours. SUMO-GUI visualization is shown in Figure 67. Note that the edges representing the reserved lanes now contain buses (green figure) and high-occupancy vehicles (yellow object) where the private passenger vehicles (red figure) remain in the regular lanes.

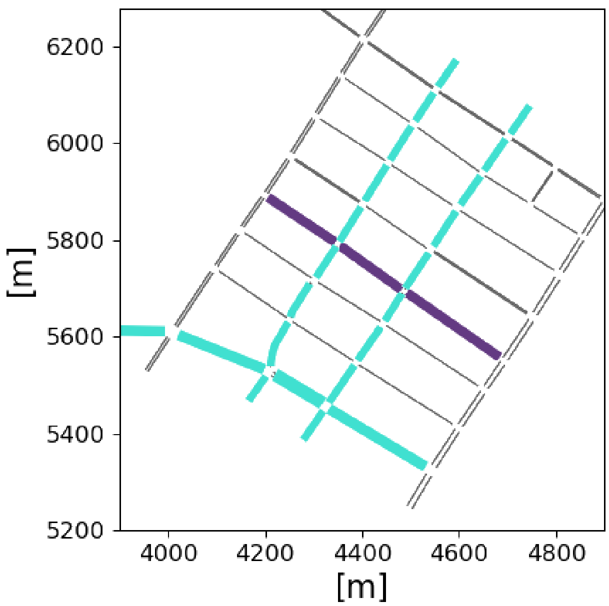


Figure 66: Affected edges of the network according to transit policy of Scenario-D
Software: Python

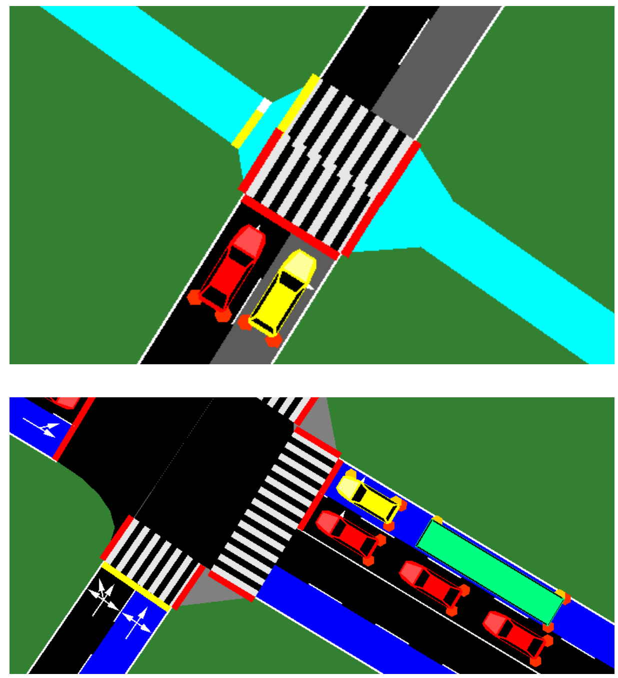


Figure 67: Simulated scenario showcasing combined pedestrian zone and reserved lanes
Top: pedestrian zone in Crescent St. with reserved lane. **Bottom**: Reserved lane used by both HOV and buses.
Software: SUMO-GUI

5.6. Evaluation of experiments

In this work, multiple scenarios have been tested seeking to benefit the greatest number of people. Note that **all scenarios have the same population size accommodated in different modes** of transportation. The summary of the scenarios tested are:

- **Scenario-A**: the current state of the network
- **Scenario-B**: reserved lines for public transit including a 20 percent user share shift from single-passenger vehicle to public transit
- **Scenario-C**: closure of Crescent Street for pedestrians only from the segment between Sherbrooke Street and René-Lévesque Boulevard.
- **Scenario-D**: includes de properties of Scenario-B plus a 7.5 percent user share shift from single-passenger vehicle to HOV.

After having created the artificial populations by modifying the parameters of the `build.bat` script, edited the network to test the new transit-policies, I proceeded to run the simulations, first for visualization inside `SUMO-GUI` and after for output file creation and data processing.

5.6.1. *Time loss*

One of the main output files of the simulations is the `--tripinfo-output`. It contains several output measures as listed in (German Aerospace Center (DLR), 2019c). The test-evaluation scope involves using time loss as an indicator of transit-policy performance. When the simulated population is driving below the ideal speed they will incur in `timeLoss`, where scheduled stops do not count (German Aerospace Center (DLR), 2019c). By improving this indicator, the interpretation is that **people are spending less time commuting**.

Overall scenario performance

Scenario-D results as the best solution to improve urban mobility from the simplified synthetic demand. Assuming a 27.5% of user modal shift from single-passenger vehicle to a high-occupancy mode of transportation (public and private), the scenario economizes a 27% of the time compared to the baseline when summing-up the time lost of all users (not vehicles) inside the simulation.

Scenarios B and D have the best performance since fewer vehicles exist in the system. However, the effect of restrained lanes is not conclusive by this measure.

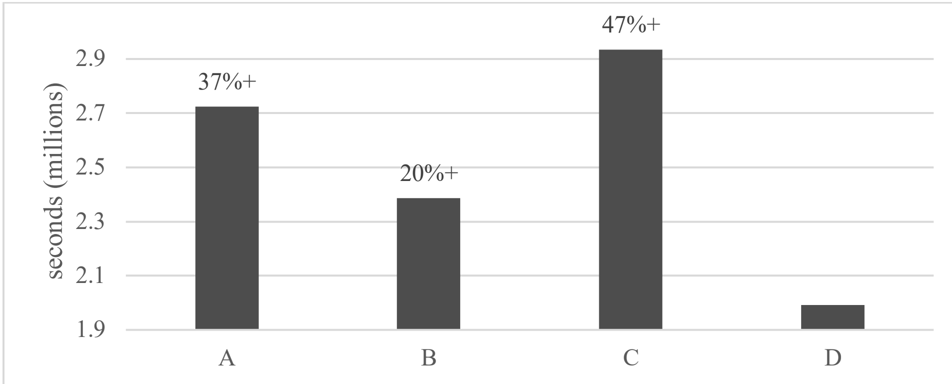


Figure 68: Aggregation of time loss of 14,000 simulated users per scenario
Scenario-D has the best performance since the total aggregation is the minimal of the four. Upper label compares the performance of the scenario with the one of Scenario-D

Performance by mode of transportation

When zooming-in the aggregated time loss by mode of transportation (Figure 69), the reserved lanes scenarios (B and D) favoured both single-passenger vehicles and buses unexpectedly. Despite being targeted to improve, the HOV mode "priority" scenario worsens the time loss by this mode of transportation. This can be interpreted as they have a higher degree of freedom when not being pushed towards a restrained single-lane. Future work can experiment with reserved dual-lane.

Also, the redirection of both buses and HOV to specific lanes, combined with the decrease of single-passenger vehicles, made Scenario-D improve urban mobility for single-passenger vehicles.

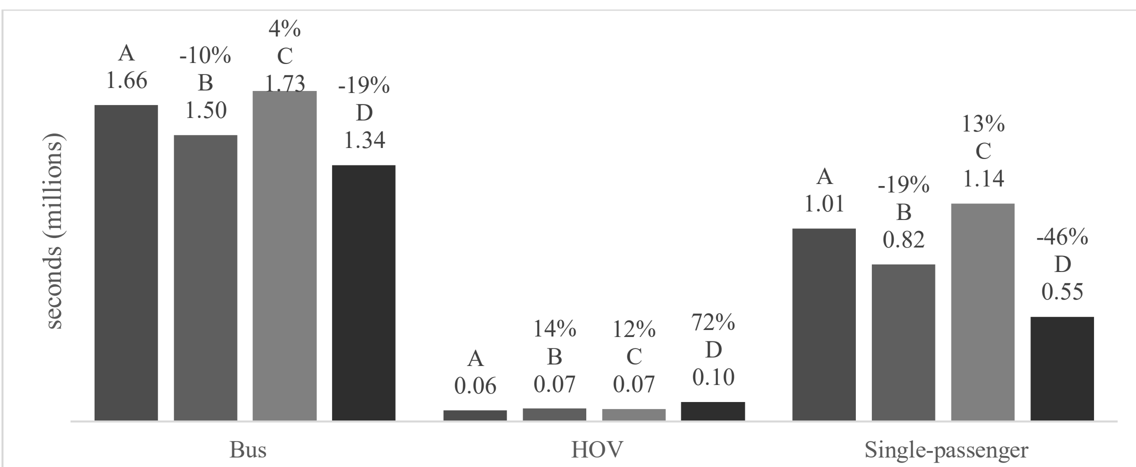


Figure 69: Cumulative time loss of all users per mode of transportation
Single-passenger vehicles were the most improved mode in Scenario D since fewer vehicles exist in the network. Buses were also benefited at a minor degree, contrary to HOV mode that unexpectedly was affected. Upper percentages represent the economization compared to their baseline scenario.

Time loss per user per mode

Each simulation population was constructed by calculating ratios for the period. Therefore, the number of vehicles and users of each mode varies according to share, modal shift and vehicle capacity. By calculating a ratio of time loss per user, a different behaviour than explained above is presented. Single-passenger and buses are still benefited by reserved lanes scenarios, but when taking in account the occupancy per vehicle, HOV mode is benefited in Scenarios A and D. This exists since the total time loss of the mode increased less than twice in Scenario D compared to A, but users using this mode increased by more than twice. This compensates the ratio meaning an actual benefit for the users if considered individually, but not their aggregation.

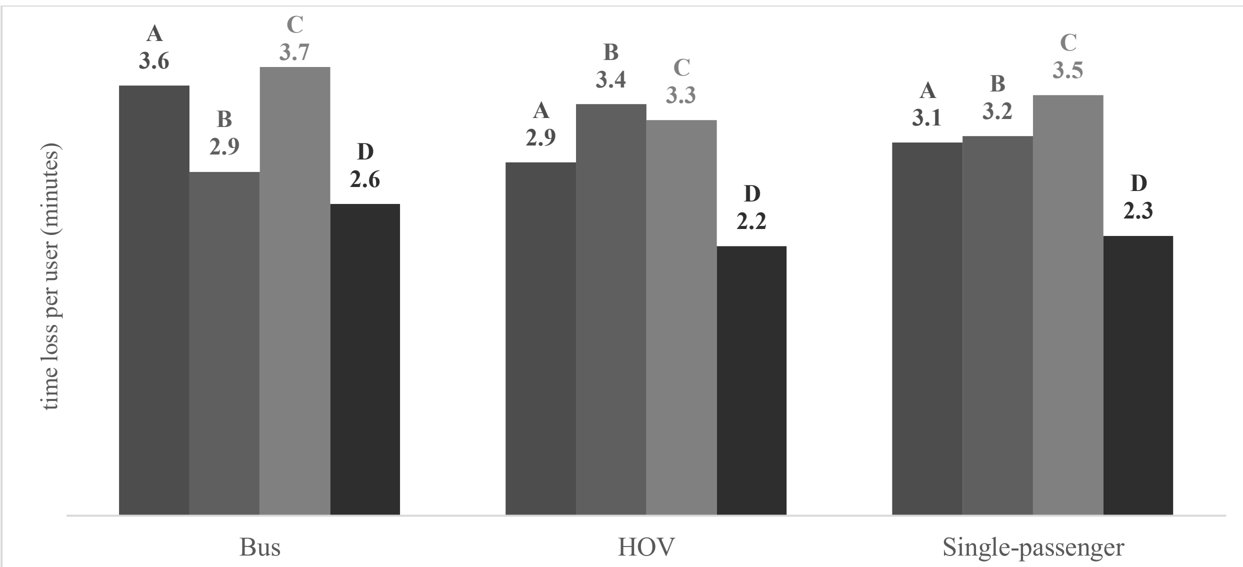


Figure 70: Average time loss per user per mode
HOV mode, when considered as a whole, was negatively impacted by Scenario D. However, the increase of users changed at a different pace than the time loss make an individual benefit.

Chapter 6

Conclusion and Future Work

This thesis presented a study aiming decision-making for urban mobility at macro, meso and micro-scale. Outputs for each level were presented from different conversation angles.

The René-Lévesque quarter in the borough of Ville-Marie is the most transited zone for both origins and destinations at macro-scale analysis. This aligns with the perception of downtown Montreal as the main economic area. It is also the neighbourhood that has the greatest number of people that live in the same quarter as their routine activity.

By filtering specific network elements at mesoscale, one is able to see relations among them, such as the lack of pedestrian zones close to Concordia University and École de technologie supérieure, and the limited coverture of public transit at École de technologie supérieure.

At micro-scale, four scenarios including new transit-policies were simulated. Results show an overall benefit from reserved lines for specific modes of transportation as long as there is a voluntary user modal shift.

Project limitations

- Computing power was a constraint during the data processing stage, as this type of task relies on a great source of RAM and hard drive speed. 32 GB of RAM and a Solid State Drive (SSD) are recommended for this task.
- Software dependency was an obstacle during the execution of the original scope. A software composed of different software packages had incompatibility issues during 2019 that made it impossible to run the end program.
- No relevant nor detailed public information was found regarding vehicle occupancy preference in Montreal, Canada. Again, this interfered with the original scope of the thesis. It is considered that it has great importance for the subject.

What is the next era of simulation for policy-making?

In this thesis, some conclusions are linked with the literature review to highlight some aspects applicable to future directions in this subject:

- There is scarce information regarding the estimation of health impacts from urban mobility using simulation techniques. This information might be complex to estimate and homogeneous for interpretation, but efforts seen in medical journals exist as found in (Levy et al., 2010). An interdisciplinary area of opportunity exists here.
- Simulation techniques are evolving to include novel approaches such as AI-powered vehicles. As seen in the literature and articles from the industry experts, there is yet not an agreement on the link between simulation and AI techniques.
- At the timeline of this review, there is yet much to experience regarding the introduction of new technologies to society. Adoption rates, customer acceptance, market development and system safety, in reality, are still out of testing, meaning that unforeseen challenges might arise.

Final statement

Disruptive technologies, intermodal mobility models, growing environmental constraints and increasing densities of cities will require more and more disruptive and radical actions. The impact on sustainability is increasing and solutions for this problem gets more complex and difficult to address. City administrations can deploy solutions, but due to the increasing size of the world population and collective mobility habits, eventually, a sole and final answer will be clear: people have to leave single-passenger transportation by heavy motorized vehicles.

References

Alonso, A., Monzon, A., & Wang, Y. (2017). Modelling land use and transport policies to measure their contribution to urban challenges: The case of Madrid. *Sustainability (Switzerland)*, *9*(3). https://doi.org/10.3390/su9030378

Anda, C., Ordonez Medina, S. A., & Fourie, P. (2018). Multi-agent urban transport simulations using OD matrices from mobile phone data. *Procedia Computer Science*, *130*, 803–809. https://doi.org/10.1016/j.procs.2018.04.139

ArcGIS. (n.d.). *Create spider diagram (desire lines)—Help | ArcGIS Desktop*. Retrieved January 14, 2020, from https://desktop.arcgis.com/de/arcmap/latest/extensions/business-analyst/create-spider-diagrams-desire-lines.htm

Ayed, H., Khadraoui, D., & Aggoune, R. (2015). Using MATSim to simulate carpooling and car-sharing trips. *2015 World Congress on Information Technology and Computer Applications (WCITCA)*, 1–5. https://doi.org/10.1109/WCITCA.2015.7367046

Babulak, E., & Ming Wang. (2009). Discrete event simulation: State of the art. *International Journal of Online Engineering*, *4*(2), 60–63.

Basaric, V., Djoric, V., Jevdjenic, A., & Jovic, J. (2015). Efficient methodology for assessment of targets and policy measures for sustainable mobility systems. *International Journal of Sustainable Transportation*, *9*(3), 217–226. https://doi.org/10.1080/15568318.2012.756088

Bastani, S., Libman, L., & Waller, S. T. (2014). Impact of beaconing policies on traffic density estimation accuracy in traffic information systems. *15th IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks, WoWMoM 2014, June 19, 2014*. https://doi.org/10.1109/WoWMoM.2014.6918963

Batur, rfan, & Koc, M. (2017). Travel Demand Management (TDM) case study for social behavioral change towards sustainable urban transportation in Istanbul. *Cities*, *69*, 20–35. https://doi.org/10.1016/j.cities.2017.05.017

Bazzan, A. L. C., & Klügl, F. (Eds.). (2009). *Multi-agent systems for traffic and transportation engineering*. Information Science Reference.

Bhatia, A., Varakantham, P., & Kumar, A. (2018). Resource constrained deep reinforcement learning [arXiv]. *ArXiv*, 5 pp.

Bodde, D. L., & Jianan Sun. (2016). Emergent entrepreneurial networks for the transition to automated urban mobility. *2016 IEEE Transportation Electrification Conference and Expo (ITEC), 27-29 June 2016*, 6 pp. https://doi.org/10.1109/ITEC.2016.7520274

Borrego, C., Cascao, P., Lopes, M., Amorim, J. H., Tavares, R., Rodrigues, V., Martins, J., Miranda, A. I., & Chrysoulakis, N. (2011). Impact of urban planning alternatives on air quality: URBAIR model application. *19th International Conference on Modelling, Monitoring and Management of Air Pollution, AIR 2011, September 19, 2011 - September 21, 2011*, *147*, 13–24. https://doi.org/10.2495/AIR110021

Bruemmer, R., October 4, M. G. U., & 2019. (2019, October 4). *Montreal plans carbon-neutral neighbourhood at Hippodrôme site | Montreal Gazette*. https://montrealgazette.com/news/local-news/montreal-eyes-carbon-neutral-neighbourhood-for-hippodrome-site

Buil, R., Piera, M. A., Gusev, M., Ginters, E., & Aizstrauts, A. (2015). MAS simulation for decision making in urban policy design: Bicycle infrastructure. *17th International Conference on Harbor, Maritime and Multimodal Logistics Modelling and Simulation, HMS 2015, September 21, 2015 - September 23, 2015*, 95–102. http://www.msc-les.org/proceedings/hms/2015/HMS2015_95.pdf

Caiati, V., Bedogni, L., Bononi, L., Ferrero, F., Fiore, M., & Vesco, A. (2016). Estimating urban mobility with open data: A case study in Bologna. *2nd IEEE International Smart Cities Conference, ISC2 2016, September 12, 2016 - September 15, 2016*, IEEE Smart Cities; University of Trento. https://doi.org/10.1109/ISC2.2016.07580765

Carteni, A., & De Luca, S. (2014). Greening the transportation sector: A methodology for assessing sustainable mobility policies within a sustainable energy action plan. *International Journal of Powertrains*, *3*(4), 354–374. https://doi.org/10.1504/IJPT.2014.066420

Categorical Data. (n.d.). Department of Statistics and Data Science, Yale University. Retrieved May 18, 2019, from http://www.stat.yale.edu/Courses/1997-98/101/catdat.htm

Chrysostomou, K., Petrou, A., Aifadopoulou, G., & Morfoulaki, M. (2019). *Microsimulation Modelling of the Impacts of Double-Parking Along an Urban Axis* (pp. 164–171). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-030-02305-8_20

Concordia University. (2020). *Fast facts*. http://www.concordia.ca/content/concordia/en/about/fast-facts.html

DeLorenzo, N., & Dugger, A. (n.d.). *Choropleth Map*. Retrieved January 14, 2020, from https://www.arcgis.com/apps/MapJournal/index.html?appid=75eff041036d40cf8e70df99641004ca

Dresner, K., & Stone, P. (2004). *A Protocol for Multi-Agent Traffic Control at Intersections*. 10.

Dresner, K., & Stone, P. (2007). Sharing the Road: Autonomous Vehicles meet Human Drivers. *The 20th International Joint Conference on Artificial Intelligence*, 1263–68.

Dynamic Transportation Systems. (2019). *QGIS Edge Bundling* [Python]. Dynamic Transportation Systems. https://github.com/dts-ait/qgis-edge-bundling (Original work published 2017)

Ebru, E. (2013). Pedestrian Zones. In M. Ozyavuz (Ed.), *Advances in Landscape Architecture*. InTech. https://doi.org/10.5772/55748

Edwards, S., Hill, G., Goodman, P., Blythe, P., Mitchell, P., & Huebner, Y. (2018). Quantifying the impact of a real world cooperative-ITS deployment across multiple cities. *Transportation Research Part A: Policy and Practice*, *115*, 102–113. https://doi.org/10.1016/j.tra.2017.10.001

Elahi, M., Steverson, G., Dey, S., Dock, S., & Green, L. (2016). Framework for assessing effectiveness of peak hour parking restrictions: Case study from Washington, D.C. *Transportation Research Record*, *2554*, 27–36. https://doi.org/10.3141/2554-04

Elbanhawy, E. Y., Dalton, R., & Nassar, K. (2013). Integrating space-syntax and discrete-event simulation for e-mobility analysis. *2013 Architectural Engineering National Conference: Building Solutions for Architectural Engineering, AEI 2013, April 3, 2013 - April 5, 2013*, 934–945. https://doi.org/10.1061/9780784412909.091

Engineering Services - Transportation, City of Vancouver. (2006, June 3). *Transportation Plan (1997 Report)—Glossary*. https://web.archive.org/web/20060603041834/http://vancouver.ca/engsvcs/transport/plan/1997report/glossary.htm

Engineering Village Database. (n.d.). Retrieved May 15, 2019, from https://www.elsevier.com/solutions/engineering-village

Ettema, D., Arentze, T., & Timmermans, H. (2011). Social influences on household location, mobility and activity choice in integrated micro-simulation models. *Transportation Research Part A: Policy and Practice*, *45*(4), 283–295. https://doi.org/10.1016/j.tra.2011.01.010

European Commission. (2016, September 22). *Green Paper on urban mobility* [Text]. Mobility and Transport. https://ec.europa.eu/transport/themes/urban/urban_mobility/green_paper_en

Feng, T., & Timmermans, H. J. P. (2014). Trade-offs between mobility and equity maximization under environmental capacity constraints: A case study of an integrated multi-objective model. *Transportation Research Part C: Emerging Technologies*, *43*, 267–279. https://doi.org/10.1016/j.trc.2014.03.012

Ferrara, A., Sacone, S., & Siri, S. (2018). Microscopic and Mesoscopic Traffic Models. In A. Ferrara, S. Sacone, & S. Siri (Eds.), *Freeway Traffic Modelling and Control* (pp. 113–143). Springer International Publishing. https://doi.org/10.1007/978-3-319-75961-6_5

Forbes Staff. (2017, June 6). El tope inteligente existe y fue desarrollado por mexicanos. *Forbes México*. https://www.forbes.com.mx/tope-inteligente-existe-fue-desarrollado-mexicanos/

Fournier, N., Chen, S., Viegas de Lima, I. H., Needell, Z., Deliali, A., Araldo, A., Prakash, A. A., Azevedo, C. L., Christofa, E., Trancik, J., & Ben-Akiva, M. (2018). Integrated simulation of activity-based demand and multi-modal dynamic supply for energy assessment. *2018 21st International Conference on Intelligent Transportation Systems (ITSC), 4-7 Nov. 2018*, 2277–2282. https://doi.org/10.1109/ITSC.2018.8569541

Garfield, L. (n.d.). 13 cities that are starting to ban cars. *Business Insider*. Retrieved January 5, 2020, from https://www.businessinsider.com/cities-going-car-free-ban-2017-8

German Aerospace Center (DLR). (n.d.). *Eclipse SUMO – Simulation of Urban MObility*. DLR - Institute of Transportation Systems. Retrieved March 29, 2019, from https://www.dlr.de/ts/en/desktopdefault.aspx/tabid-9883/16931_read-41000/

German Aerospace Center (DLR). (2010). *RandomTrips.py* [Python]. https://github.com/eclipse/sumo

German Aerospace Center (DLR). (2019a). *Contributed/SUMOPy—SUMO Documentation*. https://sumo.dlr.de/docs/Contributed/SUMOPy.html

German Aerospace Center (DLR). (2019b). *Demand/Introduction to demand modelling in SUMO - SUMO Documentation*. https://sumo.dlr.de/docs/Demand/Introduction_to_demand_modelling_in_SUMO.html

German Aerospace Center (DLR). (2019c). *Simulation/Output/TripInfo—SUMO Documentation*. https://sumo.dlr.de/docs/Simulation/Output/TripInfo.html

German Aerospace Center (DLR). (2020a). *Definition of Vehicles, Vehicle Types, and Routes—SUMO Documentation*. https://sumo.dlr.de/docs/Definition_of_Vehicles,_Vehicle_Types,_and_Routes.html

German Aerospace Center (DLR). (2020b). *Simulation/Randomness—SUMO Documentation*. https://sumo.dlr.de/docs/Simulation/Randomness.html

German Aerospace Center (DLR). (2020c). *SUMO - SUMO Documentation*. https://sumo.dlr.de/docs/SUMO.html

German Aerospace Center (DLR). (2020d). *Tools/Trip—SUMO Documentation*. https://sumo.dlr.de/docs/Tools/Trip.html#randomtripspy

German Aerospace Center (DLR). (2020e). *Tutorials/OSMWebWizard—SUMO Documentation*. https://sumo.dlr.de/docs/Tutorials/OSMWebWizard.html

Gössling, S., & Choi, A. S. (2015). Transport transitions in Copenhagen: Comparing the cost of cars and bicycles. *Ecological Economics*, *113*, 106–113. https://doi.org/10.1016/j.ecolecon.2015.03.006

Government of Canada, S. C. (2017). *The Daily — Journey to work: Key results from the 2016 Census*. https://www150.statcan.gc.ca/n1/daily-quotidien/171129/dq171129c-eng.htm

Grimaldo, F., Lozano, M., Barber, F., & Guerra-Hernandez, A. (2012). Towards a model for urban mobility social simulation: A perspective from J-MADeM decision-making. *Progress in Artificial Intelligence*, *1*(2), 149–156. https://doi.org/10.1007/s13748-012-0012-z

Grimaldo, F., Lozano, M., Barber, F., & Guerra-Hernandez, A. (2011). A J-MADeM agent-based social simulation to model urban mobility. *Advances on Practical Applications of Agents and Multiagent Systems: 9th International Conference on Practical Applications of Agents and Multiagent Systems*, *88*, 1–11. https://doi.org/10.1007/978-3-642-19875-5_1

Gudwin, R. R. (2016). *Urban Traffic Simulation with SUMO: A roadmap for Beginners*. DCA-FEEC-UNICAMP.

Han, Q., Arentze, T., Timmermans, H., Janssens, D., & Wets, G. (2009). A Multi-Agent Modeling Approach to Simulate Dynamic Activity-Travel Patterns. In A. Bazzan & F. Klügl (Eds.), *Multi-Agent Systems for Traffic and Transportation Engineering* (pp. 36–56). IGI Global. https://doi.org/10.4018/978-1-60566-226-8.ch002

Henriquez, G. (2017, February 20). Canada's worst cities for spending hours and hours in traffic. *Global News*. https://globalnews.ca/news/3261815/canada-worst-traffic/

Hill, J. (2018, July 2). Simulation: The bedrock of AI. *Simudyne*. https://medium.com/simudyne/simulation-the-bedrock-of-ai-12153eaf7971

Hofer, C., Jager, G., & Fullsack, M. (2018). Large scale simulation of CO2emissions caused by urban car traffic: An agent-based network approach. *Journal of Cleaner Production*, *183*, 1–10. https://doi.org/10.1016/j.jclepro.2018.02.113

Holtz, Y. (n.d.). *Chord diagram*. From Data to Viz. Retrieved January 27, 2020, from www.data-to-viz.com/caveat/chord.html

Hörl, S., Ruch, C., Becker, F., Frazzoli, E., & Axhausen, K. W. (2019). Fleet operational policies for automated mobility: A simulation assessment for Zurich. *Transportation Research Part C: Emerging Technologies*, *102*, 20–31. https://doi.org/10.1016/j.trc.2019.02.020

Houli, D., Zhiheng, L., & Yi, Z. (2010). Multiobjective Reinforcement Learning for Traffic Signal Control Using Vehicular ad hoc Network. *EURASIP Journal on Advances in Signal Processing*, 724035 (7 pp.). https://doi.org/10.1155/2010/724035

Isaac Olson/CBC News. (2019a, March 11). Montreal will reduce speed limits to make streets safer for pedestrians | CBC News. *CBC*. https://www.cbc.ca/news/canada/montreal/vision-zero-reduce-speed-limits-montreal-1.5051449

Isaac Olson/CBC News. (2019b, July 22). Montreal becoming more pedestrian friendly—One car-free zone at a time. *CBC*. https://www.cbc.ca/news/canada/montreal/pedestrian-zones-montreal-c%C3%B4te-des-neiges-notre-dame-de-gr%C3%A2ce-1.5216210

i-SUSTAIN. (2008). *The Commuter Toolkit*. www.i-sustain.com

Jlassi, S., Tamayo, S., & Gaudron, A. (2018). *Simulation Applied to Urban Logistics: A State of the Art*.

Jones, M. N., Frutiger, J., Ince, N. G., & Sin, G. (2019). The Monte Carlo driven and machine learning enhanced process simulator. *Computers & Chemical Engineering*, *125*, 324–338. https://doi.org/10.1016/j.compchemeng.2019.03.016

Kanaroglou, P., Mercado, R., Maoh, H., Paez, A., Scott, D. M., & Newbold, B. (2008). Simulation framework for analysis of elderly mobility policies. *Transportation Research Record*, *2078*, 62–71. https://doi.org/10.3141/2078-09

Khan, S., Maoh, H., Lee, C., & Anderson, W. (2016). Toward sustainable urban mobility: Investigating nonwork travel behavior in a sprawled Canadian city. *International Journal of Sustainable Transportation*, *10*(4), 321–331. https://doi.org/10.1080/15568318.2014.928838

Kristensen, T., & Ezeora, N. J. (2017). Simulation of intelligent traffic control for autonomous vehicles. *2017 IEEE International Conference on Information and Automation (ICIA), 18-20 July 2017*, 459–465. https://doi.org/10.1109/ICInfA.2017.8078952

Kroese, D. P., Brereton, T., Taimre, T., & Botev, Z. I. (2014). Why the Monte Carlo method is so important today. *Wiley Interdisciplinary Reviews: Computational Statistics*, *6*(6), 386–392. https://doi.org/10.1002/wics.1314

Kwang Ming Lion, Kae Hsiang Kwong, & Weng Kin Lai. (2018). Smart speed bump detection and estimation with kinect. *2018 4th International Conference on Control, Automation and Robotics (ICCAR), 20-23 April 2018*, 465–469. https://doi.org/10.1109/ICCAR.2018.8384721

L'Association des marchands de la rue Crescent. (2018). *Crescent*. Crescentmontreal.Com. https://www.crescentmontreal.com

Lazarus, J., Ugirumurera, J., Hinardi, S., Zhao, M., Shyu, F., Yexin Wang, Shuai Yao, & Bayen, A. M. (2018). A Decision Support System for Evaluating the Impacts of Routing Applications on Urban

Mobility. *2018 21st International Conference on Intelligent Transportation Systems (ITSC), 4-7 Nov. 2018*, 513–518. https://doi.org/10.1109/ITSC.2018.8569622

Levy, J. I., Buonocore, J. J., & von Stackelberg, K. (2010). Evaluation of the public health impacts of traffic congestion: A health risk assessment. *Environmental Health*, *9*, 65. https://doi.org/10.1186/1476-069X-9-65

Li, W., & Kamargianni, M. (2018). Providing quantified evidence to policy makers for promoting bike-sharing in heavily air-polluted cities: A mode choice model and policy simulation for Taiyuan-China. *Transportation Research Part A: Policy and Practice*, *111*, 277–291. https://doi.org/10.1016/j.tra.2018.01.019

Lucas Torres, O., & Awasthi, A. (2019). Transit Policy Simulation: Towards a Sustainable Urban Mobility. In *Sustainable City Logistics Planning: Methods and Applications* (Vol. 1). Nova Science Publishers. https://novapublishers.com/shop/sustainable-city-logistics-planning-methods-and-applications-volume-1/

Maggioni, F., Perboli, G., & Tadei, R. (2014). The Multi-path Traveling Salesman Problem with Stochastic Travel Costs: Building Realistic Instances for City Logistics Applications. *17th Meeting of the EURO Working Group on Transportation, EWGT2014, 2-4 July 2014, Sevilla, Spain*, *3*, 528–536. https://doi.org/10.1016/j.trpro.2014.10.001

Marczuk, K. A., Soh, H. S. H., Azevedo, C. M. L., Lee, D.-H., & Frazzoli, E. (2016). Simulation framework for rebalancing of autonomous mobility on demand systems. *2016 5th International Conference on Transportation and Traffic Engineering (ICTTE 2016), 6-10 July 2016*, *81*, 01005 (6 pp.). https://doi.org/10.1051/matecconf/20168101005

McKay, R. B. (2000). Consequential Utilitarianism: Addressing Ethical Deficiencies in the Municipal Landfill Siting Process. *Journal of Business Ethics*, *26*(4), 289–306. https://doi.org/10.1023/A:1006345600415

Menezes, E., Maia, A. G., & de Carvalho, C. S. (2017). Effectiveness of low-carbon development strategies: Evaluation of policy scenarios for the urban transport sector in a Brazilian megacity. *Technological Forecasting and Social Change*, *114*, 226–241. https://doi.org/10.1016/j.techfore.2016.08.016

MIT SDEP. (1997). *What is System Dynamics?* http://web.mit.edu/sysdyn/sd-intro/

Mocanu, T. (2018). *The travel demand impacts of fare-free regional public transport in Germany*. https://elib.dlr.de/120469/

Musso, A., & Corazza, M. V. (2006). Improving Urban mobility management case study of Rome. *Management and Public Policy 2006*, 52–59. https://doi.org/10.3141/1956-07

NextGIS. (2019). *OSMInfo* [Python]. NextGIS. https://github.com/nextgis/osminfo (Original work published 2015)

Niazi, M., & Hussain, A. (2011). Agent-based computing from multi-agent systems to agent-based models: A visual survey. *Scientometrics*, *89*(2), 479. https://doi.org/10.1007/s11192-011-0468-9

Occelli, S., & Staricco, L. (2009). Learning about urban mobility: Experiences with a multiagent-system model. *Environment and Planning B: Planning and Design*, *36*(5), 772–786. https://doi.org/10.1068/b34145t

OpenStreetMap Wiki. (2020, January 3). *Key:highway*. https://wiki.openstreetmap.org/wiki/Key:highway

Pageaud, S., Deslandres, V., Lehoux, V., & Hassas, S. (2018). Co-construction of adaptive public policies using smartgov. *29th IEEE International Conference on Tools with Artificial Intelligence, ICTAI 2017, November 6, 2017 - November 8, 2017*, *2017-November*, 1328–1335. https://doi.org/10.1109/ICTAI.2017.00199

Pavone, M., Smith, S. L., Frazzoli, E., & Rus, D. (2012). Load Balancing for Mobility-on-demand Systems. *2011 Robotics: Science and Systems (RSS), 27 June-1 July 2011*, *vol.7*, 249–256.

Perboli, G., Ferrero, F., Musso, S., & Vesco, A. (2018). Business models and tariff simulation in car-sharing services. *Transportation Research Part A: Policy and Practice*, *115*, 32–48. https://doi.org/10.1016/j.tra.2017.09.011

Perboli, G., & Rosano, M. (2019). Parcel delivery in urban areas: Opportunities and threats for the mix of traditional and green business models. *Transportation Research Part C: Emerging Technologies*, *99*, 19–36. https://doi.org/10.1016/j.trc.2019.01.006

Perronnet, F., Abbas-Turki, A., El-Moudni, A., Buisson, J., & Zeo, R. (2013). Cooperative Vehicle-Actuator System: A sequence-based optimal solution algorithm as tool for evaluating policies. *2013 International Conference on Advanced Logistics and Transport, ICALT 2013, May 29, 2013 - May 31, 2013*, 19–24. https://doi.org/10.1109/ICAdLT.2013.6568428

QGIS. (2020). https://www.qgis.org/en/site/

Ramos, A., & de Abreu e Silva, J. (2019). *New Indicators in the Performance Analysis of a Public Transport Interchange Using Microsimulation Tools—The Colégio Militar Case Study* (pp. 123–130). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-030-02305-8_15

Rivenburgh, N., & Chase, Patricia. (2019). *Envisioning Better Cities*.

Samaranayake, S., Spieser, K., Guntha, H., & Frazzoli, E. (2018). Ridepooling with trip-chaining in a shared-vehicle mobility-on-demand system. *20th IEEE International Conference on Intelligent Transportation Systems, ITSC 2017, October 16, 2017 - October 19, 2017*, *2018-March*, 1–7. https://doi.org/10.1109/ITSC.2017.8317603

Sarker, A., Li, Z., Kolodzey, W., & Shen, H. (2017). Opportunistic Energy Sharing between Power Grid and Electric Vehicles: A Game Theory-Based Pricing Policy. *37th IEEE International Conference on Distributed Computing Systems, ICDCS 2017, June 5, 2017 - June 8, 2017*, *0*, 1197–1207. https://doi.org/10.1109/ICDCS.2017.219

Sayyadi, R., & Awasthi, A. (2017). A system dynamics based simulation model to evaluate regulatory policies for sustainable transportation planning. *International Journal of Modelling and Simulation*, *37*(1), 25–35. https://doi.org/10.1080/02286203.2016.1219806

Sayyadi, R., & Awasthi, A. (2018). An integrated approach based on system dynamics and ANP for evaluating sustainable transportation policies. *International Journal of Systems Science: Operations & Logistics*, 1–10. https://doi.org/10.1080/23302674.2018.1554168

Schneider, A. (n.d.). *Reverse Geocoding*. Retrieved January 23, 2020, from http://geotag.sourceforge.net/ReverseGeocoding/

Schumann, B. (2018, May 7). Time to marry simulation models and machine learning. *Benjamin Schumann Consulting*. https://www.benjamin-schumann.com/blog/2018/5/7/time-to-marry-simulation-models-and-machine-learning

Takama, T. (2009). Adaptation and Congestion in a Multi-Agent System to Analyse Empirical Traffic Problems: Concepts and a Case Study of the Road User Charging Scheme at the Upper Derwent. In Ana Bazzan & Franziska Klügl (Eds.), *Multi-Agent Systems for Traffic and Transportation Engineering* (pp. 1–35). IGI Global. https://doi.org/10.4018/978-1-60566-226-8.ch001

TRIP Lab. (2019). *Itinerum*. https://itinerum.ca/

Tsiropoulos, A., Papagiannakis, A., & Latinopoulos, D. (2019). Development of an aggregate indicator for evaluating sustainable urban mobility in the City of Xanthi, Greece. *4th Conference on Sustainable Urban Mobility, CSUM 2018, May 24, 2018 - May 25, 2018*, *879*, 35–43. https://doi.org/10.1007/978-3-030-02305-8_5

UC San Diego. (n.d.). *Writing a Literature Review*. Retrieved May 20, 2019, from https://psychology.ucsd.edu/undergraduate-program/undergraduate-resources/academic-writing-resources/writing-research-papers/writing-lit-review.html

United Nations. (2018, May 16). *68% of the world population projected to live in urban areas by 2050, says UN*. UN DESA | United Nations Department of Economic and Social Affairs. https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html

UTC to EST Converter. (2020). Savvy Time. https://savvytime.com/converter/utc-to-est/oct-5-2017/10-30pm

Vallati, M., Magazzeni, D., Schutter, B. D., Chrpa, L., & McCluskey, T. L. (2016). Efficient macroscopic urban traffic models for reducing congestion: A PDDL+ planning approach. *30th AAAI Conference on Artificial Intelligence, AAAI 2016, February 12, 2016 - February 17, 2016*, 3188–3194.

Vance, C., & Hedel, R. (2007). The impact of urban form on automobile travel: Disentangling causation from correlation. *TRB 2007 Trnasportation Research Board. The Built Environmenr and Travel Behaviour: Making the Connection*, *34*, 575–588. https://doi.org/10.1007/s11116-007-9128-6

VDA. (2015). Youth without cars? *Verband Der Automobilindustrie e. V.*, 8.

Ville de Montréal. (n.d.). *MTL Trajet*. Retrieved January 8, 2020, from https://ville.montreal.qc.ca/mtltrajet/en/

Ville de Montréal/Service de l'habitation. (2019). *Quartiers de référence en habitation [Data file]*. https://www.donneesquebec.ca/recherche/fr/dataset/vmtl-quartiers

Ville de Montréal/Service de l'urbanisme et de la mobilité. (2017). *Déplacements MTL Trajet [Data file]*. http://donnees.ville.montreal.qc.ca/dataset/mtl-trajet

Ville de Montréal/Service des infrastructures du réseau routier. (2019). *Limite administrative de l'agglomération de Montréal (Arrondissements et Villes liées) [Data file]*. http://donnees.ville.montreal.qc.ca/dataset/polygones-arrondissements

Ville de Montréal/Son-Thu Le. (2020). *Feux de circulation – feux pour piétons [Data file]*. http://donnees.ville.montreal.qc.ca/dataset/feux-pietons

Volkov, M., Aslam, J., & Rus, D. (2012). Markov-based redistribution policy model for future urban mobility networks. *2012 15th International IEEE Conference on Intelligent Transportation Systems, ITSC 2012, September 16, 2012 - September 19, 2012*, 1906–1911. https://doi.org/10.1109/ITSC.2012.6338848

Wagner, P. (2019, July). *Personal interview* [Personal communication].

Wang, Q., & Taylor, J. E. (2016a). Data-driven simulation of urban human mobility constrained by natural disasters. *2016 Winter Simulation Conference (WSC), 11-14 Dec. 2016*, 3357–3364. https://doi.org/10.1109/WSC.2016.7822366

Wang, Q., & Taylor, J. E. (2016b). Diffusion and Simulation of Human Mobility Using Online Network Data to Examine Mobility Constraints. *Construction Research Congress 2016: Old and New Construction Technologies Converge in Historic San Juan, CRC 2016, May 31, 2016 - June 2, 2016*, 1497–1506. https://doi.org/10.1061/9780784479827.150

Weilong Song, Guangming Xiong, & Huiyan Chen. (2016). Intention-aware autonomous driving decision-making in an uncontrolled intersection. *Mathematical Problems in Engineering*, *2016*, 1025349 (15 pp.). https://doi.org/10.1155/2016/1025349

Yao, E., & Morikawa, T. (2015). *A study of an integrated intercity travel demand model*. https://doi.org/10.1016/j.tra.2004.12.003

Zambom Santana, E. F., Kanashiro, L., Bogado Tomasiello, D., Kon, F., & Giannotti, M. (2018). Analyzing urban mobility carbon footprint with large-scale, agent-based simulation. *7th International Conference on Smart Cities and Green ICT Systems, SMARTGREENS 2018, March 16, 2018 - March 18, 2018*, *2018-March*, 143–150.

Zhou, B., Schwarting, W., Rus, D., & Alonso-Mora, J. (2018). Joint Multi-Policy Behavior Estimation and Receding-Horizon Trajectory Planning for Automated Urban Driving. *2018 IEEE International Conference on Robotics and Automation (ICRA), 21-25 May 2018*, 7 pp. https://doi.org/10.1109/ICRA.2018.8461138