Agent-based modelling of commuting patterns in Geneva, Switzerland, towards portraying urban expansion and land cover changes.

Flann Chambers (flann.chambers@unige.ch)
Centre Universitaire d'Informatique, Institute of Service Science, Université de Genève
Christophe Cruz
Laboratoire Informatique Carnot de Bourgogne, Université de Bourgogne
Giovanna Di Marzo Serugendo
Centre Universitaire d'Informatique, Institute of Service Science, Université de Genève

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Flann Chambers[1*], Christophe Cruz[2] and Giovanna Di Marzo Serugendo[1]

[1*]Centre Universitaire d'Informatique, Université de Genève, Suisse.
[2]Laboratoire Interdisciplinaire Carnot de Bourgogne, Université de Bourgogne, France.

*Corresponding author(s). E-mail(s): flann.chambers@unige.ch;
Contributing authors: christophe.cruz@u-bourgogne.fr; giovanna.dimarzo@unige.ch;

Abstract

Agent-based modelling has been used in many studies of urban expansion, land use and land cover change patterns. Indeed, this method represents a powerful tool for depicting and formulating predictions about the evolution of interconnected complex systems. We present an agent-based model developed in GAMA for analysing commuting patterns in the canton of Geneva, Switzerland, and fully document our modelling methodology, to provide inspiration and a materials and methodology basis for future modelling efforts. All datasets and codes related to this work are distributed in open access, and a general methodology for adapting the model to other use cases is discussed. Main findings revolve around the analysis of the impact of public transportation offer changes on journey by tram length. With our given set of initial conditions, when decreasing tram offer on the major Cornavin-Meyrin-CERN axis, journey-to-work length skyrockets for a handful of commuters. This phenomenon is correlated with an observed increase in overcrowded trams in the system. Furthermore, increasing tram offer alongside the emergence of a new large eco-district helps dampen the steady increase in journey length caused by the influx of new commuters and the saturation of the network. The model presented in this paper is early work in developing agent-based models for simulating urban expansion and land cover change dynamics.

Keywords: Agent-based modelling, Urban expansion, Land cover change, Land use, Commuting patterns

Contents

1 Introduction

Urban management decision-makers, policy makers, and the scientific community recognise the high importance of monitoring the dynamics of land cover change and the evolution of public transportation offer, before, during, and after, urban expansion projects are planned and achieved [1–4].

In those complex social-ecological systems, Agent-Based Modelling (ABM) is proven to be particularly well suited to understand, describe, but also predict phenomena arising from the intricate interactions between the involved parties (such as transportation network, rural surfaces in competition with newly built areas) in a context of rapid urban consolidation [5–7].

However, ABM research has encountered many challenges and setbacks inherent to this method, such as the requirement of large amounts of data at a fine resolution [1, 3], rigorous model testing and validation [3, 6], and clear presentation of results in the form of calibration, validation, and output data exploration and visualisation [6]. We develop an agent-based model for the analysis of commuting patterns in urban areas, and document all sources of data, pre-processing and post-processing methodologies, and model building endeavours. An online repository[1] provides full open access to all materials produced in the scope of this study, including input and output datasets, data analysis scripts, model source code and visualisations. For this task we benefit from open access to a large database of vector geomatic data[2], which both solves the data hungriness aspect of such a model, and provides highly relevant [1, 3] fine spatial detail to the simulation. This version is early work towards using validated agent-based models to describe, predict and prescribe phenomena related to urban expansion, land use and land cover change in a way that will be able to inform decision-making processes. Our work is built upon the first version of our model presented in the related extended abstract [8], in which we discussed how the model prototype works and how to visualise a sample output dataset using a python data visualisation module. Here, we delve further upon our modelling and results analysis methodologies, with the hope of providing some guidance and inspiration for similar future projects in the agent-based modelling field.

The following sections will navigate us through the context for this study (section 2) enhanced with situation maps. Then, a full discussion of our research methodology will follow (section 3), including data collection and pre-processing, model building, and output data analysis. Results will be presented and discussed in section 4, starting with the model validation results, before moving to the output datasets analysis. Finally, we sum up our findings and discuss possible and planned future works in section 5.

[1] https://gitlab.unige.ch/cas/ANS_TCMC_ABM
[2] *Système d'Information du Territoire Genevois.*

2 Contextualisation

2.1 Case study details

Urban planning occupies a central space in any government's agenda. Rapid urban consolidation bears tremendous impacts on the ecosystems' as well as the residents' well-being. Indeed, not only do negative side-effects build up on the local biodiversity, such as habitat loss from the conversion of rural areas and forests to built areas [9, 10], they also affect the population, who may suffer for instance from the emergence of isolated zones of abnormally high temperatures during heat spells in summer [11].

We focus on the use case of the canton of Geneva and its desire to develop large axes of public transportation in the form of tram lines. Already expressed in policies enacted in 1988[3], this resolution has been concretized more recently through the establishment of tram lines 14 and 18 connecting most notably the city center to Meyrin and CERN – located north-west, next to the international airport of Geneva. By itself, this decision already heavily impacts the urban dynamics along this high-traffic axis. However, it may also prompt the development of additional residential and commercial centers which would benefit from the increased accessibility of the area, resulting into accrued urban consolidation and land cover changes.

Motivated by the works of ABM researchers in the field of urban planning related to land use and land cover change [1–4] and reviews from An et al. [6], Groeneveld et al. [7], and Rounsevell et al. [5], we develop an agent-based model for the Cornavin-Meyrin-CERN axis, one of the most important transportation axis in the canton of Geneva. Its main purpose is to model and visualise the evolution of commuting patterns in the area during the 2010-2022 time frame, in response to the establishment of new buildings, and to changes in the public transportation offer. By representing individual behaviors at the smallest scale (i.e. the commuter's perspective and decision-making), and by integrating complex interactions between heterogeneous agents, agent-based modelling proves to be particularly well suited in representing commuting patterns [12] and related urban consolidation processes. Indeed, agent-based modelling encapsulates emerging phenomena, that, despite being only witnessed at the global scale, can not be simply explained and represented by the sum of its parts [13]. It, in facts, remedies the lack of representation of the individuals' agency that can be found in other types of urban models [6].

2.2 Situation maps

Figure 1 depicts a map of the main transportation axis between Meyrin and the city center. Locations of interest are the Cornavin station, Meyrin and CERN, but also the eco-district "*Les Vergers*" which has been constructed in the past decade. This mixed complex of residential and retail buildings is home to a sizeable amount of residents. The emergence of the district can be more clearly seen on Figure 2, which represents a map of all new buildings that were erected between 2010 and 2022 on the same geographical extent. A high resolution version of Figure 2 is included in supplementary materials.

[3] *Votation populaire du 12 juin 1988.*

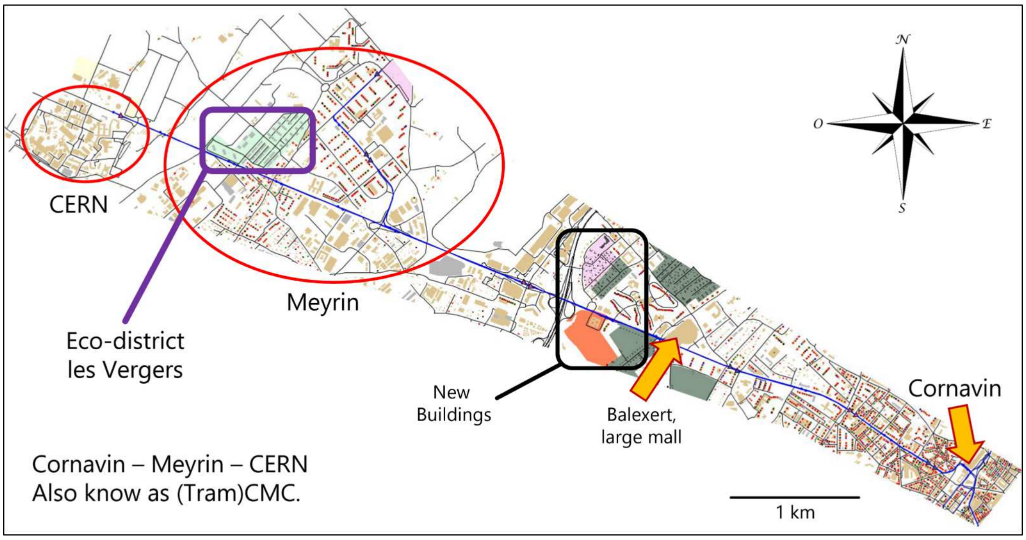

Fig. 1 Situation map for the Cornavin-Meyrin-CERN axis.

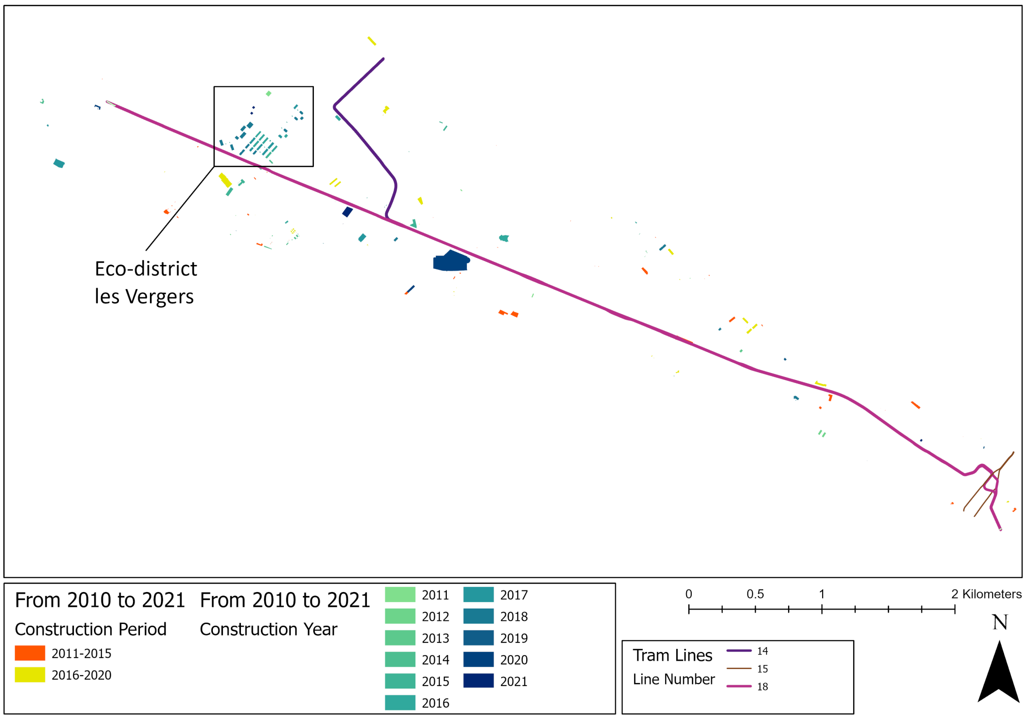

Fig. 2 Buildings established between 2010 and 2022 on the Cornavin-Meyrin-CERN axis.

3 Method

This section presents all methods used when developing the model, including the collection of input and validation datasets, the model design and building, and the data compilation and analysis processes.

3.1 Data

3.1.1 Datasets for model building

We use data sourced from the SITG[4], a platform of geomatic data about the Geneva canton that is made available in open access. We gather vector data in the form of shapefiles and preview them with the proprietary software ArcGIS Pro, however any software for working with geomatic data, such as the open-source QGIS, is suitable here. The spatial extent and useful attributes of the following entities are harnessed from these shapefiles.

- Buildings: activity type (from which is inferred one category among workplace, school, shop, leisure), spatial extent, height, construction date.
- Tram lines: spatial extent.
- Tram stops: position, stop name, lines serviced, direction.
- Roads: spatial extent.
- Commuter homes: number of commuters, location.

Each of these shapefiles is clipped to fit the spatial extent of our area of interest. The buildings layer is subject to further pre-processing steps in order to classify building activity types into four major categories: workplace, school, shop and leisure. This is done with ArcGIS Pro and the arcpy module for the *python* programming language. Relevant datasets and scripts are provided in open access in the supplementary materials.

We also use governmental statistics from the OCSTAT[5] to divide the virtual population into an accurate representation of age classes.

Finally, some other pieces of information are sporadically gathered from the Geneva public transportation (TPG) website[6], such as tram capacity, timetable, stops count. A tram is declared "fully crowded" if its current passenger count is equal to its maximum capacity. Two types of vehicles service lines 14 and 18, with maximum capacities of 247 and 261 passengers [14, 15].

All input datasets are available in the model source code folder, which can be found in open access in the supplementary materials.

3.1.2 Dataset for model validation

For validation we choose to compare the average capacity and overcrowdedness of our simulated trams with the figures available on the TPG open data platform[7]. The dataset we choose to examine is the recording of the passengers boarding and exiting

[4] *Système d'Information du Territoire Genevois.*
[5] *Office Cantonal des Statistiques.*
[6] *Transports Public Genevois.*
[7] *Transports Publics Genevois* open data platform.

a tram events by sensors located near the tram's doors. The dataset is filtered in order to select only the stops related to tram lines 14 and 18, as well as the stops inside our area of interest, for a single given day. Boarding figures are then summed up over this subset of data to get our final measurements.

3.2 Model building

We use the GAMA platform [16] to develop our agent-based model, to take advantage of its versatility, advanced features in designing agent-based models, and ease of geospatial data integration. Full model source code is made available in open access in the supplementary materials. We also include a sample video of a running simulation for an easy-to-access overview.

Figure 1 is based on the main view of a simulation produced by the model inside the GAMA platform. The interface is composed of monitors, user-defined parameters and user interaction through specific action buttons. A screenshot of this interface is available in the supplementary materials.

We define roads, tram lines and stops, buildings, tram vehicles and commuters as agent species, which is the terminology used in GAMA to construct groups of agents. Please refer to Table 1 for a summary of agent species and their action plans. Tram vehicles and commuters are able to move through space, and commuters have their own action plan and decision-making framework. Commuter granularity is defined by the number of individual people represented by a single commuter agent, which is set to 10 by default.

Table 1 Summary of the main agent species with their evolution rules and behaviors.

Species	**Commuters**	**Trams**	**Roads & Rails**	**Buildings**
Mobile ?	Yes	Yes	No	No
Decision-makers ?	Yes	No	No	No
Actions and behaviors	Follow own action plan	Follow tram rails	None	None
	Evaluate transportation options	Service stops		
	Drive car	Reverse at terminal stations		
	Walk			
	Wait for tram			
	Ride tram			

Whereas tram lines, tram stops, roads and buildings simply provide information about their locations and some attributes, such as building type (residential, business, school, leisure, shop), trams and commuters play a more active role by virtue of being able to move in the virtual environment. Trams service tram stops and follow the path given by the tram lines. They automatically reverse at terminal stations. Among the vast Geneva public transport offer, two different tram lines are represented: line 14 starts from Meyrin center and line 18 starts from CERN. They join shortly after their departure and service the same major axis. Despite continuing their journey past the station of Cornavin towards the communes of Onex and Carouge, respectively, for the interests of this case study, we simplify and set their second terminal station as the station of Cornavin, where they reverse and continue their journey the opposite way. Tram maximum capacity is set to the average of 237 and 261, i.e. 249. This number is then expressed in terms of commuter capacity by dividing it by the commuter granularity and rounding down. Trams will be able to welcome new passengers if their current capacity is strictly lower than their maximum capacity.

Commuters represent people who use some transportation method to go to work (or other building types) every day. At model initialisation, they are assigned a place of residence, and an age class (child, student, adult, or retired). Depending on their age class, they adopt different actions plans, which are depicted in Table 2. Based on their action plan and their current intention, commuters evaluate the transportation options and choose the option that fits their needs based on multiple factors: the distance between their origin and their destination, the availability of tram stops within 400 meters of their origin and their destination, and whether or not a tram line directly services both the corresponding stops of their origin and their destination. If commuters encounter a suitable yet fully crowded tram, they will wait at the stop for the next suitable non-crowded tram. Commuters will simply walk from point A to point B if the Euclidean distance is less than 800m, and otherwise take the tram or the car. Among adult commuters, 50% will always journey by car. This initial value is arbitrary and can be user-defined. The remaining commuters will evaluate if the journey by tram is possible and if there are stops within 400m of their origin and destination, if yes, they will take the tram, otherwise they will journey by car.

The model proceeds in steps of 10 seconds and simulates whole days starting from 6:00 am. The day ends when all commuters have finished their action plans and reached home. Another day then starts. The model starts in the year 2010, and at the end of each day, may also advance to a new year, as defined by the user. In this case, based on their construction year, new buildings appear and may welcome new commuters inside the virtual world. These new commuters are initialised in the same way as the existing ones, and will also evolve in the system.

3.3 Output data analysis

Output data is collected from the simulations using the "save" commands in the source code for the model. Data can be saved in .csv or .shp formats and can include any subset of each entity's attributes. Table 3 recapitulates which attributes are saved with which species datasets.

The main objectives revolving around these output data collection methods include the assessment of journey length for tram-inclined commuters for four different scenarios of varying public transportation offer, as well as the evaluation of the amount of overcrowded trams in the system.

Table 2 Commuter agents action plan details, as initially designed by the modeller based on a typical workday.

Age class	*Action plan*	*Time of day*
Children	1) Go to closest school.	Anytime between 7:00 and 7:59.
	2) Leave school:	Anytime between 17:00 and 17:59.
	a. Go to closest leisure (50%).	
	b. Go home (50%).	
	3) If 2a., go home.	2 hours after arrival.
Students	1) Go to university (Cornavin).	Anytime between 7:00 and 7:59.
	2) Go home.	Anytime between 17:00 and 17:59.
Adults	1) Go work.	Anytime between 6:00 and 8:59.
	2) Go home.	10 hours later.
Retired	1) Choose activity:	Anytime between 8:00 and 20:59.
	a. Closest shop (20%).	Spend one hour.
	b. Closest leisure (60%).	Spend two hours.
	c. Stay home (20%).	
	2) If relevant, go home	1 or 2 hours after arrival.

Table 3 Attributes recorded in the simulations' output datasets, in order. Each dataset is associated with a given agent species.

Species dataset	**Commuters (.csv)**	**Trams (.csv)**	**Roads (.shp)**
Attributes	Journey number	Line number	Spatial extent
	Demographic class	Number of passengers at recording time	Traffic metering
	Is tram considered when choosing a transportation method?	Recording time (expressed as cycle number)	
	Chosen transportation method	Recording time (expressed as time)	
	Journey length	Location at recording time	
	Time spent inside tram		
	Time spent waiting for tram		
	Selected tram stops		
	Location		

Distribution graphs and time-series plots for the aforementioned quantities are generated from the raw datasets using R scripts. These pieces of code and datasets are included in the supplementary materials.

4 Results and discussion

This section guides us through all results gathered during this work, from validation outcomes to output data analysis results, including a brief discussion of model specifications in between.

4.1 Validation

4.1.1 Results

Validation dataset informs us about the measured number of passengers boarding trams of a given line for each stop during an entire day. Thus, we compare these figures with the amount of journeys by tram simulated by the model. In 2022, this figure was 1'959, which corresponds to 19'590 individual passengers boarding trams when the commuter granularity of 10 is factored in. For the day of December 12, 2022, measured figure is 77'331. Simulated figure is approximately 75% lower with respect to the measured data.

We also queried the validation data for other dates during the year 2022, and found seasonal variations for the same year. For instance, the day of August 22 had 66'692 individual boardings, in deficit of approximately 13% with respect to the data for December 19.

4.1.2 Discussion

Many factors could explain the discrepancy between observed and simulated data. First of all, our model only includes roughly half of the stops on lines 14 and 18 (exact figure is 28 out of 61, or 46%). Entire regions serviced by these lines are eclipsed from the simulations, which represents a sizeable amount of potential passengers who are included in the validation dataset but not in the simulation. Unfortunately, it is difficult to evaluate the contribution of non-simulated regions to the total amount of individual boardings recorded in the validation dataset.

Moreover, the percentage of agents who take the tram is difficult to evaluate. The number of journeys is correlated with the exact timetable of these agents, more precisely the amount of tasks and places to visit, and their relative distance.

Many factors influence the usage of the public transportation system, such as holiday seasons and weather, which are both dependant on the month, as observed when querying the data for different periods of the year 2022. Our model does not currently take into account such variables.

In summary, the validation of our model proved unsuccessful and unfortunately can not be adequately addressed in the scope of this study. However, the validation steps carried out brought to light some important variables that influence public transportation usage throughout the year.

4.2 Model results and discussion

The GAMA code for the model is used to build simulations based on the evolution rules defined in the model as well as user-defined variable values and interactive action triggers. As a result, the same model serves as a basis for many different simulations, each with their own initial parameters, evolution rules and emergent behaviors. Model peculiarities will be discussed in the following paragraphs.

The model is subject to some random components. For instance, each commuter is assigned a random job place at the start of each simulation. Timetables also present some random elements. These aspects determine the commuter's trips and their preferred transportation method. Future works could include performing batches of simulations and averaging the results to eliminate this randomness.

The model is also characterized by a large parameter space which heavily influences model behavior and results. Examples of such variables are the way timetables are drawn up and preferred transportation methods are conditionally calculated. This specificity comes with various pros and cons. The model is highly adaptable to the user's needs, who can fine tune these parameters to reconstruct a high diversity of cases. Scenarios can also be explored, akin to using the model as a virtual laboratory. However, the sheer amount of possibilities can prove particularly daunting to deal with, and reaching accurate and relevant simulation settings is often arduous and time-consuming.

The model is defined by both its input datasets and evolution rules. Both aspects can be altered to fit another case study's needs. The general methodology to achieve this feat starts by examining the material and knowledge available for the new case study, then collecting all matching datasets for the new case study and integrating them one-by-one in place of the old datasets. Then, some modifications of the model's evolution rules may be necessary in order to accommodate differences between the inner workings of both systems. We provide full access to the model's source code as well as to all datasets and data analysis code, in the hopes that they prove useful to the application of such a methodology to another case study.

4.3 Simulation data analysis

4.3.1 Results

Journey by tram statistics were gathered for each of the four scenarios and are presented in figures 3 to 6. For the normal situation, a small increase in average journey length is observed (maximum amplitude of +8.2%, measured between 2013 and 2021, the years corresponding to the shortest and longest average journey length).

When tram frequency for line 18 is decreased (from 5 to 3 vehicles), this figure jumps to +32.2%, which is correlated to a sharp increase in time spent waiting for a tram at a stop, while time spent in tram bears no significant evolution. Similar behavior can be observed for the scenario where tram frequency for line 14 is decreased (from 11 to 7 vehicles), with a +28% increase in journey length that is also correlated with the time spent waiting at a stop. In both cases, the distribution of journey lengths across all journeys is characterized by the emergence of a trail that extends towards the high values, which is confirmed by a higher standard deviation. Steady increases in journey length over time happen after the year 2016.

When increasing the offer for line 18 (from 5 to 8 vehicles), while average journey length does not change significantly, the steady increase in journey length after the year 2016 observed during the normal situation is almost completely erased (down to +1.8% maximum amplitude from +8.2%).

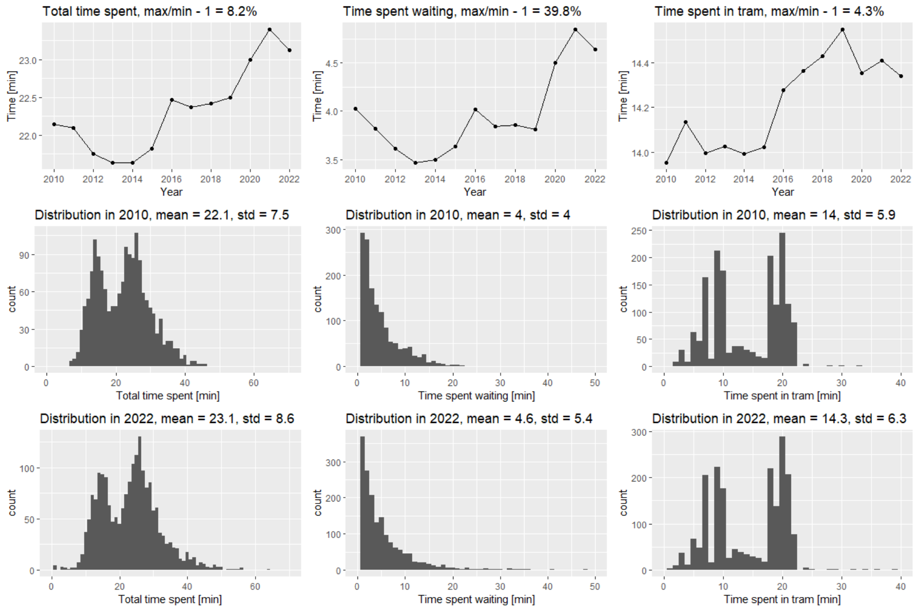

Fig. 3 Commute statistics for all commuters travelling by tram. Scenario 1 - normal situation: 11 vehicles for line 14, 5 vehicles for line 8.

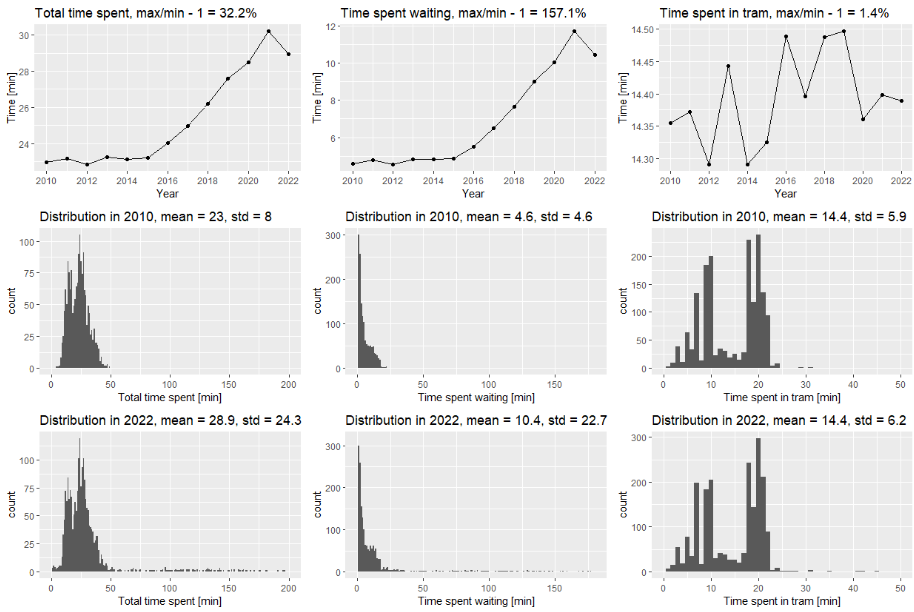

Fig. 4 Commute statistics for all commuters travelling by tram. Scenario 2 - decreased offer for line 18: 11 vehicles for line 14, 3 vehicles for line 18.

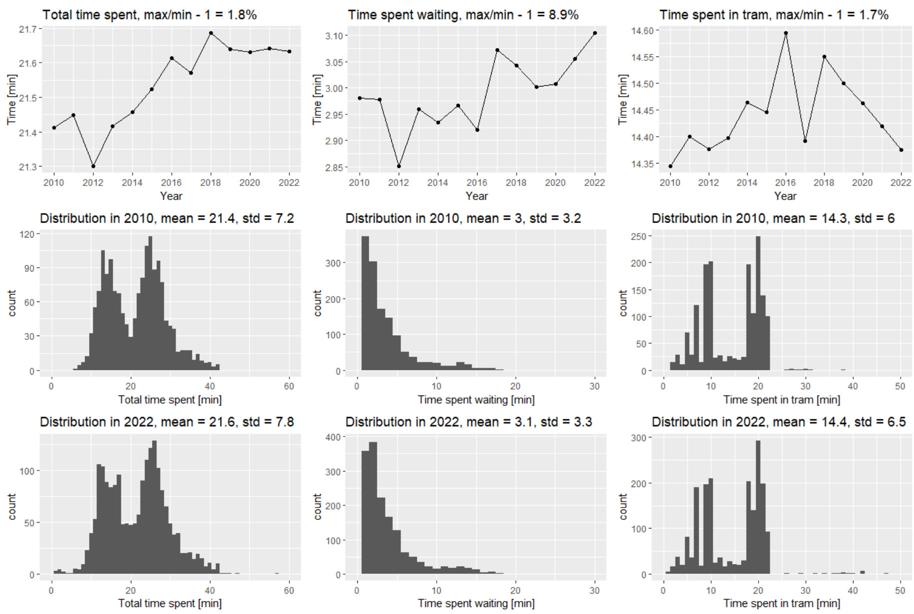

Fig. 5 Commute statistics for all commuters travelling by tram. Scenario 3 - increased offer for line 18: 11 vehicles for line 14, 8 vehicles for line 18.

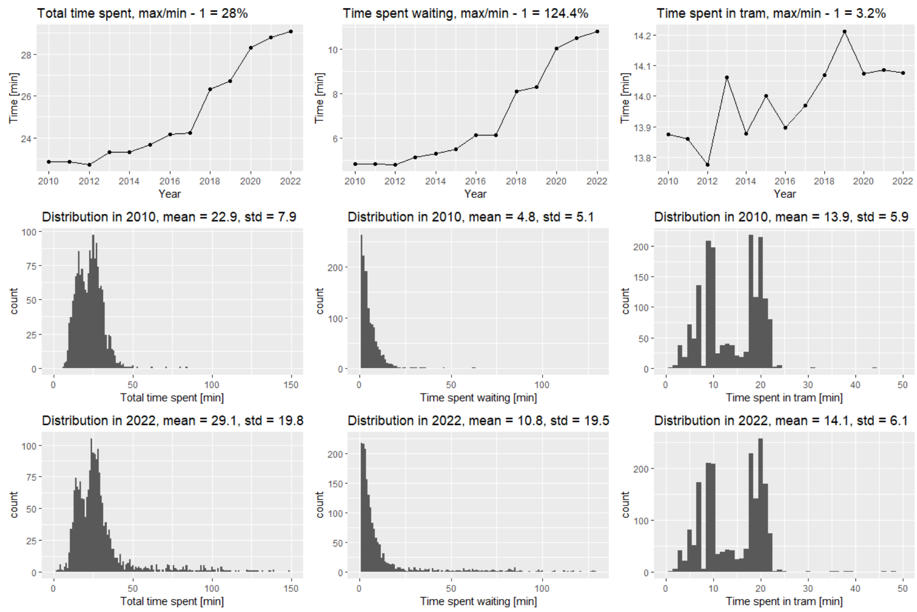

Fig. 6 Commute statistics for all commuters travelling by tram. Scenario 4 - decreased offer for line 14: 7 vehicles for line 14, 5 vehicles for line 18.

Figure 7 presents the average duration tram vehicles remain fully crowded during a typical day of each year between 2010 and 2022. Scenarios where tram offer is reduced on either line present significantly higher values than the normal and increased offer situations.

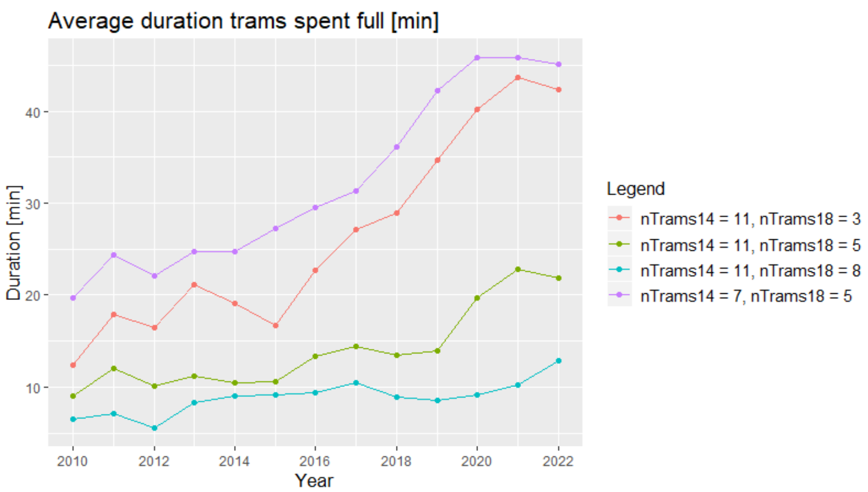

Fig. 7 Tram statistics for all four scenarios: average duration spent full.

4.3.2 Discussion

Reducing tram offer bears drastic impacts on average journey length. While most commuters are barely affected by these changes, some commuters spend an unreasonably high amount of time waiting for a suitable tram (up to 3 hours). When compared with the sharp increase in duration tram vehicles spend full with respect to the normal situation, it can inferred that these commuters keep on encountering full trams and cannot pursue their journey further. In these situations, the public transportation offer is insufficient and some passengers have to wait for a tram that is not at maximum capacity.

Steady increases after the year 2016 can be correlated with the map on Figure 2 and the construction of the Les Vergers district, which provided the system with a large influx of commuters on line 18's axis. This increased pressure can be dampened by increasing the offer on line 18.

4.4 Contextualisation of results

To place these experimental results into context, we asked the TPG (*Transports Publics Genevois*) for timetables of lines 14 and 18 from 2011 to 2023. Number of departures from Cornavin to *Meyrin-Gravière*/CERN are collated, and results are presented in Figure 8. Full dataset is included in the supplementary materials.

Contrary to what could be expected with the establishment of the *Les Vergers* eco-district in 2016, which would increase the demand for trams along the Cornavin-CERN axis, a notable decrease in line 14 and 18 offer can be observed for the years 2016 to 2018. One possible hypothesis for this surprising behavior is the effect of construction works on the line, namely the establishment of a new storage hangar for public transportation vehicles near the stop *Jardin-Alpin-Vivarium*, called the *Dépôt En Chardon*. Works of this magnitude could force a decrease in public transportation offer on this axis.

Some additional insight can be gleaned from the exploration and analysis of ridership data. TPG offers an open data platform for counts of boarding and disembarking passengers aboard their vehicles[8]. Unfortunately, the dataset is not able to go back far enough in time, with the earliest records dated 2019, whereas our study focused on the years 2010-2023. Nevertheless, the platform can still be used to appreciate the overall trend over the past three years. A full analysis of this dataset is beyond the scope of this study, however, we provide a quick methodology guide for navigating the ridership dataset on the platform. Data can be filtered and useful graphs can be generated on-the-fly.

On the left of the page, a multitude of filters are available. We select our lines of interest (14 and 18), weekdays (*1-Lundi* to *5-Vendredi*), normal schedule type and our stop of interest. Examples include CERN, *Meyrin-Gravière* (terminal stations) or *Hôpital-La-Tour* (stop closest to the *Les Vergers* eco-district). Then, we identify which stop is facing which direction. This information is recorded in the "Long Code Stop" column, as a 4-letter stop identifier and '00', '01' or '02' appended. For stops close to a terminal station (such as *Hôpital-La-Tour*, which is close to CERN), the stop

[8] https://opendata.tpg.ch/

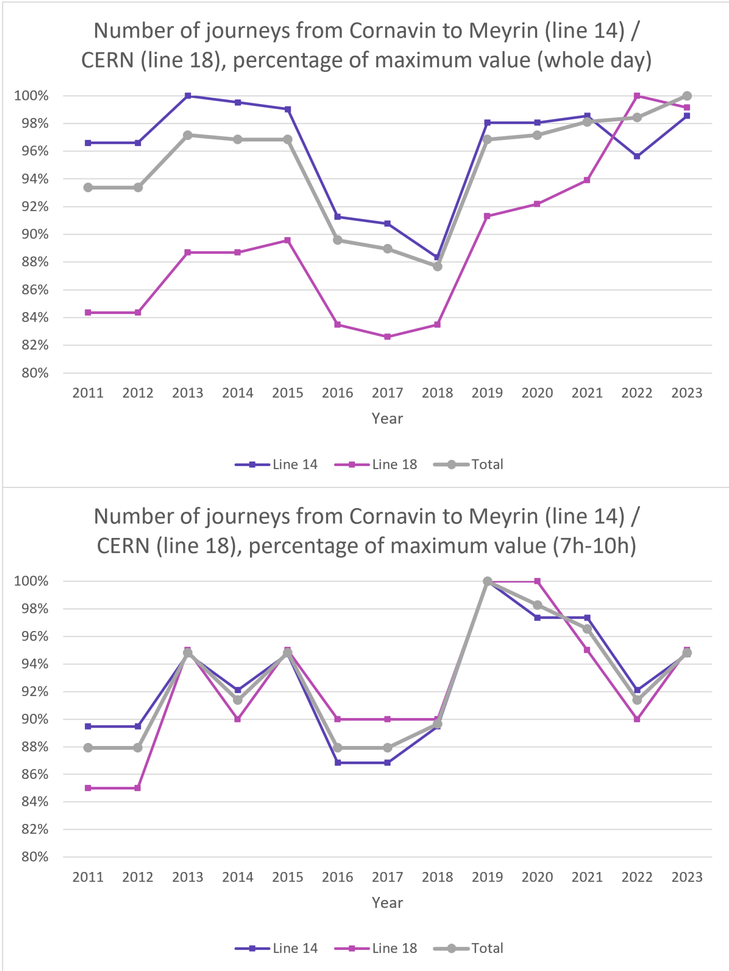

Fig. 8 Number of departures from Cornavin to *Meyrin-Gravière* (line 14) and CERN (line 18), expressed in percentage of highest value. Whole day (top) and morning peak hours (7h - 10h, bottom).

serviced by trams going towards the close terminal station will see a larger amount of disembarking passengers than boarding passengers, and vice versa. We finally select our "Long Code Stop" of '00', '01' or '02', based on this information, and turn our attention to the "Analyze" tab. Here, a time series graph will be generated on-the-fly based on the filtered data we have selected in the "Table" tab.

Such visualisation of data (see Figure 9 for an example) for lines 14 and 18, at terminal stops *Meyrin-Gravière* and CERN, as well as lines 64 and 68, which ensure a connection of, respectively, tram lines 14 and 18 terminal stations, with neighbouring French villages, indicate an increase in ridership over the years 2020 to 2023, of which intensity differs from one line to another.

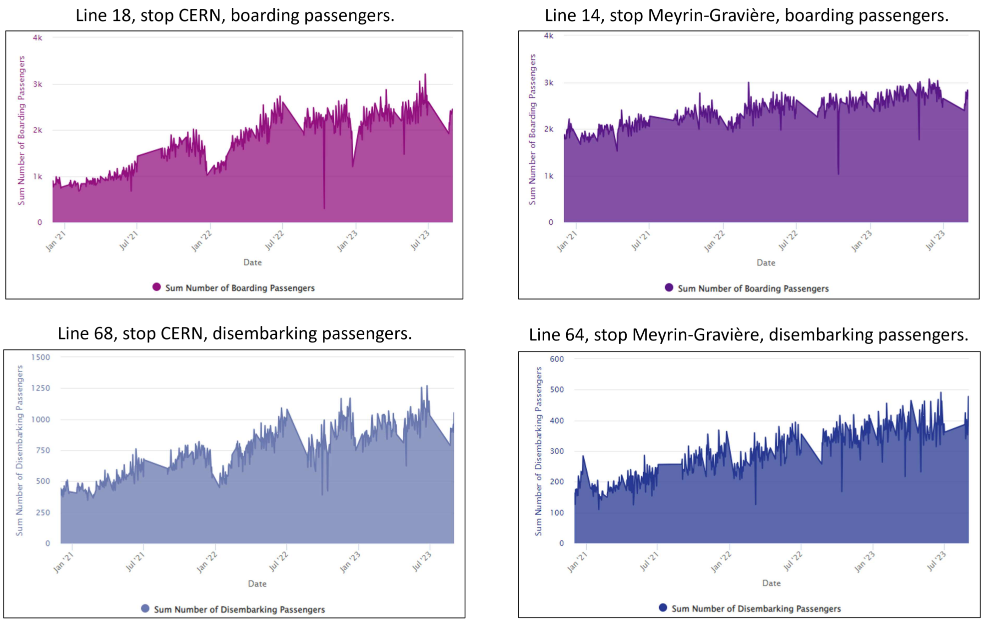

Fig. 9 Ridership graphs of lines 18 and 14 at their northmost terminal stations, towards Geneva center, as well as their associated extension bus lines incoming from neighboring France, respectively lines 68 and 64. Generated by TPG open data platform (https://opendata.tpg.ch/), on October 3, 2023, x-axis date range: December 1, 2020 to August 31, 2023.

5 Conclusion

5.1 Discussion summary

In this paper, we continued the works presented in the first published article about the Cornavin-Meyrin-CERN axis model [8]. We explained in more detail the model's inner workings, outlined a methodology to replicate and transfer the model to other use cases, and provided some results to analyse and discuss. We performed experiments on the model, by decreasing or increasing the public transportation offer along this high-capacity axis. With our given initial parameters and hypotheses, our main findings are the sharp increase in journey length for a portion of commuters when public transportation offer is decreased, which can be correlated with more overcrowded trams during rush hours. Increasing tram offer will also decrease average journey length and, in the case of line 18, dampen the pressure caused by the establishment of the Les Vergers eco-district, towards the north-western end of line 18.

5.2 Future works

Future improvements to the model could include running batch simulations to eliminate random aspects of the model discussed in section 4.2. Validation steps also need to be fleshed out by searching for more suitable datasets and establishing a sound protocol. This validation will enable the model to formulate more accurate predictions about the system. An example of an interesting addition to the model is the incorporation of a government-level decision making agent, who decides where to build what type of buildings and when to establish new public transportation axes, either spontaneously or in response to an increasing demand by the commuters.

In the scope of the TRACES project for modelling Environmental Trajectories of Territories, a new model is being developed by the authors and will be applied to the whole canton of Geneva. The model's evolution rules will be based on the DPSIR framework, and simulations will strive to recreate urban expansion and land cover changes associated phenomena. The above possible improvements will be applied to this new model.

Supplementary materials. All supplementary materials can be perused freely on the following gitlab repository: https://gitlab.unige.ch/cas/ANS_TCMC_ABM

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