Modelling and Multi-agent Simulation of Urban Road Network

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Abstract. In many African cities, there is a constant increase in road network usage, while we notice an absence of proper means of traffic regulation. Decision-makers should make decisions about road network improvement to ease the management and availability of the road network. They must consider the smart city's concept because of its features that will enable smart mobility. The most popular and tedious method to provide mobility data is the traditional traffic count, which is used in many cities. However, this method does not make it possible to assess mobility according to travel scenarios and requires significant financial and human resources compared to a computer simulations-based way.

We propose, a simulation tool based on multi-agent technology to facilitate the testing of mobility scenarios and to help in decision-making about traffic regulation. The tool we designed has been applied to the city of Cotonou to simulate mobility and to have a fully functional representation of the existing road network. This virtual representation can help to identify the key metrics decision-makers can leverage to improve the traffic and get an insight into the city road network. To test it, we simulated the traffic by considering a travel scenario: the home-work journey of the citizens of Cotonou. The results help in decisions making to improve mobility under this scenario. Even though our example is applied to the city of Cotonou, our model from its design is flexible enough to support the peculiarity of African cities.

Keywords: Smart mobility · Multi-agent system · Road network simulation

1 Introduction

According to the World Bank report [9], African cities are getting increasingly crowded. This increase in the city's inhabitants requires better infrastructure management in different sectors such as transport, energy, finance, and governance. The concept of smart cities offers a framework for improvement in each

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of those sectors, promising a better and sustainable use of the existing resources to of the quality of life and even a reduced impact on the environment.

To improve transportation by following some features of smart mobility, avoiding traffic jams, and optimizing the usage of the infrastructures involved in transport, the takers of the rules must have a deep understanding of the traffic. This understanding can be made available using one MAS application field: simulation. However, it requires knowledge of the existing traffic and a MAS model that is extensible enough to represent of the actual traffic scenarios. With a good model and good modelling of the existing transportation system, we can predict a city's transportation needs and its inhabitant's behaviour toward the transportation infrastructure for each transportation activity. Unfortunately, the current MAS transport simulation models are not extensive enough or not built to account for the quirks of transportation in African cities.

The motivation for our work is the difficulty of foreseeing the impacts of regulatory policies on the current mobility of cities like Cotonou. The lack of good regulatory policies and road congestion strongly impact the economy of countries. Also, most of the software that helps measure the impact of mobility regulation policies needs to be adapted to the singular mobility in cities like Cotonou.

In our work, we set up a multi-agents system model, which makes it possible to describe the traffic in the city of Cotonou. We have considered the unique features of mobility in a town like Cotonou. To show the feasibility of our system, we set up a simulation considering a simple scenario which can serve as a basis for setting up other scenarios.

Our paper is organized as follows. The Sect. 3 presents our approach to designing a MAS model targeted toward the transportation simulation through data gathering and the model's design. We dedicate Sect. 4 to implementing our system with the MAS simulation framework GAMA. We discuss the result of our experiment modelling the commute in Cotonou in Sect. 5 and conclude in Sect. 6.

2 Related Work

A remarkable amount of work has been done in the field of traffic simulation, either using agent-based models or using finite state machines. We focus on multi-agents systems because of their ability to model complex systems, especially for traffic simulation.

For example, Transim [14] began in 1995 intending to provide a software suite that uses simulation to set up a realistic environment for analyzing regional transportation. Transim [14] uses an activity-based approach and microscopically simulates traffic. That is, it considers the individual behavior of vehicles and their local interaction. The activity-based method [8] associates trips with a need and a reason. It also allows for the analysis of the reasons for travel in the event of congestion. Transim [14] does not allow motorcycle cab drivers or street vendors. Its major problem is that it is no longer maintained.

In 2013, the authors of the work [15] created a traveller mobility simulation tool to help understand and predict road network usage. In order to archive this, they multi-agents systems consists of three main components:

- Planner Agent
- Car Agent
- TravelerAgent
- Public Transport Vehicle Agent
- Itinerary Monitoring Agent

It uses a multi-agents approach but does not model motorcycle cab drivers and the entire ecosystem around them.

Like our study, the paper [7] aims to provide a decision-support tool. To operate, the simulator takes as input data describing:

- the public transport network
- the possible stops
- the pedestrian network (roads that can be taken)
- the displacement model
- traveler profiles

However the initial motivation and aim of this study differ from our aim in that the authors were interested in the impact of real-time information provision on the quality of transit trips.

The objective of the work [11] is to provide a decision-support tool to help better study the impact of regulatory decisions. However, the paper did not address some aspects of the possible scenarios. For example, the article does not offer the possibility of adding a road to the transport network or modelling the transport encountered in Cotonou. Also, the research did not consider the ecological impacts of preparing a framework for intelligent mobility.

3 Methodology

3.1 Data Gathering

The mobility of the citizen of Cotonou and more generally west African cities is different from that of developed countries. It is mainly characterized by a high presence of motorcycles for mobility demand, instead of taxi-car. To create a model of such a mobility schema, we gathered data from the ministry in charge of transport in Benin (MIT). The data we collected consists of the following:

- The road network map of Cotonou
- The reason for travelling inside the city
- The number of motorcycles, cars, and other vehicles grouped because of travel
- The driving behavior of the drivers

The road network is GIS data that can be visualized as a map, as shown in Fig. 5.

All the other data we collected are road usage stats, which help us understand the Driver's behaviour, the reason for the travel and the expected travel scenarios in Cotonou. Understanding how the inhabitant of Cotonou handles mobility is essential to providing a model that can describe transport.

3.2 Design

Like other modelling paradigms, a multi-agent based system, has its own methodologies, tools, and framework to help the modeler in his task. Through the MUC-CMAS [10] methodology comparison framework and the comparison work in the paper [3], we compared four multi-agent based methodologies according to the needs of our target domain, transport system modelling. We compared Gaia [5,6], Mase [1]]), Passi [4] and Prometheus [2] through the different criteria in Table 1.

Table 1. Comparison of SMA methodologies

Criterion	Methodology			
	Gaia	Prometheus	Passi	Mase
Easy identification of modelling phases	Yes	Yes	Yes	Yes
Top-down method	Yes	No	No	No
Requirements specification phase	Yes	Yes	Yes	Yes
Model reusability	Yes	Yes	Yes	Yes
Graphical representation of models	Yes	Yes	Yes	Yes
Autonomy and heterogeneity of agents	Yes	Yes	Yes	Yes
Mobility of agents	Yes	No	Yes	Yes
Representation of organisation	Yes	Yes	Yes	Yes
Modelling of communication types and communication channel	Yes	Yes	Yes	Yes
Comprehensive documentation	Yes	No	Yes	Yes

The criteria are selected based on the requirements of travel modelling. We need to represent mobile, heterogeneous and collaborative agents in such a system. Gaia [5,6] is a methodology that suits such a system well. In the Gaia methodology [5,6] specifications, the analysis phase following the requirement's definition should be characterized by two abstracts models:

- System roles specification through the role model
- System interaction specification through the interaction model

a. Role and interaction model – The role model helps to identify the different features of the agents that should be represented in the system, while the interaction model help to describe how the different role communicate to perform the global system task. Figure 1 shows the different roles that are useful for our system and how the different roles communicate to achieve the global system task.

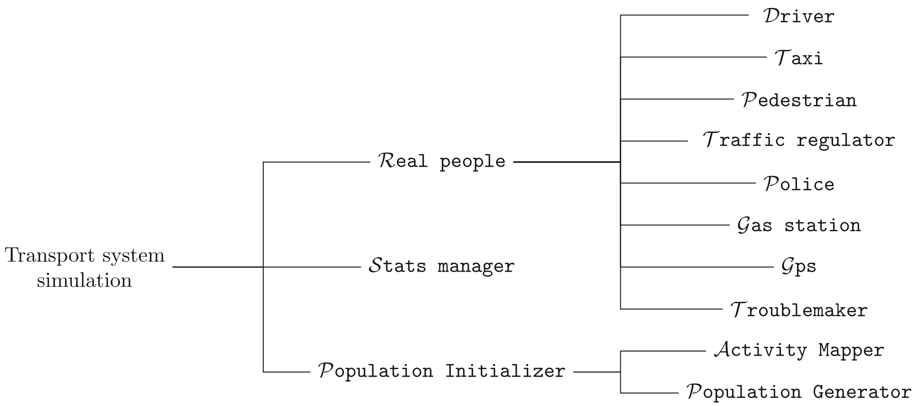

Fig. 1. Role hierarchy of our system

To be able to simulate a transportation system, our model should consist of some roles such as:

Drivers: This role is to represent those that drive. There is a vehicle that will be used on their journey.

Taxi: This role helps outline drivers that make a business from their trips. It can be for public or private transportation. Any vehicle used to help anyone on a trip is part of the Taxi role.

Traffic regulator: In current transportation systems, the drivers and all the transport actors are managed by a centralized or decentralized entity. This entity can either consist of passive objects, such as road signs, or active tools, such as the traffic light system or police officers in some situations. This represents those actors that are part of the traffic regulation.

Police officers: in addition to the standard traffic regulation, police officers are entitled to enforce the respect of the traffic regulations by performing further arbitrary control on the drivers. We represent their actions through this role.

Gas and fuel station: Most vehicle engines are either gas or fuel powered. Those essential products must be available for the drivers before and during a trip. Here come the gas or fuel stations. Even though Cotonou vehicles are powered by fuel, we present both possibilities through the gas and fuel station.

GPS role: When a traveller does not know about his travel destination, he uses GPS to find the best itinerary, or requests help from pedestrians or people around him during his travel. Those people are represented in our system with their role named GPS.

Pedestrians: This role consists of those that should request taxi services to perform their travel.

Troublemaker: In the traffic of cities such as Cotonou, many external actors are involved in the disorder that causes traffic trouble. This role is the representation of that reality in our systems.

Apart from the roles that help represent real traffic scenarios, we need some meta roles to help us collect stats about what is happening in the simulation and determine from the actual date which agent should be created. The meta-role **Stat manager** in our role model is responsible for data collection in the system. On the other hand, the meta-role **Population generator** is responsible for creating an agent from actual data of real-world traffic. To efficiently implement the feature of agent generation, we divided the latest meta-role into two meta-roles:

– As its name suggests, the activity scheduling mapper assigning activities to the agents. Activity means to travel and planning reasons.
– Population generator, which is the one that should create the agents and add them to our simulator. It determines which agent should be created and added to the running simulation.

Table 2. *Liveness properties* operators

Operator	Description
$x.y$	x followed by y
$x\|y$	x where y happen
$x*$	x happen 0 or more time
$x+$	x happen 1 or more time
x^{ω}	x happen infinitely
$[x]$	x is optional
$x\|\|y$	x and y happen simultaneously

The Gaia methodology [5,6] requires us to describe a role using a formal template. The template comprises the role description, permissions, protocols, activities and responsibilities. Approval for a role represents the different resources the role should access to accomplish its responsibilities. Responsibility is a function of the role, an accomplishment expected from the role's presence in the system. There are two categories of responsibility, responsibilities that define a constraint on the behaviour of a role (Safety properties) and those that specify the functions of a role (Liveness properties). A Liveness properties type responsibility comprises "activities" or "protocols". An activity is a task that does not require interaction or cooperation with the other roles of the system. At the same time, a protocol is a task that involves negotiation with different roles in the system to be completed. In the Gaia methodology [5,6], we represent a responsibility of the Liveness properties type as a composition of the activities and protocols with the operators illustrated in Table 2. For simplicity, we will describe only the interaction model behind the Driver role. Those interactions are shown in Fig. 2.

Role: $\mathcal{D}$river

Description :
The $\mathcal{D}$river represents a person who carries out travel activities in real life. He has daily activities to carry out.

Protocols :
AskForPath, NegotiateGasPrice, LookForParking, ProduceStats

Activities :
ToMove, LookForGasStation, ToPark, CollectLocalStats

Permissions :
HaveActivities, UseFuel, UseRoads

Responsabilities :
Liveness properties:
$\mathcal{D}\texttt{river} = (\texttt{ToMove}.(\texttt{LookForGasStation}.\texttt{NegotiateGasPrice})^*.\texttt{AskForPath}^*.(\texttt{LookForParking}.\texttt{ToPark})^*.\texttt{CollectLocalStats}.\texttt{ProduceStats})^\omega$
Safety properties:
LimitedSetOfActivities, $Fuelquantity > 0, Money > 0$

Fig. 2. Description of the role **driver**

A driver interacts with other system roles by buying fuel into his vehicle, asking where he should park, his destination to the GPS role, and producing data about his travel. That is what we represent in the protocols of the role of Driver. In some scenarios, such as purely driving, he does not need to interact with other roles or when he searches for a gas station. The activities listed in Fig. 2 represent those tasks. However, like approval, the Driver needs to be able to use the roads or to have some activities and finally use fuel. The liveness responsibility sums up well what is expected from a driver role in our model.

b. Agent model – After planning to describe the abstract models that are part of our systems, he comes up with a concrete model that we can extract from them (Fig. 3).

In reality, there is more than one type of Taxi driver in Cotonou, those that use a car, motorcycle or bus. Hence, three different agent types Motorcycle-TaxiAgent, BusTaxiAgent and CarTaxiAgent. In addition, a PedestrianAgent is made of a Pedestrian role, Gps role and Troublemaker role. This helps to represent the scenarios in which they can be involved. As with the Taxi role, there is more than one type of gas station in Cotonou. We have legal gas stations and illegal ones in the city. That's why we define two agent types for the Gas station role. Police officers serve as traffic regulators and their traditional police role, such as a checking of the Driver's activities. We have only one type of agent for each meta-role: PopulationGeneratorAgent, ActivityMapperAgent, and StatManagerAgent.

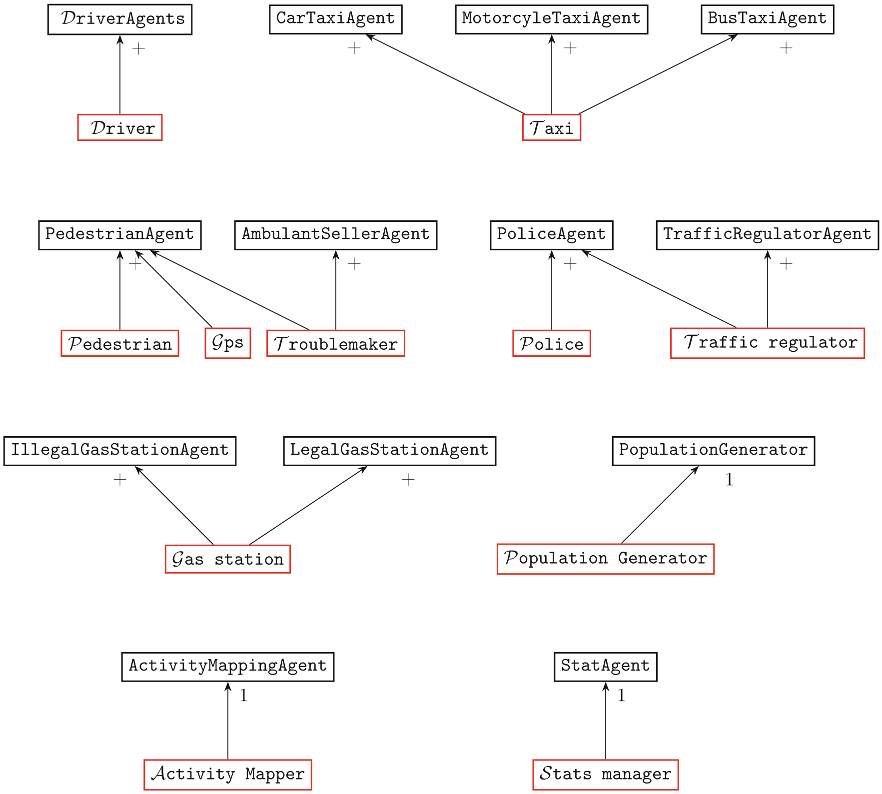

Fig. 3. Agent model: Roles are bordered by a red rectangle while a black rectangle borders Agent Types. (Color figure online)

4 Implementation

Table 3. Comparison of simulation tools

Features	Specialized tools		Generic tools	
	MATSim	MITSimlab	GAMA	Repast Symphony
Can model agent	Yes	Yes	Yes	Yes
Can model agent organisation	-	-	Yes	Yes
Can model agent environnement	-	-	Yes	Yes
Can model interactions	-	-	Yes	Yes
Open source	Yes	Yes	Yes	Yes
Comprehensive documentation	Yes	Yes	Yes	Yes
Community	Yes	No	Yes	Yes
Urban mobility	Yes	-	Yes	Yes

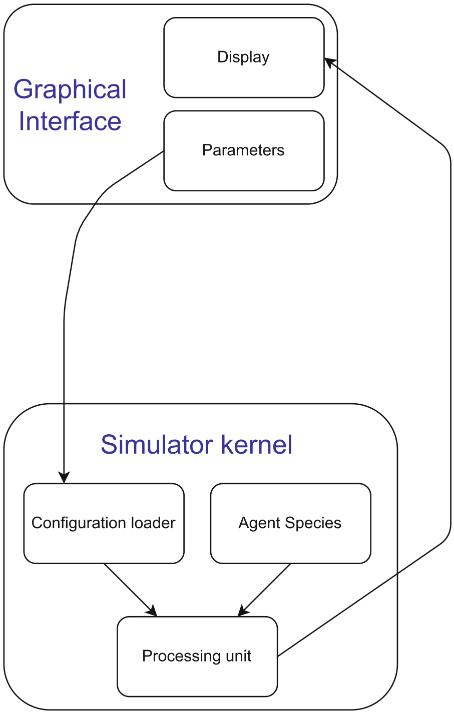

Fig. 4. Our system architecture

Our simulator is made up of two main modules (Fig. 4). The interface which allows the user to interact with our simulator and the kernel of our simulator, which is responsible for interpreting queries, is provided via the graphical interface (Fig. 5). The simulation kernel consists of a configuration loader which reads the data about the environment that should be simulated. In our case, we need a map of Cotonou city described in a Shapefile format and data relating to the Driver's behaviour. The Agent Species module is the actual definition of the agents we discussed earlier. At the same time, the processing unit is responsible for creating the environment, the agents of the environment, the roads, and the buildings.

For our implementation, we used GAMA [12,13], a simulation platform that made it easy to implement spatial agent-based simulation. In addition, to be convenient for mobility-driven multi-agent systems, it is open source and well documented. We made an initial benchmark of pertinent simulation tools in Table 3.

To test the operation of our model, we represented using our simulator a scenario in which we simulated the commute of the residents of Cotonou. For example, a DriverAgent in our method starts a day at 6 a.m. and ends at 9 p.m, travels to work, and then returns home. This scenario, even though it seems simple, allows us to represent an activity which constitutes an essential part of the reasons for travel in the city of Cotonou.

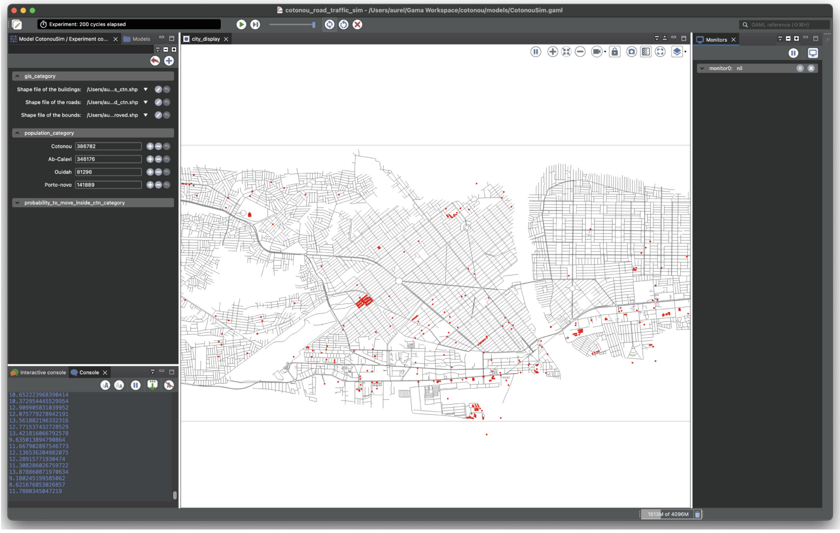

Fig. 5. Simulator overview

In figure Fig. 5, you can see how the GAMA [12,13] simulator interface is represented.

The left side shows the configuration (Fig. 6) panel that should be used to change the simulation parameters. On the right side, we have the variables that describe the state of the simulation. This module is configured to display the current date inside our simulated environment. Our implementation with GAMA [12,13] allows us to run the simulation and collect data about the running system. We discuss the results in the next section.

5 Results and Discussion

Our simulation consists of 10000 drivers agents, with both car and motorcycle drivers. It's the average number of Drivers for the scenario we plan to run. From the data that we have collected from the ministry in charge of transport in Benin (MIT), we have the different reasons for travel within the city as well as the statistics related to these reasons. These statistics contain the destinations of drivers for each reason and their itinerary. After analyzing these data, we can assume that 10000 drivers for the home journey scenario is a representative number of drivers.

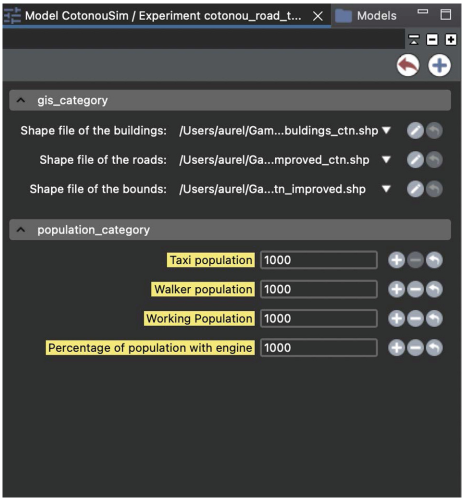

Fig. 6. Simulator configuration panel

The agents used in our scenario are the Drivers, the Police Agents. Roads and Buildings are some artefacts for the simulation. The Drivers represent the inhabitants of Cotonou that are going to work or coming back home.

Fig. 7. Running simulation

In Fig. 7, we have an overview of the simulation which represents a complete map of the road network of the city of Cotonou and its division into two large pieces connected by three bridges. The road free spaces are uninhabited places, either because it is a lake, a lowland or an area prohibited from traffic such as Cotonou airport located in the southwest of the figure.

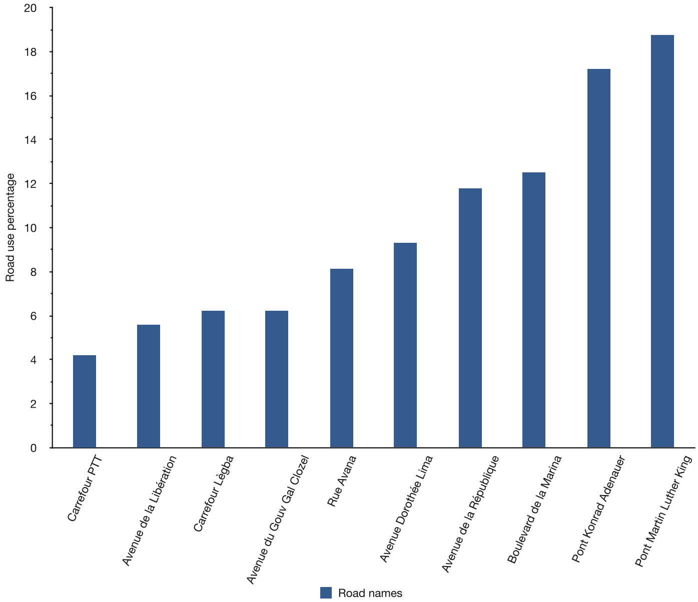

Fig. 8. Most used roads

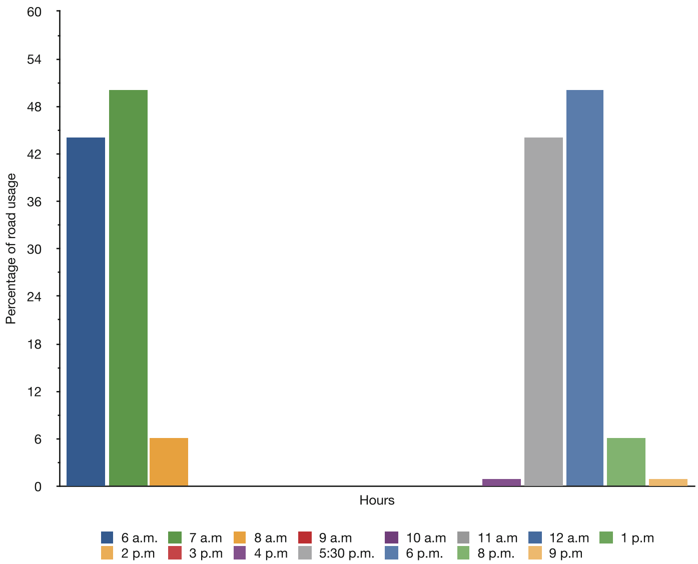

Fig. 9. Road usage per hour

In the simulation perspective, the blue trails represent the commuting drivers, while the red dots represent the buildings that are their final destinations. The building points are placed according to the traffic data we collected from the MIT and the drivers are placed in such a way that they represent the observations we made.

This figure provides an interactive and real-time display of the running simulation. It helps to visualize, at a high scale, the transportation network of the whole city. Even though this kind of data is not as detailed enough as the data we gathered, it helps the viewer to see the traffic behaviour on a large scale.

For example, we can notice the traffic density on two of the bridges that connect the two parts of the city. Those bridges help to connect two densely populated areas of Cotonou, where either the population is heading to one side or the other. A moment before the traffic is dense on the bridge, the traffic is dense on one of the main traffic roundabout in the city: the roundabout of *Etoile Rouge*.

This figure is a good example of visualizing the traffic density on a large scale, before we go into more details about the traffic density on a smaller scale. Such information is useful for a quick insight into the traffic behaviour and represents a good starting point for further analysis.

While the simulation was running, we collected data about the traffic behaviour using the GAMA [12,13] platform built-in data collection tools. A csv file that dumps all the events that happened during the simulation was generated. With the help of the Python programming language, we were able to extract the data from the csv file and process it to get the data we needed The result of this processing is two useful graphs that help to understand the traffic behaviour in Cotonou. The first one Fig. 8 shows the most used roads in the city whereas the second one Fig. 9 shows the road usage per hour of the day.

As you can see in Fig. 8 the most used roads are the ones that connect the two parts of the city together and the main road that goes through the city. This result is coherent with the hypothesis made in [16], that the high density in traffic faced by the city is due to its geographical aspect, which increase the mean time to reach the city center from the outskirts. In addition, the most used roads are the ones that are the most convenient to use, as they are the shortest and the most direct routes to reach the city center.

The interests of having such data combined are multiple:

1. First, it helps to understand the traffic behaviour in the city especially for having a deeper understanding of the traffic density on the most used roads and having a better understanding of the traffic density on the bridges.
2. Second, it helps to plan the road network in the city according to specific improvement needs. For example, if the goal of the regulatory authority is to reduce traffic density on the bridge for the workers, it can be done by designing or improving the existing roads to be suitable for the workers. Not only this decision will help to reduce the traffic density for this scenario, but it can also be used to reduce the traffic density for other scenarios such as the school journey scenario or even reduce the carbon footprint of the city. Reducing the footprint of a city is one of the axis of improvement required by smart cities concept.

3. Third, it helps to reduce the humain workload, and error generated by the current traditional data collection methods.

As we can see in Fig. 9, the traffic density is the highest during the morning and evening rush hours. A couple of hours before 8 a.m, which is the conventional office opening hour, the traffic density is increasing. This is due to the fact that drivers are leaving their homes to work and some are aware of the traffic density and leave earlier to avoid the traffic. The traffic density is also increasing a couple of hours before 5 p.m, which is the conventional office closing hour. We can clearly see that, because the workers are at work, there is almost no traffic during the work hours (8 a.m to 5 p.m).

The availability of such data is very useful for regulatory authorities in many ways. For example, this simple information can help to know at which hours the traffic density is almost zero, and that road maintenance can be done during this time. A more useful use cas of this information is to know at which hours the emergency vehicles and services can use the roads without being stuck in traffic. Such information are interesting when planning the economic activities of the city, especially when it comes to the transportation of goods, people.

Both graphs in Fig. 9 and Fig. 8 help us understand the road usage of the network in this scenario. One of the main aspect of the simulation is the reusability of the model and the ability to have an overview of the traffic scenario. Multiple scenarios can be run on the same model, and the results can be compared to each other, and to the real life data to gain a valuable insight into the traffic behaviour of the city.

6 Conclusion and Future Work

In this paper, we have described a MAS model that helps to represent traffic in cities like Cotonou. We used the well-known MAS methodology GAIA to ease the modelling process. The model we created has been implemented and used in the simulator we created based on GAMA. The simulation outcome gives some understanding of the different scenario traffic. We simulate Cotonou inhabitant's commutes, and we have been able to gather data related to road usage and traffic jam hours. The data we collected are just a few amounts of what is possible.

Our work is original, as we designed a model specifically to target the traffic in west African cities (taking data from Cotonou). Due to the peculiarity of their inhabitant mobilities, the African cities require a traffic model designed explicitly for them. Because it is built with that problem at its core, our model is generic enough to be extended and adapted for other kinds of mobility.

In future works, we plan to simulate more complex scenarios with our simulator and optimize the performance. For example, we could represent shopping activity and leisure of citizens along with the homework to evaluate the interrelation between those reasons for travel. In addition, we are planning with the ministry in charge of transport to make it commercial-ready and available for use by enterprises.

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