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Analyzing Urban Mobility Carbon Footprint with Large-scale, Agent-based Simulation

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Abstract: The growth of cities around the world bring new challenges to urban management and planning. Tools, such as simulators, can help the decision-making process by enabling the understanding of the current situation of the city and comparison of multiple scenarios with regard to changes in the urban infrastructure and in public policy. This paper presents an analysis of mobility parameters, such as distance, cost, travel time, and carbon footprint, for different simulated scenarios in a large metropolis in a developing country. We simulated the scenarios using an open source, large-scale, agent-based Smart City simulator that we developed.

1 INTRODUCTION

Most large cities around the world, especially in developing countries, have significant problems with regard to the mobility of their inhabitants; normally, the low-income populations in underprivileged neighbourhoods are the ones that suffer the most. A valid approach to tackle this problem is the idea of Smart Cities, that proposes, among other things, the use of Information and Communication Technologies (ICT) to improve the quality of life and sustainability in cities.

On the one hand, intelligent information systems working in conjunction with the city infrastructure can provide applications based on the collection and analysis of real-time data offering services to the population and city servants to mitigate mobility difficulties. On the other hand, planning and decision-support tools can help city managers take better decisions in the long run and design more effective public policies. Simulators can be a valuable tool for understanding the behavior of the city and analyzing the impact of changes in the city infrastructure and public policies.

A simulation can show to city planners the behaviour and dynamics of the city in different hypothetical scenarios. For example, a servant working in the Transportation Secretariat could simulate the impact of building different subway lines across the city or the impact of locating subway stations in different places. A servant working in the Health Secretariat could simulate the impact of changing the medical specialties offered in a certain city hospital. Well-designed simulations can be instrumental in planning changes in the mobility infrastructure and in government actions, enabling informed decision-making.

The work presented here involves a case study in using a large-scale, agent-based traffic simulator to analyze the impact of a new subway line under construction in São Paulo, Brazil. We examined four simulated scenarios based on an origin-destination survey and compared their travel time, financial cost, and carbon footprint of the simulated population. We based all the scenarios on realistic changes that might occur with the new subway line. In this study, we considered the inhabitants of a large slum in the city that will be potentially benefited by this new subway line.

We chose to compare the travel time and cost, which can impact positively on the population quality of life. The carbon footprint can help the analyzes of the city sustainability, measuring the impact of each transportation mode. Normally, the carbon footprint is measured by the traveled distance multiplied by a constant number based on the transportation mode. After studying several carbon footprint models (Kenny and Gray, 2009), we choose one that is well-detailed (Chester and Horvath, 2008) and have already an implemented version (Shankari et al., 2014).

This paper is organized as follows. Section 2 presents related work in Smart Cities, Transportation, and Agent-Based Simulators. Section 3 describes the simulated scenarios and the data used in their modeling. Section 4 describes the tool used to simulate the scenarios. Section 5 presents the data collected and analyzed from the simulation, it also discusses the results of the analyses. Finally, Section 6 addresses our conclusions and future work.

2 RELATED WORK

We now present some of the most relevant work related to our research, separating them in the Smart Cities, Transportation, and Agent-Based Simulation areas.

2.1 Smart Cities

"Smart City" has been widely and variously defined. Some definitions exceed the software context, focusing only on social or business aspects. Regarding software systems, many authors describe a Smart City as the integration of social, physical, and IT infrastructures to improve the quality of city services (Caragliu et al., 2011). Other authors focus on a set of Information and Communication Technology (ICT) tools used to create an integrated Smart City environment (Santana et al., 2017a; Washburn et al., 2009).

(Giffinger et al., 2007) assert that a Smart City has six main dimensions: smart economy, smart people, smart governance, smart mobility, smart environment, and smart living. Many authors adopt this definition (Hernández-Muñoz et al., 2011). In our work, we focus on two dimensions: smart governance and smart mobility.

Smart Governance is related to a better management of cities by using tools to improve the planning of governmental initiatives such as modifications in the infrastructure and public policies. Smart Mobility is related to actions that facilitate the movement of the population within the city. Both dimensions can benefit from the use of simulators. For example, allowing the understanding of the current traffic conditions and the impacts of changes in the infrastructure and the behavior of citizens.

There are many works proposing tools to facilitate the management of Smart Mobility actions. For example, (Schnemann, 2011) presents a platform to simulate vehicular networks with Intelligent Transportation Systems (ITS), testing and experimenting with current and future mobility scenarios. (Benevolo et al., 2016) relate different smart mobility initiatives, including the use of tools to facilitate the planning, implementation, and evaluation of integrated mobility initiatives.

2.2 Transportation

The transportation systems in developing countries metropolis share several problems. Most of them are related to the sudden increase in the urban population, poor land use and transport policy, and relatively small investments in transport infrastructure (Pucher et al., 2005).

A common consequence of the poor public transport infrastructure is the mass migration to the motorized private transport, which is the root of other problems like traffic congestion, air pollution, and traffic accidents (Salon and Gulyani, 2010).

When it comes to slums in developing countries, all the problems are enlarged. According to (Carruthers et al., 2005), the main issues faced by low-income populations in developing countries are the long trips and travel times, lack of fare system integration, and lack of public transit supply in the outskirts of municipalities.

Mass public transport infrastructure like metro systems is rarely designed to serve low-income neighborhoods due to the need for subsidies to make fares cost-effective (Gwilliam, 2003). However, studies conducted by (Zegras, 2010), identified that higher urban density areas located close to metro stations are related to a lower number of kilometers traveled by vehicles, decreasing air pollution and, consequently, the carbon footprint.

The analysis of the impact of mass public transport infrastructure for the population with respect to travel distance, travel time, and air pollution is vital to anticipate if the investments are going to be effective, bringing real benefits to citizens. Agent-based simulation is one of the tools to help decision makers in this matter.

2.3 Agent-Based Traffic Simulation

Agent-Based simulation is widely used to model traffic scenarios (Bazzan and Klügl, 2014). An example is MATSim (Horni et al., 2016), a mesoscopic multi-agent traffic simulator. In this simulator, each person is modeled as an agent that can move around the city. MATSim uses a queue model to simulate the traffic using the flow and storage capacity of each link to calculate the speed of the vehicles. MATSim was used to simulate many city scenarios such as taxi optimization (Maciejewski and Nagel, 2013), freight traffic

(Zilske et al., 2012), and autonomous cars (Bischoff and Maciejewski, 2016).

SUMO (Behrisch et al., 2011) is a microscopic traffic simulator that also simulates each agent individually. The difference is that SUMO uses a Car-Following model (Tang et al., 2014) to simulate the traffic flow. In this simulation type, car speed is calculated considering the vehicles ahead. Usually, microscopic simulators are more detailed. However, they have a high computational cost and are not suitable for the simulation of a large metropolitan area with millions of agents.

(Song et al., 2017) present a mesoscopic traffic simulator based for GPUs (Graphical Processing Unit). Its aim is to use the processing power of GPUs to speed up the execution of large-scale traffic scenarios. The results presented in the paper showed a two times improvement in the execution time of the simulation compared to a standard C++ implementation of the simulator. However, the authors describe two main problems in using GPUs: the communication of the CPU and the GPU is a bottleneck to the simulation and the amount of memory of the GPU can significantly limit the size of the simulated scenario.

Many academic and city management projects use the simulators mentioned in this section. However, none of them is suitable for the simulation of an entire day of a large metropolis with several million users in multiple modes of transportation such as cars, subways, trains, buses, bicycles, and pedestrian. Therefore, in our work, we implemented a flexible and powerful smart city simulator, capable of simulating more than ten million agents using multimodal trips. This simulator will be presented in Section 4.

3 SCENARIO DESCRIPTION

The area of interest is Paraisópolis, a large slum in São Paulo with a population of approximately 50 thousand people. Besides several specific characteristics, this slum differs from others mainly because of its location. While most of the slums of the city are on the periphery, this one is located in a central area, making access to transport and other services less costly.

The mobility characteristics of the analyzed population is changing dramatically in the last decades. The motorization ratio is increasing rapidly. In 2007, the number of motorized trips was only 10%, while in 2011 it raised to 33%.

In the future, the mobility of the slum region might change with the governmental plan to build two new subway stations that are going to connect the slum to other four metro lines and several bus corridors of the city.

Due to the changes in the public transport offer in the next years, the importance of simulating transport scenarios considering different modal splits and its impacts in carbon footprint, travel time, and travel cost is essential to understand the implications of the new transport infrastructure.

3.1 Collected Data

We based our simulation in real data collected from different sources. The databases considered in the paper are:

- Origin-Destination (OD) Matrix derived from a survey conducted by the city subway company for the year 2007[1]
- Shapefile of the planned Subway Lines
- Map of the city based on OpenStreetMaps [2]
- Transit lines and stops for São Paulo

The origin-destination database provided the information of all the trips originated in the slum. Each trip has the origin, destination, travel mode, and start time. As the trips are the most important data for the simulation, we made a exploratory analyses of this data.

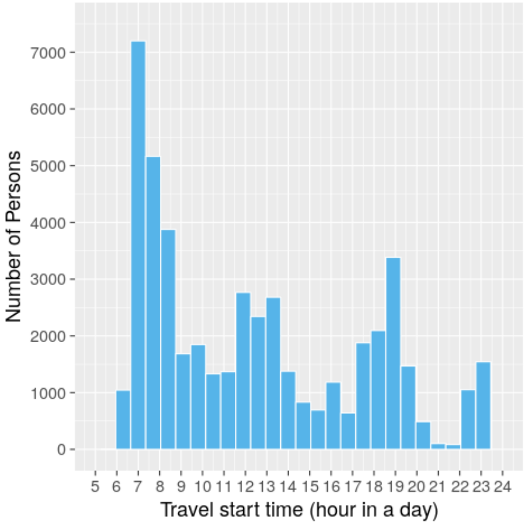

Figure 1: Travel Start Time

Figure 1 presents the distribution of the trips by the start time across the day. The figure shows that most of the trips occur in the morning, when people

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[1] Origin-Destination Survay - `http://goo.gl/Te2SX7`

[2] OpenStreetMap - https://www.openstreetmap.org

leave to work. Changing the morning trips from cars or buses to subway can improve the traffic and avoid the overcrowded buses. Also, there is a significant number of late night travels, the new line can benefit the bus users because the interval between the buses in the night are much larger than during the day.

3.2 Data Preparation

Based on the panorama described in the last section, we created four simulation scenarios to compare changes in the modal split considering the new proposed subway line. To create these scenarios, we changed the travel mode of the people that work and live near a metro station from bus or car to subway. The description of the new scenarios is the following:

Current Scenario: we used the current data of the OD matrix considering the travel mode, the start time of the travel, the origin, and the destination of each person. We used the current subway network of the city.

Replace Buses: we added the new line in the subway network of the city and changed the travel mode of the population that used buses in the OD matrix to subway if the person lives and works less than 500 meters from a subway station.

Replace Cars: we added the new line in the subway network of the city and changed the mode of transportation of all trips that use cars to subway if the person lives and works less than 500 meters from a subway station.

Replace Both: we combined the scenario 2 and 3, changing all the trips to subway if the person lives and works less than 500 meters from a subway station.

In all scenarios, we did not change the mode of the trips with less than 2 kilometers because it is unlikely that a person that has the origin and destination very close will use the subway. Table 1 presents the travel mode of all the simulated population. All the scenarios have the same population. Hence the total population is the same in all simulations, only the travel mode of a subset of the people changes from one scenario to the other.

Table 1 shows that, with the new line, 9877 people can change their transportation mode, 20% of the total. Of this people, 5004 are car users, indicating a potential to improve the traffic in the region and decrease the pollution emission. The other 4873 people are bus users, which can potentially reflect in a reduction of travel time and improvement of quality of life.

From Scenario 1 to Scenario 3 the number of bus lines required to serve the simulated population also reduced from 54 lines to 45, what can indicate that some lines can have their route changed or eliminated. We created this four scenarios to compare the impact of changing each travel mode and then the impact of changing all the potential population.

	Current Scenario	Replace Buses	Replace Cars	Replace Both
Car	8,867	8,867	3,863	3,863
Walk	21,373	21,373	21,373	21,373
Subway	168	5,041	5,172	10,045
Bus	17,785	12,912	17,785	12,912
Total	48,193	48,193	48,193	48,193

Table 1: Modal-split of the simulated population.

3.3 Simulation Research Questions

With the data collected from the simulation of the four scenarios, we can compare the different situations and compute several metrics to evaluate the impacts of changes in the modal split of the population. The research questions explored in the study are related to the impact of the new subway stations and subway line for the analyzed population with regard to travel time and travel cost and the impact in the city measured in terms of carbon footprint. The research questions are:

RQ1: "What is the impact of a new subway line in the travel time of its potential users?"

RQ2: "How the new line will impact the cost of the transportation to the population?"

RQ3: "If the potential users change its transportation mode, will it have an environmental impact?"

Section 5 will present the answers to these research questions based on the data from the simulation of the scenarios.

4 Simulation

In this section, we present our agent-based, smart city simulator, the execution of the scenarios presented in the previous section and a brief description of the results of the simulation.

4.1 Large-Scale Smart City Simulation

We developed InterSCSimulator, an open-source, scalable, mesoscopic, agent-based Smart City simulator capable of simulating millions of actors faster than real-time (Santana et al., 2017b). In previous experiments, we could simulate more than four million agents in a 24 hours simulation in approximately 3 hours. The current version of the simulator is capable of running single and multi-modal trips using cars, buses, subway, and pedestrian as the travel mode.

The simulator expects, as input, four XML files describing the simulated scenario. We create these files based on the databases described in Section 3.1, and we describe them in the following:

subway.xml defines the city subway system. In this file, each station is a vertex, and the connection of two stations are the links of the graph.

map.xml describes the city road network graph. In this file, each road stretch is a link, and the corners are the vertices of a graph. We used the map from Open Street Maps to generate this file.

buses.xml lists all the bus lines of the city. Each line must have a code, the time in which the service starts and ends, all its bus stops, and the inter-bus interval of the line.

trips.xml contains all the trips that must be simulated. The trips must have the time that it will start, the transportation mode, the origin, and the destination.

Listing 1 presents, as an example, a file with two trips that will be simulated, each one with a different transportation mode. In the file, there are two trips; in the first one, the travel mode is car, in the second, bus. When the travel mode is subway or bus, the person must walk from the origin to a bus stop or a subway station and then walk from another bus or subway station to the final destination.

Listing 1: XML file with examples of trips

```
<trip origin=”4197294783”
  destination=”28637975”
  start=”27601” mode=”car” />
<trip origin=”2197654483”
  destination=”284356975”
  start=”27651” mode=”walk” />
  <trip origin=”1740921857”
    destination=”1107272621”
    line=”8020−10−0” mode=”bus”/>
  <trip origin=”1107272621”
    destination=”304693626”
    mode=”walk”/>
</multi_trip>
```

In Listing 1, origin and destination are nodes in the city graph, start is the time that the agent must start its travel, mode is the travel mode of the agent, and line is the bus line that the agent will use. The simulator is generic and can work with the infrastructure of any city in the world, just requiring the generation of all input files of the simulator.

4.2 Scenario Execution

To analyze the impact of changes in the city infrastructure, we executed the four scenarios described in Section 3. We also created traffic in the city graph based on the complete OD matrix of the city; we simulated 1.2 million cars, which lead to realistic traffic conditions and, thus, realistic travel times for the car trips. We executed all the scenarios in a 24-core machine with 54 GB of memory in the Google Computing Engine[3], and all of them took less than one hour to execute an entire day in the city.

The agent execution depends on its mode of transportation. We describe the types of execution of each mode in the following:

Car: we start by computing the shortest path between the origin and destination and then make the agent traverse the city graph visiting all links of the calculated path. A density function is used to calculate the speed of the car in each link (Song et al., 2017) based on the number of vehicles (cars and buses) in the link in each instant.

Bus: traveling by bus, the agent walks to a bus stop and can take one or more buses until a bus stop close to its destination.

Subway: the agent walks to the nearest subway station; the subway trip duration is computed with the best path algorithm considering the travel time between the stations. After leaving the subway, the agent proceeds its journey by bus or walking.

Walk: the agent uses the same idea of the car trips, the difference is that the speed is approximately 4 Km/h.

The agents can also make multimodal trips, combining walking, bus, and subway. Using a car and another modal in a single trip is indeed possible. However, in the OD data that we have, there were no such cases. In addition to computing specific metrics defined by the user, the simulator can also present a graphical visualization of the simulation with the help of the MATSim OTFVis tool[4]. Figure 2 presents the

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[3] Google Computing Engine – http://cloud.google.com/compute/

[4] OTFVis – http://goo.gl/U8a87g

execution of the simulation in the city graph. The green points are agents moving across the city.

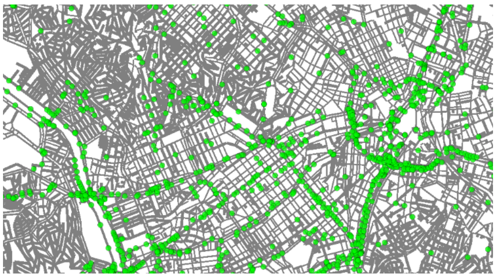

Figure 2: Simulation visualization

4.3 Results

The simulator saves an XML output file with all the agent actions. There are four possible actions: 1) When the agent starts its trip, 2) when the agent leaves a link, 3) when the agent enters a link, and 4) when the agent arrives to its final destination. All actions have the time, the location where it occurred, and the mode of transportation that the agent used. Listing 2 presents a sample output of the simulator with arrivals actions.

Listing 2: XML file with the output of the simulator

```
<event time=”22400” type=”arrival”
   person=”120” legMode=”walk”
   trip_time=”420” dist=”450”
   cost=”0”/>
<event time=”27860” type=”arrival”
   person=”122” legMode=”car”
   trip_time=”1820” dist=”4210”
   cost=”6.8”/>
<event time=”29504” type=”arrival”
   person=”123” legMode=”bus”
   trip_time=”1828” dist=”3500”
   cost=”3.8” />
```

When the agent arrives to its destination, the simulator computes the attributes of the trip such as total time, distance, and cost. This output can be used to generate the visualization of the simulation presented in Figure 2 and to make analyzes in a statistical tool such as R.

5 ANALYSIS AND DISCUSSION

We analyzed the change impact in three different perspectives: financial cost for the users, travel duration, and the carbon footprint. The objective of this analysis is to answer the research questions presented in Section 3.3.

To answer **RQ 1**, “What is the impact of a new subway line in the travel time of its potential users?”, we calculated the travel time for each person in all scenarios presented in Section 3. The time users spend on a trip directly impacts the users’ perception of the quality of the transportation system and quality of life. As Figure 3 presents, the travel time of most of the population decreased, mainly for the bus users (depicted in orange in Figure 3). For 4500 people, i.e., 90% of the people who changed from bus to subway, their travel time reduced significantly. For instance, 30.84% of buses users that started to use subway had an improvement up to 30 minutes. Moreover, 7.14% of these buses users improved their travel time for more than 2 hours.

From the population that used cars in the original scenario, approximately 1,500 had their travel times decreased and 4,000 had their travel times increased. The people that had their travel time increased by more than 30 minutes (around 2,000 people) are unlikely to change their travel mode. However, since the cost reduction can be very substantial (mainly when taking into consideration parking fees), even some of them might prefer the subway.

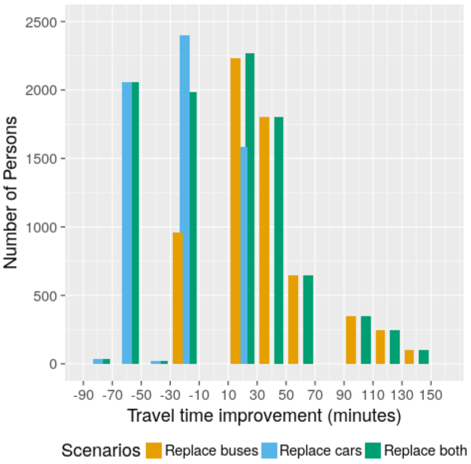

Figure 3: Travel time improvement

To answer **RQ 2**, “How the new line will impact the cost of the transportation to the population?”, We calculated the trip financial cost for each person in all scenarios presented in Section 3 since users usually want the cheapest option with a good travel condition. In our analysis, we took into account the car trip costs, as well as bus and subway fares. Using the OECD Purchasing power parities (PPP), the cost of the bus and subway fares was 1.9 USD and the car cost was 0.35 USD per kilometer.

As Figure 4 shows, the creation of this new subway line would reduce the cost for more than 2,500 people in the neighborhood that changed the mode of transportation from car to the subway. This is especially important because we are simulating a low-income community. The financial costs of trips made by bus or by subway did not change because the price of the two systems is the same in the analyzed city.

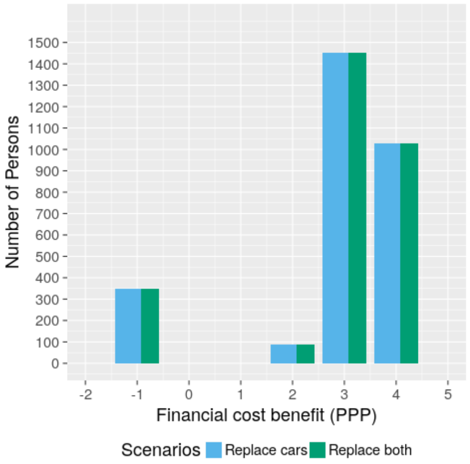

Figure 4: Financial cost benefit

To answer **RQ 3**, “If the potential users change its transportation mode, will it have an environmental impact?” we calculated the carbon footprint of each person in all scenarios presented in Section 3. The common baseline is that the carbon footprint stands for a certain amount of gaseous emissions that are relevant to climate change and associated with human production or consumption activities (Wiedmann and Minx, 2007). By analyzing Figure 5, we can notice that in the “Replace Both” scenario the carbon footprint would be reduced from 30,992 tons of CO_2 per year to 22,790, i.e., 26%. The reason that the change to the subway decreases the carbon footprint is that cars and buses emit over three times more CO_2 to the atmosphere than the subway.

In short, if the bus users start to use this new subway line, they would reduce their travel time and carbon footprint, while still paying the same fare. However, the car users would reduce their financial cost and carbon footprint but increase their travel time. Thus, with this new subway line, some of the bus users would definitely migrate to the subway because of the reduction in travel time. However, most car users would need to choose between a shorter travel time or a reduced financial cost. Indeed, decision makers should promote the usage of this new subway line, since it would decrease both the carbon footprint and the economic cost for the population as well as improve traffic in the region.

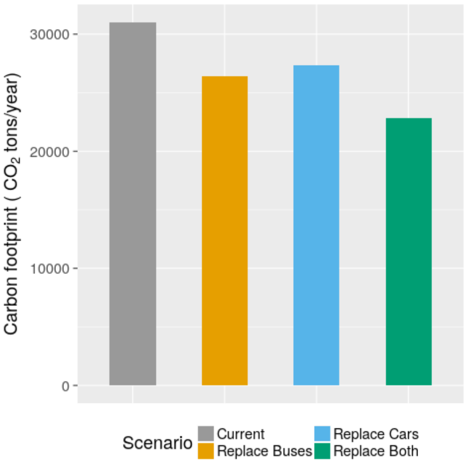

Figure 5: Accumulated Carbon Footprint

6 CONCLUSIONS AND FUTURE WORK

The growth of the cities around the world requires better planning and informed decisions to improve the citizen quality of life and optimize cities’ infrastructure. To achieve this, it is mandatory the use of tools, such as simulators, that facilitate the analysis and comparison of different alternative scenarios, leading to more effective public policies and governmental actions.

With the open source simulator we are now making available, a researcher or urban planner is capable of simulating millions of agents in an entire metropolitan area with multiple modal-splits. This simulator can now be applied to various fields such as mobility planning, comparison of potential interventions in the traffic, and measuring the impact of changes in the city infrastructure.

This paper showed that with a large-scale, smart city simulator, it is possible to analyze the impact of changes in the infrastructure of a large metropolis, with over 10 million people. We compared parameters, such as travel distance, time, and carbon footprint from the population of a slum using the current mobility infrastructure and possible scenarios with the new lines planned for the next years. The comparison of the simulation results showed many potential benefits from these modifications in the city infrastructure.

As future work, we plan to implement new transport modes in the simulator such as bicycle, car sharing, and taxis. We also intend to include new Smart City scenarios such as smart parking and garbage collection. Regarding the analyzes, we will analyze other areas in the city that also have planned very significant modifications in their infrastructure and compare the benefits of these adjustments.

To assure reproducibility of our results, the experimental package, including all source code, datasets, and scripts used in this paper is available at `http://interscity.org/software/interscsimulator`.

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REFERENCES

Bazzan, A. L. and Klügl, F. (2014). A review on agent-based technology for traffic and transportation. *The Knowledge Engineering Review*, 29(3):375–403.

Behrisch, M., Bieker, L., Erdmann, J., and Krajzewicz, D. (2011). Sumo–simulation of urban mobility: an overview. In *Proceedings of SIMUL 2011, The Third International Conference on Advances in System Simulation*. ThinkMind.

Benevolo, C., Dameri, R. P., and DAuria, B. (2016). Smart mobility in smart city. In *Empowering Organizations*, pages 13–28. Springer.

Bischoff, J. and Maciejewski, M. (2016). Simulation of city-wide replacement of private cars with autonomous taxis in berlin. *Procedia computer science*, 83:237–244.

Caragliu, A., Del Bo, C., and Nijkamp, P. (2011). Smart cities in europe. *Journal of urban technology*, 18(2):65–82.

Carruthers, R., Dick, M., and Saurkar, A. (2005). Affordability of public transport in developing countries.

Chester, M. and Horvath, A. (2008). Environmental life-cycle assessment of passenger transportation: a detailed methodology for energy, greenhouse gas and criteria pollutant inventories of automobiles, buses, light rail, heavy rail and air v. 2. *UC Berkeley Center for Future Urban Transport: A Volvo Center of Excellence*.

Giffinger, R., Fertner, C., Kramar, H., Kalasek, R., Pichler-Milanovic, N., and Meijers, E. (2007). Smart cities-ranking of european medium-sized cities. Rapport technique, Vienna Centre of Regional Science.

Gwilliam, K. (2003). Urban transport in developing countries. *Transport Reviews*, 23(2):197–216.

Hernández-Muñoz, J. M., Vercher, J. B., Muñoz, L., Galache, J. A., Presser, M., Gómez, L. A. H., and Pettersson, J. (2011). Smart cities at the forefront of the future internet. In *The Future Internet Assembly*, volume 6656, pages 447–462. Springer.

Horni, A., Nagel, K., and Axhausen, K. W. (2016). *The multi-agent transport simulation MATSim*. Ubiquity Press London.

Kenny, T. and Gray, N. (2009). Comparative performance of six carbon footprint models for use in ireland. *Environmental impact assessment review*, 29(1):1–6.

Maciejewski, M. and Nagel, K. (2013). Simulation and dynamic optimization of taxi services in matsim. *VSP Working Paper 13-0. TU Berlin, Transport Systems Planning and Transport Telematics, 2013*.

Pucher, J., Korattyswaropam, N., Mittal, N., and Ittyerah, N. (2005). Urban transport crisis in india. *Transport Policy*, 12(3):185–198.

Salon, D. and Gulyani, S. (2010). Mobility, poverty, and gender: travel choices of slum residents in nairobi, kenya. *Transport Reviews*, 30(5):641–657.

Santana, E. F. Z., Chaves, A. P., Gerosa, M. A., Kon, F., and Milojicic, D. S. (2017a). Software platforms for smart cities: Concepts, requirements, challenges, and a unified reference architecture. *ACM Computing Surveys*, 50(6):78:1–78:37.

Santana, E. F. Z., Lago, N., Kon, F., and Milojicic, D. S. (2017b). Interscsimulator: Large-scale traffic simulation in smart cities using erlang. *18th Workshop on Multi-agent-based Simulation*.

Schnemann, B. (2011). V2x simulation runtime infrastructure vsimrti: An assessment tool to design smart traffic management systems. *Computer Networks*, 55(14):3189 – 3198.

Shankari, K., Yin, M., Shanmugam, S., Culler, D. E., and Katz, R. H. (2014). E-mission: Automated transportation emission calculation using smart phones. Technical report, EECS Department, University of California, Berkeley.

Song, X., Xie, Z., Xu, Y., Tan, G., Tang, W., Bi, J., and Li, X. (2017). Supporting real-world network-oriented mesoscopic traffic simulation on gpu. *Simulation Modelling Practice and Theory*, 74:46–63.

Tang, T., Li, J., Huang, H., and Yang, X. (2014). A car-following model with real-time road conditions and numerical tests. *Measurement*, 48:63–76.

Washburn, D., Sindhu, U., Balaouras, S., Dines, R. A., Hayes, N. M., and Nelson, L. E. (2009). Helping cios understand "smart city" initiatives. *Growth*, 17(2):1–17.

Wiedmann, T. and Minx, J. (2007). A definition of carbon footprint. *CC Pertsova, Ecological Economics Research Trends*, 2:55–65.

Zegras, C. (2010). The built environment and motor vehicle ownership and use: Evidence from santiago de chile. *Urban Studies*, 47(8):1793–1817.

Zilske, M., Schröder, S., Nagel, K., and Liedtke, G. (2012). Adding freight traffic to matsim. Technical report, VSP Working Paper 12-02, TU Berlin, Transport Systems Planning and Transport Telematics.