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Evaluating a system of exclusive lanes for autonomous vehicle platoons

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Evaluating a system of exclusive lanes for autonomous vehicle platoons

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Resumo

Uma proposta para um sistema de faixas exclusivas destinadas a veículos autônomos chamado Digital Rails é apresentada e avaliada em métricas macroscópicas de trânsito, principalmente tempo médio de viagem. O sistema proposto consiste em uma rede de vias arteriais com faixas exclusivas onde veículos autônomos podem viajar em comboios. Semáforos nestas vias seguem um plano de temporização que permite aos comboios viajar sem paradas. Uma formulação em programação inteira é usada para obter tal plano. Impactos do sistema proposto são avaliados usando simulações de trânsito com modelos mesoscópicos. Os cenários simulados são baseados em dados reais da cidade de São Paulo. Os resultados das simulações mostram que o sistema proposto traria reduções no tempo médio de viagem se a proporção de véiculos aptos a usar o sistema na frota total estiver acima de um certo limiar.

Palavras-chave: veículos autônomos, simulações de trânsito, comboios veiculares.

Abstract

A proposal for a system of exclusive lanes intended for autonomous vehicles called Digital Rails is presented and evaluated for macroscopic traffic metrics, mainly average travel time. The proposed system consists in a network of arterial roads with exclusive lanes where autonomous vehicles can travel in platoons. Traffic signals on these roads follow a timing plan that allows each platoon to travel without stops. An integer-programming formulation is used to obtain such plans. Impacts of the proposed system on travel time are evaluated using traffic simulations with mesoscopic models. The simulated scenarios are based on real data from the city of São Paulo. Simulation results show that the proposed system would bring reductions on the average travel time if the ratio of vehicles in the total fleet able to use it is above a certain threshold.

Keywords: autonomous vehicles, traffic simulations, vehicle platooning.

Contents

Chapter 1

Introduction

Autonomous vehicles (AVs) technology brings new solutions and challenges for urban mobility. The development and adoption of AVs has the potential to reduce traffic jams and increase traffic safety. However, despite the advancement of automation technology in both research and commercial environments, full autonomous vehicles requiring no human intervention are not expected to be available in the short-term.

In this work, we investigate a proposal to allow AVs to share the roads with regular vehicles, with minimal changes to the current infra-structure: Digital Rails (DR). DR consists on dedicated lanes for AVs that allows AV platoons to traverse arterial roads at high speeds. Traffic signals coordinates the traffic with regular vehicles. On roads with DR lanes, traffic signals on successive intersections should be synchronized to allow the platoons to travel without stops.

The proposal for Digital Rails was first elaborated by designers at Questtonó[1], a design consultancy firm established in São Paulo, Brazil. Their proposal left open definitions for many technical aspects, such as detailed requirements for AV technology and platooning maneuvers. We assumed that vehicles can coordinate themselves to form platoons and drive on the lanes assigned for DR.

We evaluated the impact that such system could have in traffic using simulations based on the city of São Paulo, and studied how the implementation of DR lanes in selected arterial roads in the city would affect the travel time by simulating different ratios of vehicles able to use the system. To conduct the traffic simulations, we used InterSCSimulator [Santana *et al.* (2017)], a smart city simulator developed with focus on scalability. InterSCSimulator is written in Erlang[2], on top of the SimDiasca discrete event simulation engine [Boudeville (2012)]. To simulate Digital Rails, we had to implement some new features on the simulator such as traffic signals.

The first simulation scenarios were elaborated for DR on a single major road of São Paulo, Avenida Paulista. For reference, we also elaborated a benchmark scenario based on the current deployed traffic signal timing plan, which we measured on field, and on traffic counts for peak hours published by the Traffic Engineering Company of the city of São Paulo. Later we expanded the system to a larger region in the city, implementing DR lanes on roads with large traffic volumes.

On our simulations, vehicles traveling Avenida Paulista on DR platoons had travel time less than half of the average travel time on the benchmark scenario. For vehicles traveling on crossing roads, DR brought no increase in travel time. On scenarios with less vehicle density, DR had less significant effect on travel time.

[1] https://www.questtono.com/en/
[2] https://www.erlang.org/

For DR on multiple arterial roads, we found an improvement on the global average travel time compared to the benchmark scenario when the ratio of vehicles able to use DR is greater than 25%. We also found that even vehicles outside DR would have a decrease in travel time when more than 50% of vehicles is able to use DR.

The remaining of this text is organized as follows: Chapter 2 presents a short review on some related works. Chapter 3 serves as an introduction to the main concepts for this work: It begins discussing AV technology, then it introduces InterSCSimulator. Finally, it presents a more detailed description of the DR proposal and some extensions that we implemented on InterSCSimulator to simulate DR.

Chapter 4 presents the methodology used to elaborate the simulation scenarios, obtain external data and compute traffic signal timing plans for DR. Chapter 5 shows some simulation results. Finally, Chapter 6 presents our conclusions and some suggestions for future works.

We thank the people at Questtonó for their insights and suggestions, specially Barão di Sarno.

Chapter 2

Related works

Our literature review included works about AV technology, traffic signal control, and intersection management techniques which seek integration of AV with regular vehicles.

2.1 Autonomous Vehicles technology

Since the original proposal for Digital Rails did not specify a particular AV technology, we focused our review on its impacts on the transportation system, rather than specific technical details as AV control and connectivity.

Fagnant e Kockelman (2015) discuss several potential impacts of AV technology on the transportation system, such as an increase in safety, a decrease in traffic congestion, change on travel behavior and on the freight industry. They also estimate economic benefits of AV technology and some barriers to implementation. The authors also give several recommendations for policymakers on the subject. We review some of the impacts discussed by the authors on Section 3.1.

Litman (2017) presented an extensive report on AV technology, studying its impacts and economic costs. The author also compiled predictions about its availability and deployment, analyzing them based on the deployment of previous vehicular technologies. Optimistic and pessimistic predictions are given, and the general conclusion is that it should take a couple decades for AVs to become the majority on the world fleet. The author discuss AV-related planning issues and requirements. We also reference this work on Section 3.1.

Fagnant e Kockelman (2018) studied a system of shared autonomous vehicles (SAVs) with dynamic ride sharing (DRS) enabled, which pools multiple passenger with similar origin, destination and departure times in the same vehicle. Using simulations based on the city of Austin, Texas, they concluded that DRS applications may reduce total service time and vehicle-miles-traveled (VMT), and that SAVs can be economically profitable. While the original conception for Digital Rails does particularly suggest DRS, such system could be the main application for DR.

2.2 Traffic signal control

The original proposal for Digital Rails is highly dependent on synchronization of traffic signals, which is not a new research topic on traffic engineering. There are several consolidated techniques and methods to improve efficiency on a system of signalized intersections, including TRANSYT [Robertson (1969)] and SCOOT [Hunt *et al.* (1982)].

Our main reference on this subject was the formulation used on MAXBAND [Little *et al.* (1981)], which presents a method to compute a timing plan for successive traffic signals on an arterial road with maximal bandwidth progressions. The method is based on a mixed-programming formulation, which we present on Section 4.2. This formulation was used to calculated traffic signals timing plans on our evaluation of Digital Rails, as shown in subsequent chapters.

2.3 Intersection management techniques

Finally, we reviewed other proposals for intersection management suited for integration of AVs on the regular vehicle fleet:

Au *et al.* (2015) present a protocol for intersection management called *Semi-Autonomous Intersection Management* (SemiAIM), which can be extended to manage human-driven vehicles alongside its (semi-)autonomous counterparts. The system is based on a reservation paradigm, where vehicles communicate with the infrastructure to reserve space-time in the intersection. They specify the capabilities required for a vehicle to be considered semi-autonomous. Using traffic simulations, the authors showed that the system can significantly reduce the delay in a single intersection when most vehicles are semi-autonomous.

Tachet *et al.* (2016) analyze different intersection management systems using queuing theory. They compare two different strategies for slot-based intersections (SIs) with fixed cycle traffic signals, showing that SIs could increase capacity and reduce expected delay and its variance.

Despite these works proposing alternatives to regular traffic signals and showing that they could be more efficient, we stick to the original conception for Digital Rails on our subsequent evaluations. Since the original DR conception does not make detailed descriptions on the required level of vehicle automation and communication, further research is necessary to compare its requirements to those of the solutions proposed above.

Chapter 3

Main concepts

We begin our presentation of concepts with a short review on autonomous vehicles, listing some of its impacts and predictions about availability and adoption. Next, we introduce InterSCSimulator, the main tool used in our evaluations of Digital Rails. We discuss its simulation models and underlying technologies. Finally, we present the Digital Rails concept in details and describe how it was implemented on InterSCSimulator.

3.1 Autonomous Vehicles

Vehicles can be classified in different levels of automation. The SAE international[1] defines 6 levels of increasing automation, from 0 to 5. In this scale, level 0 consists of no automation at all, while level 5 consists of full-automation in all driving scenarios (e.g., high speed cruising, low speed traffic jam), called driving modes. Figure 3.1 presents the automation levels as defined by SAE.

3.1.1 Impacts

Fagnant e Kockelman (2015) and Litman (2017) list various potential impacts of AV technology on the transportation system:

- Safety: The possibility of eliminating human failings such as fatigue, distraction, and alcohol suggests a potential reduction of at least 40% in fatal crash rates in the United States. However, AV technology introduces new safety risks such as hardware and software failures and the possibility of malicious hacking.

- Congestion: With AVs sensing and possibly predicting other vehicles braking and acceleration behavior, the traffic shock wave propagation could be reduced. This would also lead to fuel savings and emission reductions. It is noted that these improvements would also depend on cooperative abilities achieved through vehicle-to-vehicle or vehicle-to-infrastructure communication.

- Travel behavior: AVs could increase the mobility for young, elderly and disabled people, which would generate additional traffic demand. Actually, the advantages of AV could provide an incentive to the total vehicle-miles traveled (VMT) to increase. AVs also would allow passengers to be productive while traveling.

[1]Former Society of Automotive Engineers: https://www.sae.org/

SAE level	Name	Narrative Definition	Execution of Steering and Acceleration/ Deceleration	*Monitoring* of Driving Environment	Fallback Performance of *Dynamic Driving Task*	System Capability *(Driving Modes)*
***Human driver* monitors the driving environment**						
0	No Automation	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	Driver Assistance	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes
2	Partial Automation	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/ deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes
***Automated driving system* ("system") monitors the driving environment**						
3	Conditional Automation	the *driving mode*-specific performance by an *automated driving system* of all aspects of the dynamic driving task with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes
4	High Automation	the *driving mode*-specific performance by an automated driving system of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes
5	Full Automation	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**

Figure 3.1: *Vehicle automation levels as defined by SAE International.*

- Parking: AVs could also change the parking patterns and reduce demand for parking space in urban centers, since vehicles could park themselves in less expensive locations.

- Freight transportation: AV technology could also be applied to trucks, reducing the need for drivers and freight costs. The authors highlight that that autonomous trucks could have much resistance from labor groups and competing industries such as the railroad freight industry.

- Urban planning: With AVs turning commute time into productive time, the urban sprawl could be affected, since the cost of living far from a urban center would be reduced. AV technology could also reduce public transit offer and decrease support for policies that encourage other mobility solutions like biking or walking.

Finally, there are moral questions regarding AVs. Some unavoidable crash situations may require for the vehicles to decide between the safety of its occupants against other vehicles or pedestrians. Bonnefon *et al.* (2016) present surveys regarding approval of proposed AV behaviours in such situations. For instance, in one study they found that "76% of participants thought that it would be more moral for AVs to sacrifice one passenger rather than kill 10 pedestrians". Such issues still require considerable public discussion and consideration from potential AV technology consumers, policy-makers and regulators.

3.1.2 Predictions about availability and adoption

As noted by Litman (2017), at least level 4 of automation is necessary for the predicted impacts discussed previously. Technology such as cruise control and automated parallel parking, currently present in vehicles available to the public, are classified as automation level

1 or 2. Vehicles used in driver-less taxi services such as the one announced by Waymo and reported by Bergen (2017) are classified with automation level 4.

Litman (2017) also compares cautious predictions made by researchers and experts against more optimistic predictions made by people with financial interests in the AV technology. As reported by Mervis (2017), experts tend to agree that significant technical progress, besides additional time for testing and regulatory approval, is needed for automation level 5. Litman (2017) argues that "it will be the 2040s or 2050s before most vehicles are capable of autonomous driving".

On the other hand, optimistic reports like Arbib e Seba (2017) predict that "by 2030, within 10 years of regulatory approval of autonomous vehicles (AVs), 95% of U.S. passenger miles traveled will be served by on-demand autonomous electric vehicles [...]".

In Figures 3.2 and 3.3 we reproduce the findings and predictions made by Litman (2017), modeled after previous vehicle technology deployment experience. We conclude that AV technology with automation level 4-5 should take at least a decade to be available, and at least another decade after that to be significantly adopted. Ubiquity of autonomous vehicles should take even longer.

Stage	Decade	Vehicle Sales	Veh. Fleet	Veh. Travel
Available with large price premium	2020s	2-5%	1-2%	1-4%
Available with moderate price premium	2030s	20-40%	10-20%	10-30%
Available with minimal price premium	2040s	40-60%	20-40%	30-50%
Standard feature included on most new vehicles	2050s	80-100%	40-60%	50-80%
Saturation (everybody who wants it has it)	2060s	?	?	?
Required for all new and operating vehicles	???	100%	100%	100%

Figure 3.2: *Predictions about autonomous vehicles implementation, as made and presented by Litman (2017).*

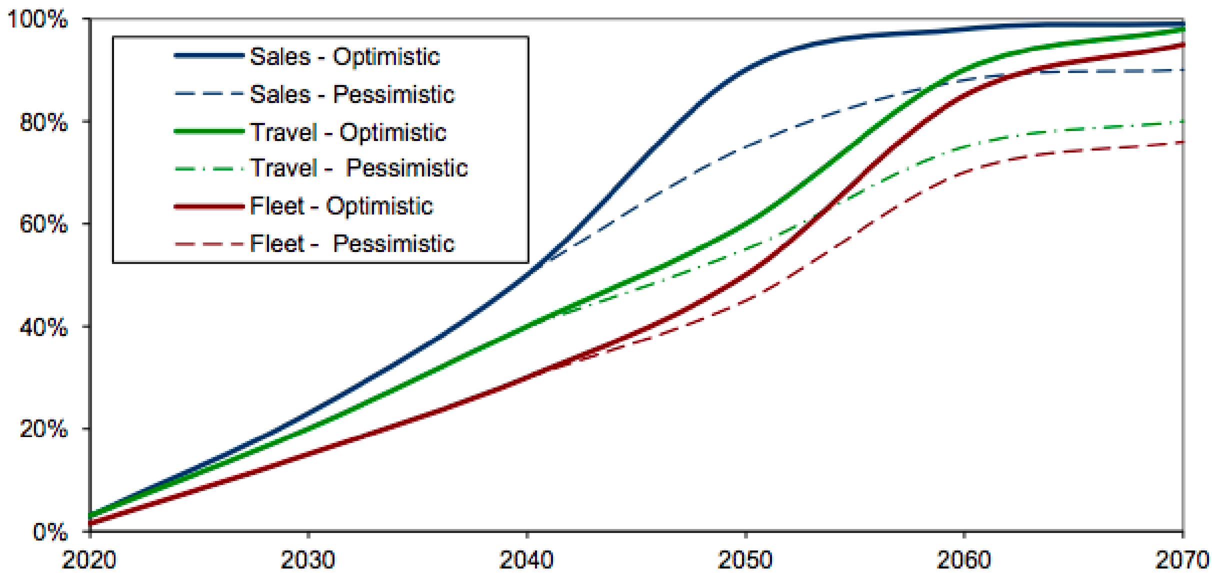


Figure 3.3: *Predictions about autonomous vehicles implementation over time, as made and presented by Litman (2017).*

3.2 InterSCSimulator

InterSCSimulator is an open-source agent-based Smart City simulator developed by Santana *et al.* (2017), with focus on scalability. The simulator is implemented in the Erlang programming language, and relies on the SimDiasca discrete-event simulation engine. In this work, we use InterSCity simulator to evaluate Digital Rails using traffic simulations.

3.2.1 Simulation models

Besides being an agent-based simulator, InterSCSimulator is based on discrete events and uses a mesoscopic model for traffic simulations. These features are described below, along with examples and specific implementation details.

Agents

For smart city simulations, agents could represent any city element: buildings, vehicles, streets, sensors etc. In the simulation scenarios used in this work, the most frequent kind of agent is vehicle. However, some aspects of the simulation are not done using agents. The road network, for example, is not an agent on itself but a public object available for all agents to call and sometimes modify.

Each agent has its own internal state, and generally communicate with other agents via asynchronous messages, following the Actor model.

Discrete event simulations

Agents in InterSCSimulator are simulated with discrete events, meaning that each agent can schedule events in a discrete time scale, measured in ticks. Each simulated tick corresponds to 1 second in real time. Generally, each event consists in a change of state for a specific agent. Events often cause more events in future ticks, but never events in the past.

To see an example of a series of simulated discrete events, suppose that we are simulating a vehicle traveling two points in the same street, say A and B, distant 100m from one another. We set that the vehicle should travel at a speed of 10m/s (this could be a speed limit present at the road network object), and that the tick size is 1s. The following discrete events would occur:

- At t = 0s, the vehicle spawns at point A, with a state indicating that it should travel to point B. The vehicle checks the road network object and sees that the distance to be traveled is 100m. Then it calculates that, with a speed of 10m/s, it would arrive 10s later. The vehicle starts its trip by updating its internal state and scheduling a new event for itself at t = 10s.

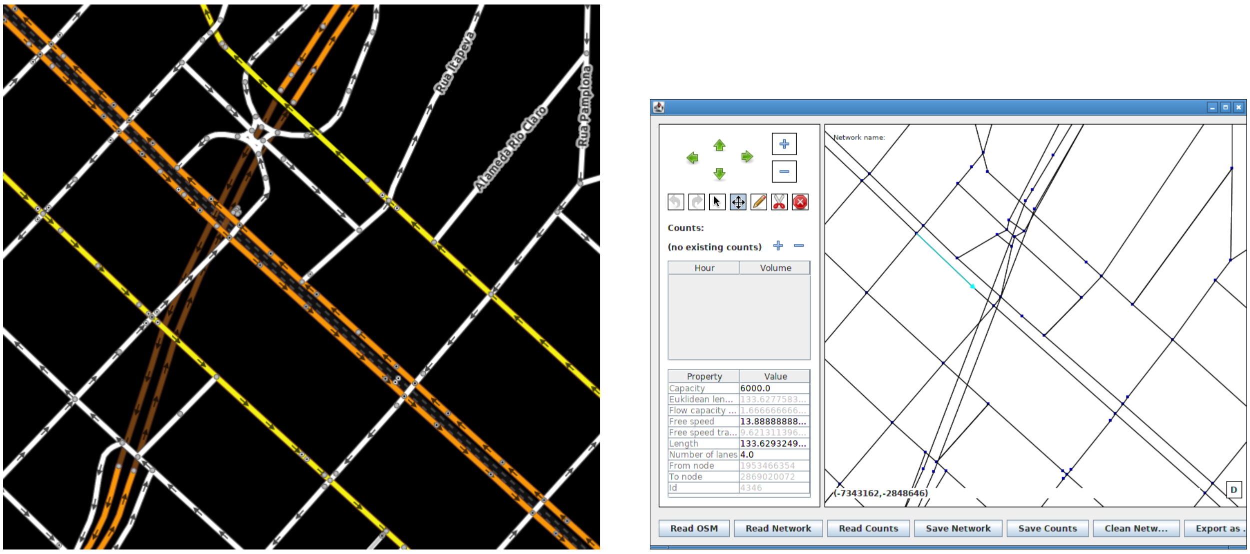
- At t = 10s, the vehicle agent is invoked again. It checks its internal state to see that the trip is finished because it have just reached its destination, and updates its internal state accordingly. The event finishes without the agent scheduling further events, since there is nothing left to do.

Mesoscopic traffic model

Traffic simulation models are usually classified as microscopic, mesoscopic or macroscopic. Boxill e Yu (2000) present an extensive review and evaluation of existing traffic models. While macroscopic models work with descriptions of collective vehicular motion in terms of vehicle density or average velocities, microscopic models often describe the motion of each individual vehicle. Mesoscopic models are something in between, modeling individual vehicles using macroscopic quantities.

The road network representation in InterSCSimulator is the same as MATSim, an agent-based traffic simulator (Horni *et al.* (2016)). In this representation, the network is represented by entities called links and nodes, structured in a graph: each node is a vertex and each link is an edge connecting two nodes.

Generally, each link represents a street segment, while vertices represent intersections. Information like number of lanes and speed limits for each segment are treated as metadata for each link. Figure 3.4a shows the road network around the São Paulo Museum of Art (MASP) represented in OpenStreetMap. The same network represented as a MATSim network is shown on Figure 3.4b.



(a) *OpenStreetMap* **(b)** *MATSim network*

Figure 3.4: *The road network around the São Paulo Museum of Art (MASP) represented in OpenStreetMap and as a MATSim network*

In InterSCSimulator, vehicles transverse each link with a constant speed v, defined at the instant that the vehicle enters the link. This speed depends on characteristics of each link, and also on the number of vehicles also crossing the link at the moment. This relation between vehicle density and speed is adapted from Song *et al.* (2017) and is defined as follows:

$$v = \begin{cases} v_{free} & \text{if } k \leq k_{min} \\ v_{free} * (1 - (\frac{k}{k_{jam}})^{\beta})^{\alpha} & \text{if } k_{min} < k < k_{jam} \\ v_{jam} & \text{if } k \geq k_{jam} \end{cases} \tag{3.1}$$

Where v_{free} is the maximum speed that a vehicle could develop in the link, usually dependent on road characteristics and traffic regulations; k is the current linear vehicle density in the link (in vehicles / m); k_{min} and k_{jam} are thresholds that classify each link as free ($k \leq k_{min}$) or jammed ($k \geq k_{jam}$); v_{jam} is the speed that vehicles would develop during a traffic jam; α and β are configurable parameters for the model.

We use $k_{min} = 0.3$, $\alpha = 0.45$, $\beta = 1.0$ and $v_{jam} = 1.0m/s$ for all links. v_{free} is set to the speed limit of the road that the link represents, and k_{jam} is calculated as:

$$k_{jam} = \frac{n_{lanes}}{l_{cell}} \tag{3.2}$$

Where n_{lanes} is the number of traffic lanes in the segment that the link represents, and l_{cell} represents the length occupied by each vehicle in a jammed condition. Despite the fact that in MATSim the default value for l_{cell} is 7.5m, we choose $l_{cell} = 5.5m$, which we found to be a better value when calibrating our model.

We note that the coefficient $\frac{k}{k_{jam}}$ in 3.1 can be obtained as:

$$\frac{k}{k_{jam}} = \frac{c}{c_{jam}} \tag{3.3}$$

Where c is the current vehicle count at the link and c_{jam} is the maximum vehicle count that the link supports before being considered jammed. c_{jam} is calculated as:

$$c_{jam} = n_{lanes}\frac{l_{link}}{l_{cell}} \tag{3.4}$$

Where l_{link} is the length of each link, in meters.

3.2.2 Underlying technologies

InterSCSimulator is written in Erlang, and makes heavy use of a discrete-event simulation framework called SimDiasca, also written in Erlang.

Erlang

Erlang[2] is a functional programming language based on the actor model. Initially created by Ericsson[3] for the development of telecommunication systems, it has built-in capabilities for large-scale concurrency and fault-tolerance.

The actor model is implemented using the Erlang process construct. Processes are scheduled and managed by the Erlang Virtual Machine, and are independent from the underlying operating system processes. Much like the thread construct in other programming languages, Erlang processes represent independent execution contexts. However, they are isolated from each other, and communication must be done using asynchronous messages. Primitives for process management and communication are also provided in the language. An introduction to Erlang programming can be found in the book by Hebert (2013).

The straightforward implementation of actor-based simulations in Erlang is having each actor on its own process. This brings the advantage of isolated actors, which remove shared-memory related problems. However, some level of synchronization is necessary, since Erlang does not offer any guarantee in process order execution.

One disadvantage of implementing actor-based simulations in Erlang is the lack of object-oriented constructs. Another caveat is the Erlang built-in term storage feature (ets[4]), which is shared among processes and can lead to shared-memory related problems.

[2] https://www.erlang.org/
[3] https://www.ericsson.com/en
[4] http://erlang.org/doc/man/ets.html

SimDiasca

SimDiasca (Simulation of Discrete Systems of All Scales) is a general-purpose discrete-event simulator written in Erlang Boudeville (2012). InterSCSimulator is built on top of SimDiasca, using it as a discrete-event simulation engine. Basic features for discrete-event simulations such as time management are provided by SimDiasca, along with a framework for modeling actor behaviors in a object-oriented fashion.

Figure 3.5 represents InterSCSimulator architecture, which is composed of three layers. The bottom layer is the SimDiasca simulator with its basic discrete-event features. The middle layer is composed by the actor definitions provided by InterSCSimulator using the SimDiasca framework. Finally, the top layer consists of the simulation scenarios, which in the case of traffic simulations, are mainly composed by the road network and trip definitions.

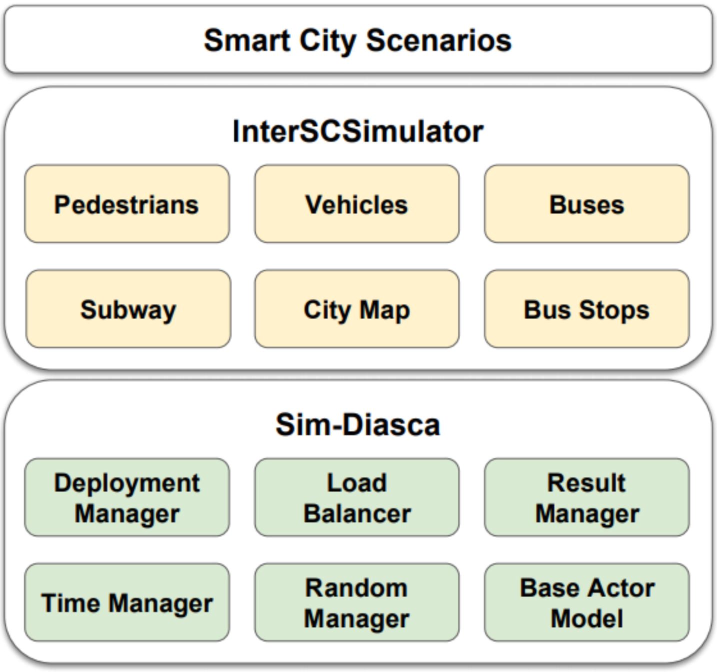


Figure 3.5: *InterSCSimulator architecture*

3.3 Digital Rails

The idea for Digital Rails (DR) began at Questtonó[5], a brazilian innovation and design consultancy. Its creators envisioned a system where autonomous vehicles would travel in platoons on exclusive lanes, achieving high efficiency through synchronization with traffic signals.

3.3.1 Concepts

On their website[6], the authors of the Digital Rails concept present three main pillars:

1. Open data network: The city would provide a network that vehicles could access in order to obtain data about traffic signals, which would run in prefixed timing plans to allow uninterrupted progressions.

[5] https://www.questtono.com/en/
[6] https://www.questtonomobility.com/english/

2. Exclusive lanes: On selected arterial roads, exclusive lanes from the current infrastructure would be assigned to the system. Vehicles using Digital Rails would have a custom design with narrower dimensions, so that a regular lane could fit two lanes of these custom-designed vehicles. One of them would be an expressway dedicated to platoons, and the other one would be used as extra space for maneuvers.

3. Vehicle platoons: Vehicles using Digital Rails would have some level of automation and organize themselves in platoons to maximize efficiency. The platoons would use the open data network to travel through the traffic signals progressions, minimizing travel time and number of stops.

Figure 3.6, extracted from Questtonó's website[7], presents a concept-art for the project. The rationale for the project is to offer an alternative for urban transportation during the period while the autonomous vehicle fleet is growing, allowing AVs to share the roads with regular vehicles. For vehicles using the system, the travel time would be reduced, since there would be no stops due to traffic signals or traffic jams.

The authors also claim that Digital Rails would initially not require large changes in the current city infrastructure. In advanced implementation stages, the system would actually reduce the demand for parking and road infrastructure, allowing for the city to claim back some of this space in form of parks, green areas, pedestrian paths and cycling ways.

Figure 3.6: *Concept art for Digital Rails, extracted from Questtonó website.*

However, the authors did not give detailed descriptions about the vehicle-to-vehicle and vehicle-to-infrastructure network protocols and technologies, the custom vehicle designs, the necessary level of vehicle automation, nor about platooning techniques. In this work, much of these details are also abstracted away. Specifically, the following assumptions were made:

1. Vehicle-to-vehicle and vehicle-to-infrastructure communications are a solved problem: Our simulation models does not take into account the need for vehicular networks, and we do not propose or evaluate protocols or techniques for these communications to happen.

[7] https://www.questtonomobility.com/

2. The custom design for vehicles that use Digital Rails is specified: We do not propose or evaluate any vehicle design neither any engineering aspect necessary for vehicles to be able to use the system.

3. Platooning maneuvers and protocols are well defined: We do not develop protocols for vehicle platooning, nor evaluate individual vehicle dynamics.

With these simplifications in sight, we proceed to elaborate into how Digital Rails was simulated in InterSCSimulator.

3.3.2 Implementation in InterSCSimulator

Simulating Digital Rails with InterSCSimulator required the introduction of DR lanes to the road network, a simplified speed model for vehicles using DR and the introduction of traffic signal agents.

Digital Rails lanes

Information about Digital Rails lanes is represented on its own input file, which contains a list of origin-destination node pairs corresponding to the links in the road network with a DR lane assigned. An example of a input file for Digital Rails is given on the following listing:

```
<digital-rails>
  <rail name="av_paulista" cycle="120" bandwidth="15">
    <links>
      <link origin="60609819" destination="60609822"/>
      <link origin="60609822" destination="303863647"/>
      <link origin="303863647" destination="1953466378"/>
    </links>
  </rail>
</digital-rails>
```

The origin-destination pairs are then used to complement the road network metadata, where a new attribute indicating that there is a DR lane is given to each link on the list.

Speed model

Each trip defined on the trips input file is marked with an attribute indicating whether the vehicle is able to use Digital Rails. On links with DR lanes, the speed model for vehicle able to use DR becomes independent of link capacity and current vehicle density:

$$v = v_{free} \tag{3.5}$$

Vehicles that are not able to use DR continue to follow the model described in equation 3.1. For links with an assigned DR lane, the link capacity is calculated as:

$$c_{jam} = (n_{lanes} - 1)\frac{l_{link}}{l_{cell}} \tag{3.6}$$

Traffic signals

Traffic signals are implemented as a new class of agents. Each agent represents the set of traffic signals located on a signalized intersection, which can span multiple nodes on the road network.

Each intersection has its own cycle duration an optional offset time, both measured in ticks. The offset is generally used to coordinate multiple intersections to create traffic progressions, colloquially known as green-waves.

The phasing of the signals in each intersection is implemented based on the node that each vehicle is coming from: all vehicles coming from the same node in a given moment will find the same signal state. The possible states are only red and green lights. For each possible origin node, we define its phasing with the green light state start (relative to the cycle) and the green light state duration, both measured in ticks.

As with Digital Rails lanes, the input for all traffic signals is located in a single file. The following listing shows an example of the definition of a signalized intersection with its cycle, offset, nodes and phasing plan:

```
<traffic-signals>
  <signal cycle_duration="90" offset="9">
    <nodes>
      <node id="60609822"/>
      <node id="60609866"/>
    </nodes>
    <phases>
      <phase origin="303863453" green_duration="45" green_start="0" />
      <phase origin="60609819" green_duration="45" green_start="0"/>

      <phase origin="4962324520" green_duration="28" green_start="46"/>
      <phase origin="60609822" green_duration="28" green_start="46"/>
    </phases>
  </signal>
</traffic-signals>
```

Since the traffic light state for a intersection only depends on the current simulation tick, the actual agent implementation does not simulate every state transition. Instead, vehicle agents arriving in a network node first checks if there is a traffic signal at the node. If there is, they send a message asking for the current state, containing the id of the previous node in their path. The response will contain the current light state, and in the case of red lights, the remaining number of ticks until the lights turn to green. The vehicle then waits the green lights until entering the next link.

We recognize that this simple implementation cannot handle more complex phasing techniques, such as the presence of left-turn only phases, or techniques for traffic signal control other than pre-timed signals.

Chapter 4

Methodology

We began our evaluation considering a single road in São Paulo with high traffic: Avenida Paulista, which is located in a central region of the city. The avenue is home to many financial and cultural institutions and receives tens of thousands of vehicles per day.

First we established a benchmark scenario, obtaining traffic counts from reports published by the São Paulo Traffic Engineering Company (Companhia de Engenharia de Tráfego: CET) and measuring the currently deployed traffic signal times in Avenida Paulista during peak hours, as described in Section 4.1.

We then defined a traffic signals timing plan for Digital Rails at Paulista using an integer-mixed programming approach, as described in Section 4.2. The next step was to develop simulation scenarios to measure the impact of Digital Rails in the region, described in Section 4.3.

Later, we expanded the scope of the evaluation by selecting a region in São Paulo and measuring the impact of Digital Rails in its main arterial ways, selected based on CET reports. Section 4.4 describes this process.

4.1 Benchmark scenario at Avenida Paulista

The first step to study the impact of Digital Rails at Avenida Paulista was to establish a simulation scenario to represent the current traffic conditions during peak hours. For this benchmark, the simulated traffic was limited to Avenida Paulista only. We considered the segment of the avenue that goes from Rua da Consolação to Oswaldo Cruz square, spanning about 2445m.

All the simulated travels were in one of two possible ways: from Oswaldo Cruz square to Rua da Consolação (called Consolação way) or from Rua da Consolação to Oswaldo Cruz square (called Paraíso way, since the square is located at the Paraíso neighborhood). Vehicles traveling in the same way would have the exact same origin and destination network nodes.

The scenario simulated one hour of peak traffic, and the total number of simulated trips each way was equal to the volume count published in the CET mobility survey 2017 (Companhia de Engenharia de Tráfego (2018)) for the morning peak hour at Avenida Paulista: 2359 vehicles in the Paraíso way and 3067 vehicles in the Consolação way. The start times for the simulated trips were uniformly distributed during the simulated hour.

There are 13 signalized intersections on the selected segment of Avenida Paulista. Figure 4.1 shows a tile from OpenStreetMap highlighting the part of the avenue that we considered, alongside with graphs indicating the points of origin and destination of the simulated trips and the location of traffic signals.

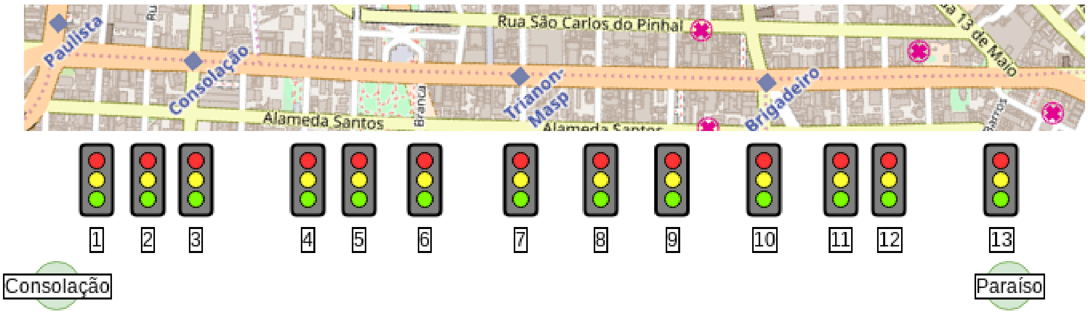


Figure 4.1: *Tile from OpenStreetMap showing the selected segment of Avenida Paulista, the location of traffic signals and the points of origin and destination for the simulated trips.*

In order to obtain the timing plan for the traffic signals, we went to the field and filmed each intersection with a smartphone for at least a whole cycle of the traffic signals. The filming was done on a Friday evening, around 19h. Later we added a timestamp with millisecond precision for each frame of the videos, using `ffmpeg`[1]. We then manually input into a spreadsheet the timestamp of the video frames in which phase transitions occurred. To determine the cycle times and duration of each phase, the following assumptions were made:

1. There are two phases with a green light in each intersection: One for both ways in Avenida Paulista and the other for the perpendicular way.

2. The green light phase for Avenida Paulista in each intersection starts at $t = 0s$, relative to the cycle.

3. The time precision for cycle times and phase duration is an integer number of seconds.

We were then able to determine the times for the phases at each intersection, along with the total cycle time, the later being 150s in every intersection. Figure 4.2 shows a frame of one of the videos used.

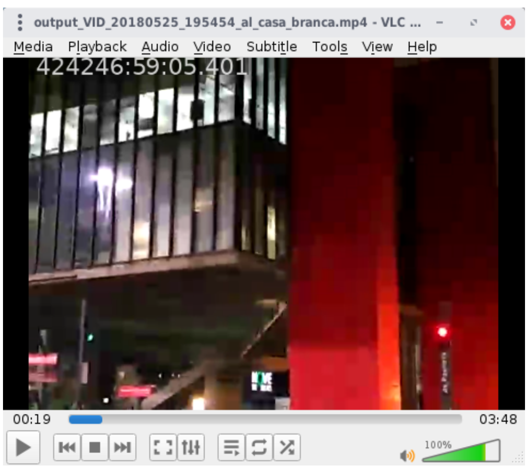


Figure 4.2: *Frame from video showing the traffic signals near to the São Paulo Museum of Art (MASP). Videos of each intersection were used to determine the traffic signal times at Avenida Paulista.*

[1] https://www.ffmpeg.org/

4.2 Traffic signal timing plan for Digital Rails at Avenida Paulista

To proceed with our evaluation of Digital Rails at Avenida Paulista, we developed a traffic signal timing plan that allows vehicle platoons going both ways to transverse the selected segment without stops, at the same time. The definition of such timing plan can be formulated as an optimization problem, as presented by Little *et al.* (1981).

In this formulation, the two opposite directions in which the progressions travel are called inbound and outbound. All traffic signals have the same cycle time. Despite the authors also presenting formulations in which the cycle time is an output of the optimization problem, we choose the simpler one in which it should be set manually. The following notation is used, in which quantities with bars refer to the inbound direction, while the ones without bars refer to the outbound direction:

- $b[\overline{b}]$: bandwidth for the outbound [inbound] direction, measured in cycles;
- S_i: ith traffic signal, $i = 1 \dots n$. Traffic signals are numbered from 1 to in the outbound direction;
- $r_i[\overline{r}_i]$: outbound [inbound] red time at S_i, in cycles;
- $w_i[\overline{w}_i]$: time from the right [left] side of red at S_i to the left [right] edge of outbound [inbound] green band. Measured in cycles.
- $t(h, i)[\overline{t}(h, i)]$: travel time from S_h to S_i outbound [S_i to S_h inbound]
- $\phi(h, i)[\overline{\phi}(h, i)]$: Time from the center of an outbound [inbound] red at S_h to the center of a particular outbound [inbound] red at S_i. The two reds are chosen so that each one is immediately to the left [right] of the outbound [inbound] green band. Positive if the center of the red in S_i lies to the right [left] of the center of the red in S_h. Measured in cycles.
- Δ_i: Time from the center of a given $\overline{r}_i$ to the nearest r_i. Positive if the center of r_i is to the right of the center of $\overline{r}_i$. Measured in cycles;
- $\tau_i[\overline{\tau}_i]$: Queue clearance time for the outbound [inbound] bandwidth upon leaving S_i; Measured in cycles;

Figure 4.3, also from Little *et al.* (1981), illustrates the notation with a space-time diagram on which the red times are drawn with horizontal lines. Solid lines are used for the outbound direction, and dashed lines for the inbound one. The authors also combined two equations expressing the time difference, measured in cycles, between the points A and B in the figure, defining the quantity $m(h, i)$:

$$m(h, i) = \phi(h, i) + \overline{\phi}(h, i) + \Delta_h - \Delta_i \tag{4.1}$$

To simplify the notation, the following definition is used:

$$x_i = x(i, i + 1) \quad \text{for} \quad x = t, \overline{t}, m, \phi, \overline{\phi} \tag{4.2}$$

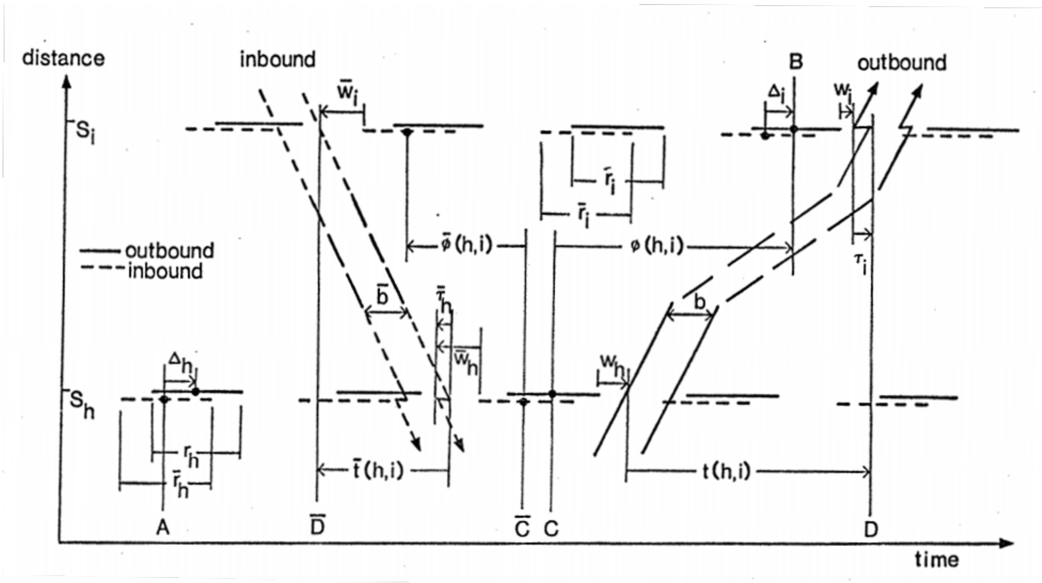


Figure 4.3: *Space-time diagram extracted from Little et al. (1981), used to illustrate the notation defined by the authors and reproduced above. Horizontal lines represent the red times of traffic signals. Solid lines are used for the outbound direction, while dashed lines are used for the inbound one.*

A timing plan for the traffic signals can then be obtained by solving the following mixed-integer programming problem:

$$
\begin{aligned}
\text{Find} \quad b, \overline{b}, w_i, \overline{w}_i, m_i \quad \text{to}& \\
\max \quad & b \\
\text{s.t.} \quad & \overline{b} = b \\
& w_i + b \leq 1 - r_i, \quad i = 1 \dots n \\
& \overline{w}_i + \overline{b} \leq 1 - \overline{r}_i, \quad i = 1 \dots n \\
(w_i + \overline{w}_i) - (w_{i+1} + \overline{w}_{i+1}) + (t_i + \overline{t}_i) +& \\
\Delta_i - \Delta_{i+1} &= (-1/2)(r_i + \overline{r}_i) + (1/2)(r_{i+1} + \overline{r}_{i+1}) + \\
& \quad (\overline{\tau}_i + \tau_{i+1}) + m_i, \quad i = 1 \dots n-1 \\
m_i &= \text{integer} \\
b, \overline{b}, w_i, \overline{w}_i &\geq 0, \quad i = 1 \dots n
\end{aligned}
\tag{4.3}
$$

In the case of Digital Rails, we made the following assumptions:

1. The red times for the inbound and outbound directions are aligned in every S_i, meaning that $\Delta_i = 0$ for $i = 1 \dots n$

2. Since the platoons will not stop, there is no need for queue clearance time, so $\tau_i = 0$ and $\overline{\tau}_i = 0$ for $i = 1 \dots n$

Applying these assumptions, the mixed-integer programming problem becomes:

$$\begin{aligned}
\text{Find} \quad b, \bar{b}, w_i, \overline{w}_i, m_i \quad & \text{to} \\
\max \quad & b \\
\text{s.t.} \quad & \bar{b} = b \\
& w_i + b \leq 1 - r_i, \quad i = 1 \ldots n \\
& \overline{w}_i + \bar{b} \leq 1 - \bar{r}_i, \quad i = 1 \ldots n \\
(w_i + \overline{w_i}) - (w_{i+1} + \overline{w}_{i+1}) + (t_i + \bar{t}_i) &= (-1/2)(r_i + \bar{r}_i) + (1/2)(r_{i+1} + \bar{r}_{i+1}) + m_i, \quad i = 1 \ldots n-1 \\
& m_i = \text{integer} \\
& b, \bar{b} \geq 0, \quad i = 1 \ldots n
\end{aligned} \tag{4.4}$$

We used the later formulation with `lp_solve`[2] to obtain timing plans with the cycle times of 60, 90, 120 and 150s. The plan with a cycle of 90s had the largest bandwidth: 0.175 cycles (15.75s).

4.3 Digital Rails at Avenida Paulista

After obtaining a timing plan as described in the previous section, we developed simulation scenarios to evaluate the impact of Digital Rails at Avenida Paulista.

4.3.1 Trips on Avenida Paulista

The first scenario was analogous to the benchmark scenario: Vehicles traveling on Paulista in both ways, without turns. The origin and destination nodes were the same as in the benchmark scenario, and we also maintained the total vehicle count in each direction.

We assigned a single lane in each direction for Digital Rails, and then studied how the ratio of vehicles using these lanes would affect the traffic by simulating different ratios from 0% to 100% using increments of 5%. Since the selected traffic signal timing plan had a cycle of 90s, platoons of vehicles using Digital Rails would leave their origins every 90s.

4.3.2 Trips on crossing roads

The second scenario was meant to study the impact of the system for vehicles travelling in roads that cross Avenida Paulista. Since the optimization formulation of the previous section only yields the green phase for the main arterial road, we defined the length of the green-light phases for each crossing road such that

$$\frac{g_m}{g_c} = \frac{g'_m}{g'_c} \tag{4.5}$$

Where g_m and g_c are the green-light phase duration for the main arterial road and for each crossing road c, respectively, as measured at Avenida Paulista for the benchmark scenario, g'_m is the green-light phase duration yield by the optimization formulation, and g'_c is the green-light phase duration for the crossing road c.

In this scenario, each vehicle travelled on a given crossing road for a couple of blocks before and after the crossing with Avenida Paulista. The simulation spanned one hour of

[2] http://lpsolve.sourceforge.net/5.5/

real-world time, and the number of vehicles in each road was chosen to fill 50% of the road capacity as reported in OpenStreetMap data: if a given road had a capacity of a 2000veh/h, we simulated 1000 vehicles traveling that road. The start times for the vehicles in each of the crossing roads were uniformly distributed during the simulated hour.

4.3.3 Random walks in the region

Finally, we elaborated a third scenario using a random walk model, where vehicles had different probabilities of entering links with or without Digital Rails depending on whether they already used the system or not. For each transition between links, if the vehicle were in DR, it would stay on the system with probability p_{stay}. If the vehicle were not in DR, it would enter the system with probability p_{enter}. We chose $p_{stay} = 0.9$ and $p_{enter} = 0.3$. The complete algorithm for picking the next link at each transition is as follows:

```
L ← links exiting the current node
DR ← links in L with DR
N ← links in L without DR
if len(N) = 0 or len(DR) = 0 then
    pick a random link in L
else
    if vehicle already been in DR then
        if rand() ≤ p_stay then
            pick a random link in DR
        else
            pick a random link in N
        end if
    else
        if rand() ≤ p_enter then
            pick a random link in DR
        else
            pick a random link in N
        end if
    end if
end if
```

We extracted the traffic restrictions such as forbidden left or right turns from OpenStreetMap, to avoid the simulated vehicles to violate them. The scenario also spanned one hour of real-world time, and we simulated vehicles starting at Avenida Paulista as well as the crossing roads on the selected region. The starting points were the same as on the first scenario (Avenida Paulista) plus the ones on the second scenario (crossing roads). The number of simulated vehicles was chosen in order to fill 50% of the capacity reported on OpenStreetMap, as in the crossing-roads scenario.

4.4 Digital Rails on multiple arterial roads

Finally, we wanted to measure the impact DR would have on a large region of the city of São Paulo. We selected a region spanning a large portion of what is called the expanded downtown (*centro expandido*) of São Paulo, on which CET applies restriction of vehicle traffic[3] during peak hours, based on their license plates.

Figure 4.4 shows the region that we selected, represented on OpenStreetMap. The region consist in a box between latitudes -23.5054 and -23.6327, and between longitudes -46.7566 and -46.5707. It has a daily traffic magnitude of hundreds of thousands vehicles.

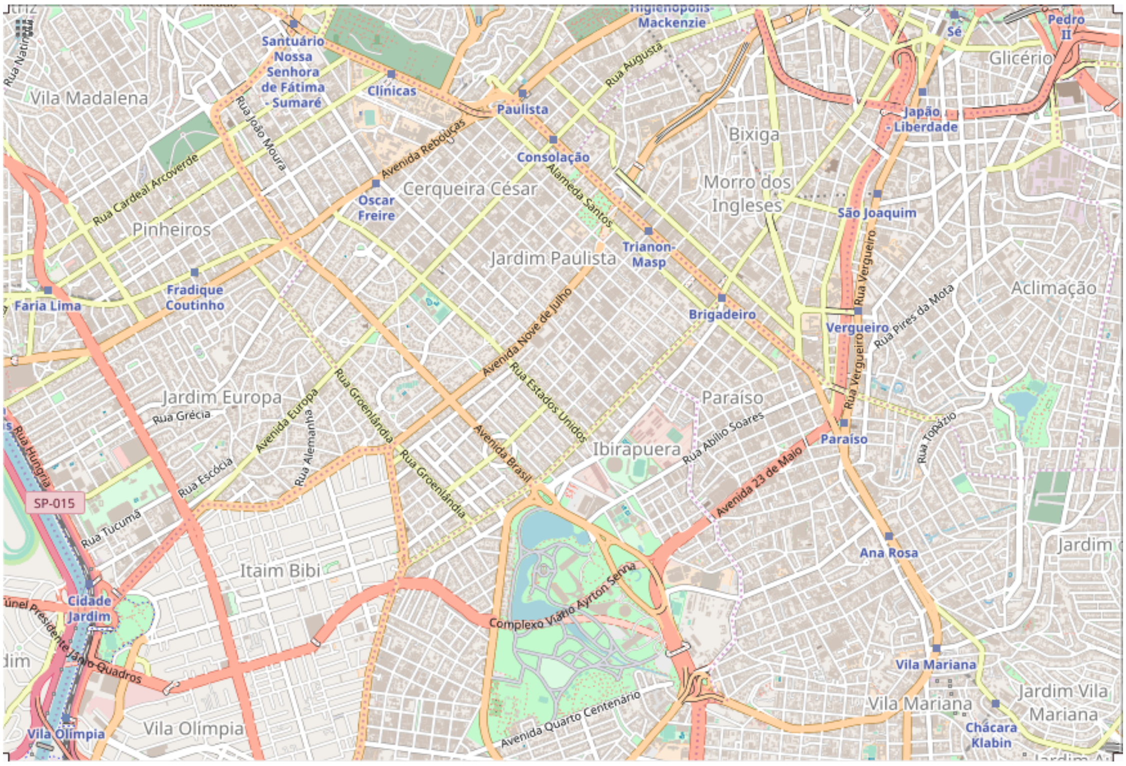


Figure 4.4: *Selected region of São Paulo to evaluate DR impact on traffic.*

We then proceeded to enumerate candidate arterial roads to host DR lanes inside the selected region. The main criteria used was the total traffic volume, as reported by CET. The rationale was that implementing DR lanes in the roads with the most volume should maximize the impact of the system.

From the two most recent reports (Companhia de Engenharia de Tráfego (2018) and Companhia de Engenharia de Tráfego (2017)), we selected the following routes:

1. Avenida 23 de Maio
2. Avenida Pedro Álvares Cabral / Avenida Brasil
3. Marginal Pinheiros (between Jaguaré bridge and Eng. Ari Torres bridge)
4. Ligação Leste-Oeste
5. Avenida Cidade Jardim / Avenida Europa
6. Avenida Paulista
7. Avenida Eusébio Matoso / Avenida Rebouças

[3] Restriction of traffic in São Paulo, in portuguese: http://www.cetsp.com.br/consultas/rodizio-municipal/como-funciona.aspx

Figure 4.5 shows the selected region with the routes highlighted in green. The next step was to generate realistic traffic input for simulation scenarios in the selected region. The starting point were the mobility trace of the city of São Paulo generated with InterSCSimulator and published by Santana *et al.* (2018), obtained by simulating the traffic of the city of São Paulo for a whole day.

From this trace, we isolated all vehicle that passed by the selected region at some point of the day. For each of these vehicles, we defined its trip starting and destinations points as the locations of its first and last appearance inside the region, respectively. This procedure yield an input file with more than 400k trips defined.

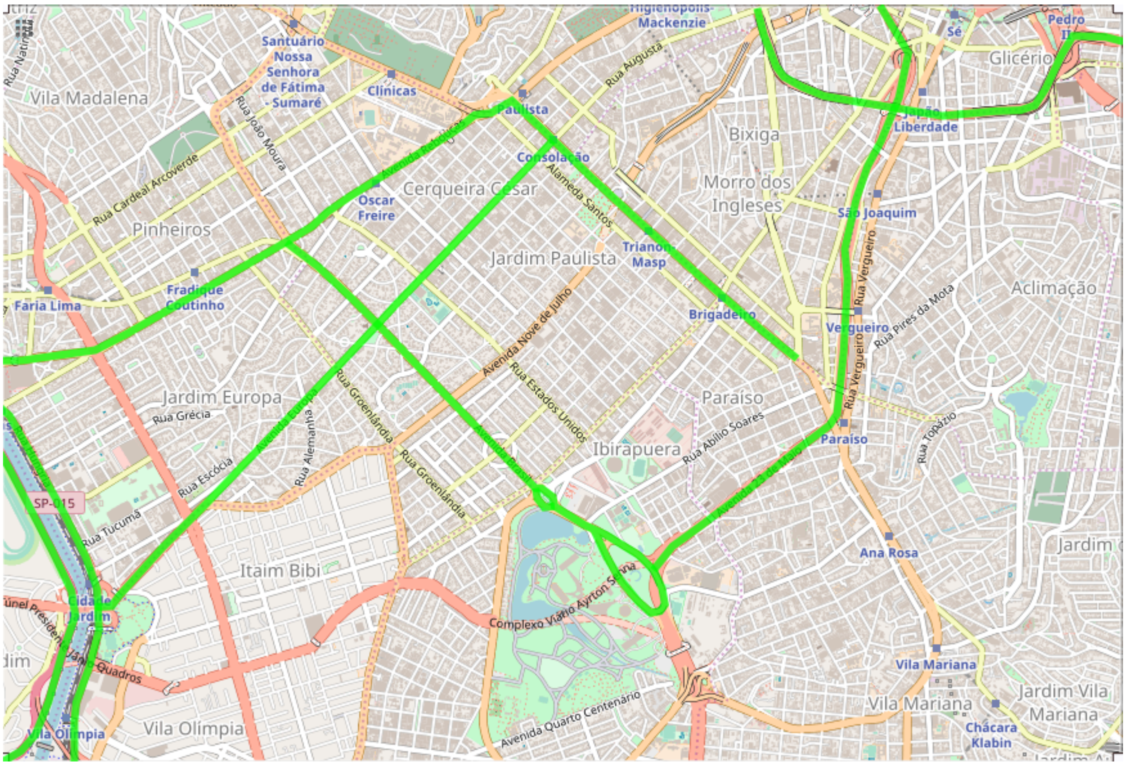


Figure 4.5: *The selected region of São Paulo showing candidate routes to host Digital Rails lanes highlighted in green.*

The last step in elaborating this simulation scenario was to account for all the traffic signals in the selected region, which count on the thousands. Instead of modelling each individual intersection, which would not fit on our straightforward framework for traffic signals, we re-calibrated the speed model described in Section 3.2.1.

The calibration was based on the simulations done for trips on Avenida Paulista, introduced in Section 4.3.1. We prepared a simulation scenario on Avenida Paulista without traffic signals agents. We then tried different values for k_{min}, α and β, and chose the ones that yield similar average speeds to the scenarios with traffic signals and the initial model parameters for InterSCSimulator.

To account for the time lost awaiting for the next platoon, we introduced a penalty in travel time for vehicles entering a DR lane: If the vehicle is entering a Digital Rails lane with cycle time c and bandwidth b, it draws a random number t distributed uniformly between 0 and c. If $t > b$, the vehicle waits t ticks until resuming its travel.

Finally, we ran the simulation scenario with different ratios of vehicles able to use DR. The ability to use the system is assigned beforehand, independently of the route that the vehicle will take.

Chapter 5

Results

As described in the previous chapter, we started with simulation scenarios in the Avenida Paulista region, which were later expanded to a larger region in São Paulo. The results are presented and discussed in the same order. Threats to their validity are presented in the last section.

5.1 Avenida Paulista

For the simulations on the Avenida Paulista region, we start presenting the results for benchmark scenario, followed by the scenario for trips on Avenida Paulista only. We continue with the scenario for trips on crossing roads and finish with the random walk scenario.

5.1.1 Benchmark scenario

First we ran the benchmark simulation scenario described in Section 4.1. The average travel time for vehicles to travel the extension of Avenida Paulista was 563s, with a standard deviation of 45s. This yields an average speed of 15.62km/h (4.34 m/s), consistent with the average speeds reported by Companhia de Engenharia de Tráfego (2018) for probe vehicles travelling at Avenida Paulista at peak hours.

5.1.2 Trips on Avenida Paulista

We proceed with the first simulation scenario described in Section 4.3.1. The chosen timing plan has a cycle of 90s, meaning that Digital Rails support 40 platoons/h. Using the notation presented in Section 4.2, the bandwidth b of the plan is 0.175 cycles (or 15.75s) for both ways.

Assuming that each vehicle using Digital Rails has a length of 2.7m (the same length of a Smart Fortwo vehicle) and travels at the speed limit of 50km/h (13.89m/s), the system supports a maximum of 3240 veh/h each way, which is more than the current vehicle flow on peak hours at Avenida Paulista. Using DR, vehicles spend 197s to travel the whole extension of Avenida Paulista.

Figure 5.1 shows the evolution of the average travel time versus the ratio of vehicles using DR. For each ratio value, we plot the average travel time of all vehicles in 10 simulation runs, complemented by a 95% CI. The black horizontal lines show the mean and 95% confidence interval (CI) for the benchmark scenario.

One can see that the average travel time decreases when the ratio of vehicles using DR increases. Other remarkable results include:

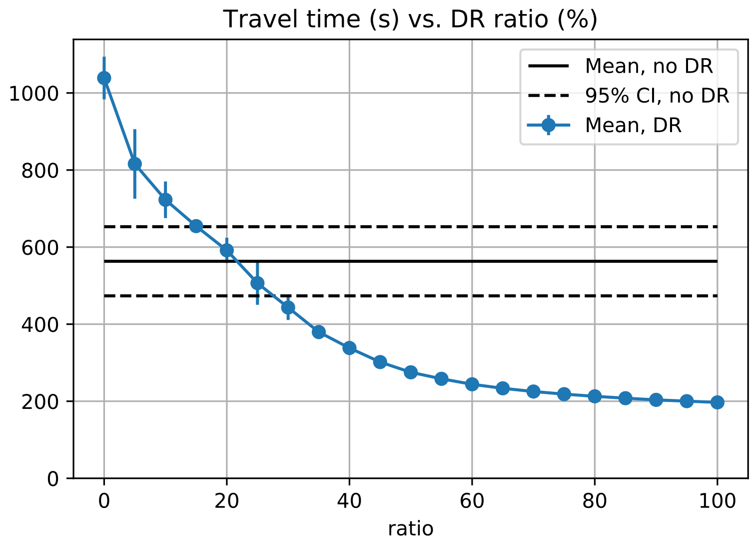


Figure 5.1: *Travel time vs. ratio of vehicles using DR on Avenida Paulista, compared to the average travel time on the benchmark scenario.*

- With a ratio of 25% vehicles using DR, the average travel time is 506s, less than the average 526s in the benchmark scenario.
- With a ratio of 45% vehicles using DR, 99% of all trips have time below 515s, which is less than the average 526s in the benchmark scenario.
- With a ratio of 75% vehicles using DR, the average travel time is 219s, less than half the average 526s in the benchmark scenario.

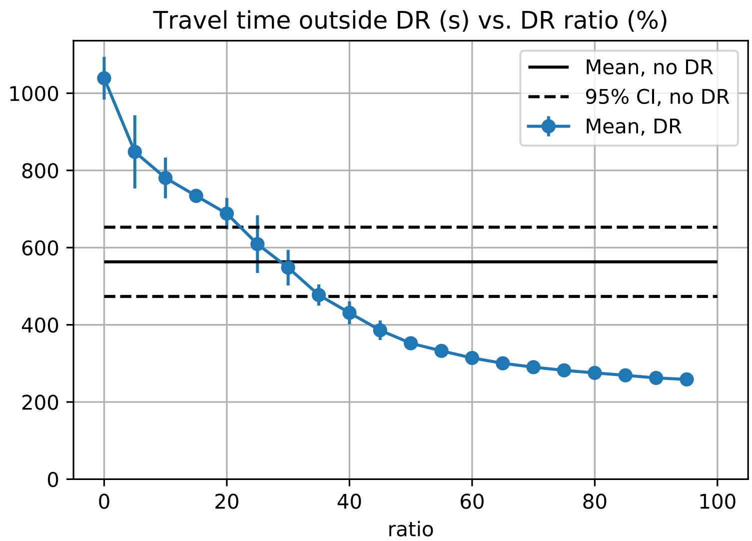


Figure 5.2: *Travel time for vehicles outside DR vs. ratio of vehicles using DR on Avenida Paulista, compared to the average travel time on the benchmark scenario.*

Figure 5.2 presents a similar chart for vehicles outside DR. It is also clear that the average travel time for vehicles outside DR also decreases when the ratio of vehicles using DR increases. Other notable results for vehicles outside DR are:

- If 35% of vehicles are using DR, the average travel time for vehicles outside DR is 466s, which is less than the average 526s in the benchmark scenario.
- If 45% of vehicles are using DR, 99% of the trips outside DR take less than 522s, which is less than the average 526s in the benchmark scenario.

The fact that trips outside DR become faster when more the ratio is greater than 35% is consistent with the speed model described in section 3.2. Since most of the considered portion of Avenida Paulista has 4 lanes each way, one would expect that the single lane assigned to DR each way must contain at least 25% of the total traffic in order to the vehicles using the remaining lanes develop greater speed than in the benchmark scenario.

It is also important to remark that this results does not take into account the time that a vehicle using DR would have to wait until the next platoon, which would make the reductions in average travel time less significant.

5.1.3 Trips on crossing roads

Figure 5.3 presents the travel time for vehicles in the second scenario, consisting of trips on the crossing roads of Avenida Paulista only, as described in subsection 4.3.2. For each crossing, the chart show the average travel time with the traffic signal timing plan used on the benchmark scenario and the average travel time with the plan used on DR. The vertical black lines show the standard deviation of these travel times.

On roads with two ways, such as Rua Augusta and Avenida Brigadeiro Luís Antônio, each way was treated apart, and shown with the "Bairro" and "Centro" suffixes, meaning uptown and downtown traffic, respectively.

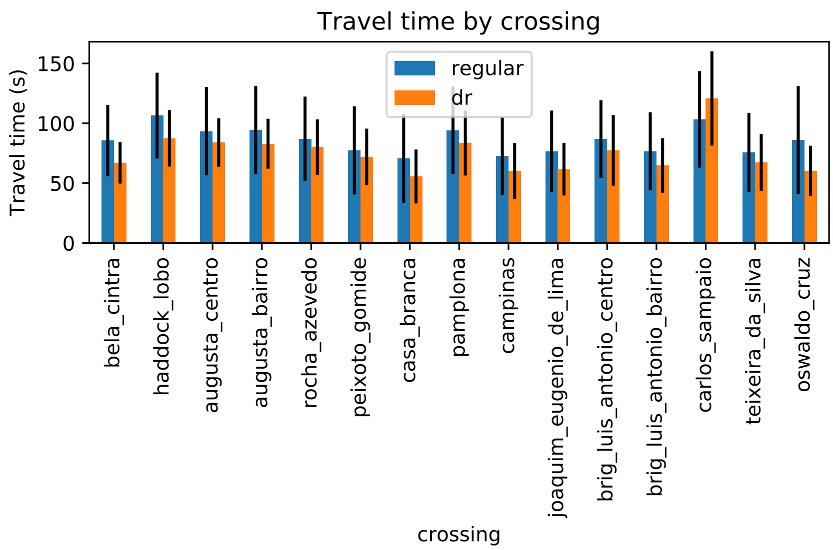


Figure 5.3: *Travel times for vehicles on the crossing roads of Avenida Paulista, using the benchmark scenario signal timing plan (called regular) and the plan used for DR. The standard deviation is shown on the black vertical lines on top of each column.*

It can be seen on the chart that there is no significant difference on travel times for any of the crossing roads, despite the mean travel time with DR being generally lower. We conclude that the traffic signal timing plan used for DR would not increase the travel time for vehicles on the crossing roads.

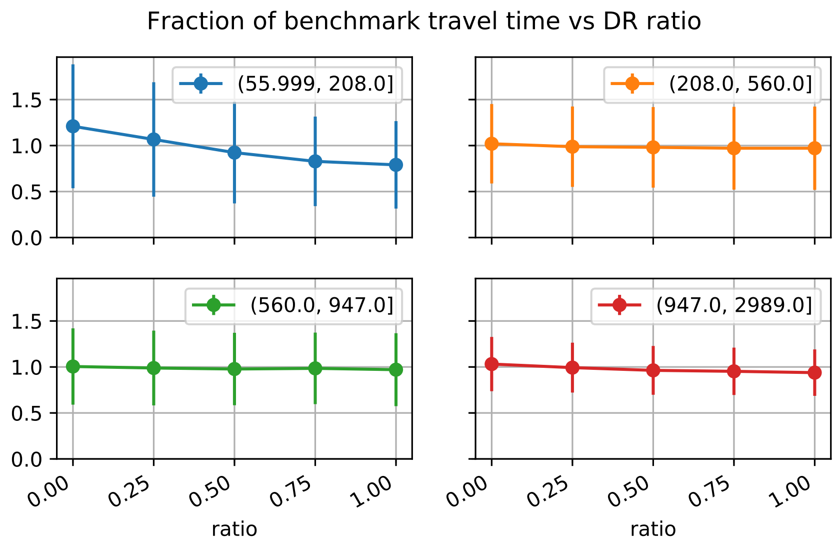


Figure 5.4: *Evolution of travel time with DR ratio for the quartiles of travel distance on the random walk scenarios on Avenida Paulista. The legend on each plot indicates the travel distance range in each quartile.*

5.1.4 Random walks in the region

The simulated travels using the random walk algorithm described in Section 4.3.3 had lengths ranging between 56 and 2989m, with an average travel time of 98s and standard deviation of 76s. Since this range is fairly large, we analyzed the travel times for travels in each distance quartile, as shown on Table 5.1.

Quartile	Travel distance (m)	Avg. travel time (s)	Std. dev. (s)
1	(55.999, 208.0]	37	20
2	(208.0, 560.0]	65	29
3	(560.0, 947.0]	89	36
4	(947.0, 2989.0]	210	57

Table 5.1: *Travel time statistics for each quartile of random walk travels on the benchmark scenario*

On the scenarios simulated, the improvement due to DR lanes was almost unnoticeable. Only the first quartile of travel distances show some decrease in travel times as the ratio of vehicles in DR grow. Figure 5.4 shows the evolution of the travel times for each quartile as a fraction of the benchmark scenario average.

This lack of improvement may be explained by the low density of vehicles, since the traffic on the scenarios was only mean to fill 50% of the capacity reported for the roads on OpenStreetMap. Many vehicles also do a significant portion of their travels in roads other than Avenida Paulista, which are not affected by the DR vehicle ratio.

5.2 Multiple arterial roads

The simulation scenarios with DR on multiple arterial roads did not include traffic signal agents. The re-calibration of the speed model described in equation 3.1 yield $\alpha = 1.0$, $\beta = 1.0$ and $k_{min} = 0.3$. We also used $l_{cell} = 7.5m$ to compute k_{jam} for each link, as described in equation 3.2. As with the scenarios for random walks on Avenida Paulista, the simulated trips in these scenarios also spanned a large range of lengths, ranging from 30m up to 33.2km. Table 5.2 presents the distance quartiles and their average travel times on the benchmark scenario.

Quartile	Travel distance (m)	Avg. travel time (s)	Std. dev. (s)
1	(29.999, 3677.0]	357	388
2	(3677.0, 6545.0]	1079	747
3	(6545.0, 11162.0]	1760	1049
4	(11162.0, 33201.0]	2052	927

Table 5.2: *Travel time statistics for each quartile on the benchmark scenario for the selected region in São Paulo.*

Since there were more than 400k total trips on the benchmark scenario, each distance quartile contains more than 100k trips, with several travel distance profiles, yielding a high standard deviation in each quartile travel time. However, the effect of assigning DR lanes on the arterial roads that we selected was still noticiable for each quartile. Figure 5.5 shows the evolution of travel times as a fraction of the benchmark scenario average for each quartile.

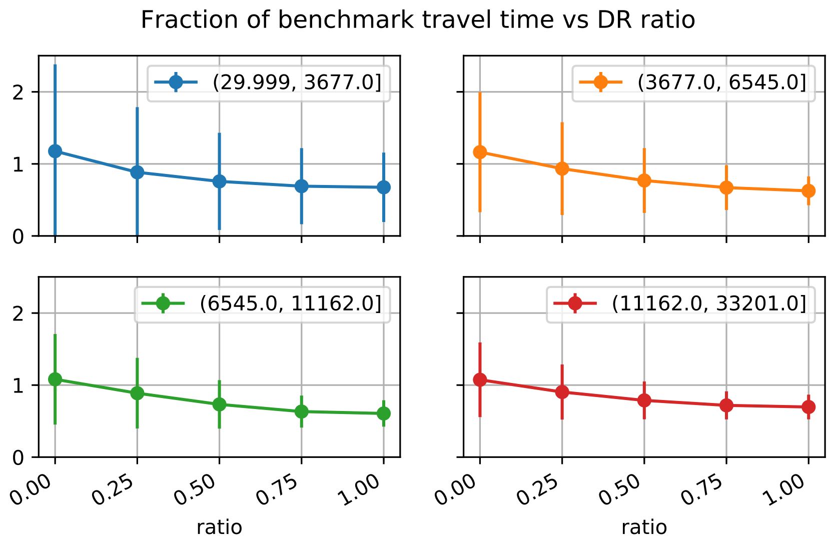


Figure 5.5: *Evolution of global travel time with DR ratio, by distance quartiles on the scenarios with DR in multiple arterial ways. The legend on each plot indicates the travel distance range in each quartile.*

As with the scenario with travels on Avenida Paulista, the travel time decreases when the ratio of vehicles able to use DR increases. It is noteworthy that a ratio of 25%, for example, does not mean that 25% of vehicles actually used DR. Instead, it indicates that 25% of vehicles were able to use DR and used the system whenever they went to a road with an assigned DR lane. We highlight the following results:

- The average travel time is bigger than the average in the benchmark scenario when the ratio is 0. This is because the assignment of a lane for DR decreased the road capacity on the selected arterial ways.
- With a ratio of 25% vehicles using DR, the average travel time were lower or very similar to the benchmark scenario on all distance quartiles.

- For ratios greater than 50% of vehicles able to use DR, all average times were lower than the benchmark.
- With 100% of vehicles able to use DR, the travel times were about 65% of the benchmark.
- The evolution of travel times appears to be similar on all distance quartiles.

We also analyze travel times considering only vehicles that are not able to use DR. Figure 5.6 shows the evolution of travel times for them, also divided in quartiles by travel distance. We highlight the following results:

- With a ratio of 25% of vehicles able to use DR, the average travel time is equal or lower than in the benchmark scenario.
- For ratios higher than 50%, the average travel time is smaller than in the benchmark scenario.
- For 75% of vehicles able to use DR, the average travel time is between 67% and 79% of the benchmark scenario, depending on the considered quartile.
- The evolution of travel times also appears to be similar on all distance quartiles.

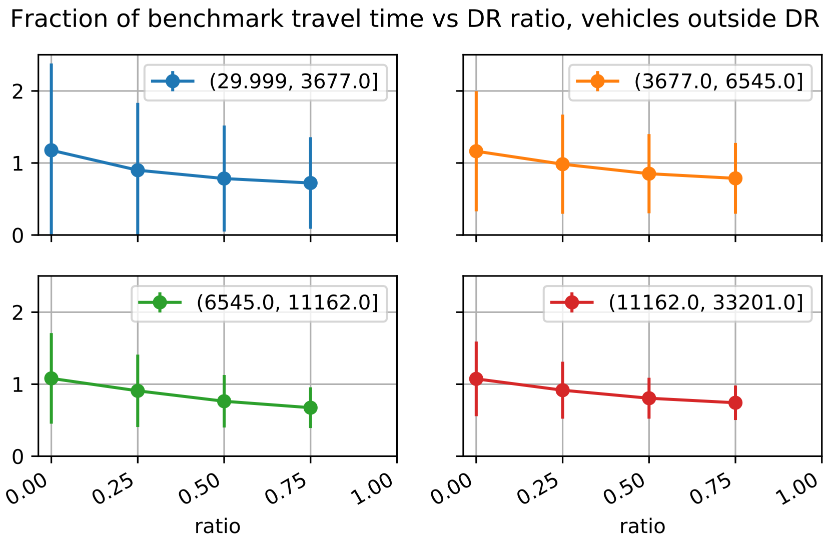


Figure 5.6: *Evolution of travel time with DR ratio for vehicles outside DR, by distance quartiles on the scenarios with DR in multiple arterial ways. The legend on each plot indicates the travel distance range in each quartile.*

In conclusion, the simulated scenarios for DR in multiple arterial ways also present significant reductions in travel times, although less dramatic than the simpler scenarios on Avenida Paulista. This is not unexpected, since the paths of the simulated trips are not always within a road with a DR lane.

5.3 Threats to validity

We now discuss some threats to the validity of our results. The first one has to do with the speed model presented in Equation 3.1. This is a simple mesoscopic model that misses individual vehicular interactions and is not able to simulate the effects of queues and traffic shock waves in great detail, which could have significant impact on the traffic on DR lanes. It could be the case that the model is not well-suited to model traffic on an urban environment, or to model traffic characteristics specific to São Paulo.

Even if the model is accurate, our calibrations may be not. For instance, we used the same α, β and k_{min} for all the links, but the model could have its accuracy increased if the calibration is performed on a link to link basis. Our calibration procedures were also very simplistic, targeting only average speeds.

Another threat lies on the quality of input data that we used. The assumptions that we made to measure traffic signal timings at Avenida Paulista may not hold. We also made assumptions when using the traffic counts from CET reports, for instance, that the vehicle count in a given point in an avenue would hold for the whole extension of the avenue.

Finally, our simulations did not consider some effects that implementing DR could have. First, we considered that the demand for transport would remain the same, and performed all simulation scenarios based on current data. Second, we did not change the routing algorithms for the simulated vehicles, which continued to find paths considering distance only.

Chapter 6

Conclusions and future work

The original formulation of the Digital Rails concept did not include definitions for many technical components, such as the custom vehicle design and detailed specifications about vehicular connectivity and the required levels of automation. While we abstracted many of these components away, we recognize that they represent significant challenges that require a large amount of further research. They must be addressed in future evaluations of the proposal.

Our simulation results show that implementing Digital Rails in a city like São Paulo could lead to reduced travel times, even for vehicles that will not use the system. For simple travels, like the ones we simulated on Avenida Paulista, the time reduction is substantial when comparing to the benchmark scenarios. In the general case, the reduction starts when the ratio of vehicles able to use the system in the total fleet is greater than 25%, signaling that implementing the system before achieving such rate would be unreasonable.

Despite these positive results, we conclude that the Digital Rails proposal should be subject to further evaluation and specification by professionals with experience in traffic operations. Regarding future work that could be done starting from ours, we highlight:

- Techniques to select roads to host the system: Our criteria was very simple, based on the vehicle counts published on the CET reports only. With the data available on them, it is also possible to select routes based on different criteria such as delay or average speed. Another possibility is to use different data sources, such as traffic cameras or even location traces from cell phones.

- Microscopic simulation models: The simulation model implemented in InterSCSimulator is a very simple one. More research could be conducted based on simulations with microscopic models, which capture individual vehicular interactions, queuing and shock wave effects. However, because they are generally more computationally expensive, it should be hard to do a large scale simulation with them.

- Optimization: Our calculation of a traffic signal timing plan, based on an integer programming formulation, uses some fixed parameters like the progression speed and cycle time. More sophisticated formulations could be used, with such parameters being subject to optimization.

- Alternatives for traffic signal control and intersection management: Another possibility is to use control techniques other than pre-timed signals. Assuming that the vehicles have a certain degree of autonomy and connectivity, it should be easy to apply protocols for intersection management such as the ones that we reviewed on the literature.

- Detailed study of single intersections: The traffic signal timing plans used in DR should be evaluated on each intersection considering how it interacts with the traffic signal phases for the crossing road, pedestrians and bicycles.
- Platooning maneuvers and strategies: Techniques for vehicle platooning inside DR lanes should also be elaborated and evaluated. Doing this using traffic simulations would require a microscopic model.
- Different routing algorithms that consider DR: The routing algorithms that we used for the simulated agents considered only the total distance to be traveled. On a scenario with a DR network, different routing strategies that takes DR into account and their effects on traffic could be evaluated.
- Communication protocols: Even the original formulation for DR states that some communication among vehicles and infrastructure is necessary. It is necessary to develop the required protocols and study their performance with simulations.

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