EVALUATING EXCLUSIVE LANES FOR AUTONOMOUS VEHICLE PLATOONS

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ABSTRACT

Digital Rails (DR) is a proposal for a system of exclusive lanes intended for autonomous vehicles. This paper presents the evaluation of this system using macroscopic traffic metrics, mainly average travel time. The DR system consists of a network of arterial roads with exclusive lanes where autonomous vehicles can travel in platoons. We evaluated the impacts of this system on travel time using mesoscopic traffic simulation and real data from the city of São Paulo to create the simulation scenarios. The results show that the proposed system would bring reductions on the average travel time of the city commuters.

INTRODUCTION

Autonomous vehicles (AVs) technology brings new solutions and challenges for urban mobility. The development and adoption of AVs have the potential to reduce traffic jams and increase traffic safety. However, despite the advancement of automation technology in both research and commercial environments, fully 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 city infrastructure: Digital Rails (DR). DR consists of dedicated lanes for AVs that allows AV platoons to traverse arterial roads at high speeds. Traffic signals coordinate the traffic with regular vehicles. On streets with DR lanes, traffic signals on successive intersections should be synchronized to allow the platoons to travel without stops.

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 focused on scalability. The first scenarios simulated DR on a single major road of São Paulo, the Paulista Avenue. For reference, we also elaborated a benchmark scenario based on the current deployed traffic signal timing plan, 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.

RELATED WORK

This section presents other research that aims to evaluate the impact of AVs though simulation. (Bischoffa and Maciejewski 2016) evaluate the replacement of all private cars with autonomous vehicles in Berlin, Germany using the MATSim simulator. Their results show that 100 thousand AVs taxis can replace the current 1.1 million private car fleet keeping almost the same travel time to the commuters. (Talebpour et al. 2017) evaluated the impact of reserved lanes to AVs to facilitate their flow in the city of Chicago, USA. Their simulation showed an increase in the vehicle throughput reserving exclusive lanes for AVs vehicles.

(Liu et al. 2017) present an agent-based simulation of shared autonomous vehicles (SAV) on Austin, Texas, USA, using the MATSim simulator. Besides the effect of SAV on the city traffic, this study presented the estimated cost of this type of vehicles and compared with traditional transportation modes. Indeed, (Zhang et al. 2015) use agent-based simulation to evaluate the changes in the parking spaces of urban areas with the SAVs, the results show that 90% of the parking spots could be eliminated in the cities. Differently, our paper presents the evaluation of an autonomous vehicle system integrated with the rest of the city traffic system. Our results show the impact on time travels for the city commuters using the AV and also regular vehicles.

MAIN CONCEPTS

We begin our presentation of concepts with a short review on autonomous vehicles. Next, we introduce InterSCSimulator, used for the evaluation of Digital Rails. Finally, we present the Digital Rails concept and describe how we implemented it on InterSCSimulator.

Autonomous Vehicles

Vehicles can be classified in different levels of automation. The SAE international 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. (Fagnant and 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 possible reduction of at least 40% in fatal crash rates in the United States. However, AV technology introduces new safety risks such as system failures and malicious hacking.
- Congestion: With AVs sensing and possibly predicting other vehicles braking and acceleration behavior, it can reduce the traffic shock wave propagation.
- Urban planning: AVs can turn commute time into productive time, lowering the cost of living far from an urban center.

Finally, there are moral questions regarding AVs. Certain crash situations may require the vehicles to decide between the safety of theirs occupants against other vehicles or pedestrians. (Bonnefon et al. 2016) present surveys regarding approval of proposed AV behaviors in such situations. For instance, in one study they found that 76% of participants think it would be better for AVs to sacrifice one passenger rather than kill 10 pedestrians.

InterSCSimulator

InterSCSimulator is an open-source, agent-based, Smart City simulator (Santana et al. 2017), with a focus on scalability. The simulator is implemented in the Erlang programming language and relies on the Sim-Diasca discrete-event simulation engine. In this work, we used the InterSCSimulator to evaluate Digital Rails using traffic simulations. For smart city simulations, agents could represent any city element such as buildings, vehicles, streets, and sensors. In the simulation scenarios used in this work, the most frequent kind of agent is vehicles. However, some aspects of the simulation are not done using agents such as the road network. Each agent has an internal state, and generally communicates with other agents via asynchronous messages, following the Actor model.

Besides being an agent-based simulator, InterSCSimulator is based on discrete events and uses a mesoscopic model for traffic 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 of a change of state for a specific agent. Events often cause more events in future ticks, but never events in the past. InterSCSimulator is written in Erlang and makes heavy use of a discrete-event simulation framework called SimDiasca, also written in Erlang. 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. Essential features for discrete-event simulations such as time management are provided by SimDiasca, along with a framework for modeling actor behaviors in an object-oriented fashion.

Digital Rails

The idea of Digital Rails was proposed by Questtonó, a Brazilian innovation, and design consultancy[1]. Its creators envisioned a system where autonomous vehicles would travel in platoons on exclusive lanes, achieving high efficiency through synchronization with traffic signals. The DR concept presents three main pillars:

- Open data network: The city would provide a system that vehicles could access to obtain data about traffic signals, which would run in prefixed timing plans to allow uninterrupted progressions.
- 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 used for extra space for maneuvers.
- 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 the number of stops.

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

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, we abstracted much of these details. Specifically, we made the following assumptions:

- Vehicle-to-vehicle and vehicle-to-infrastructure communications are a solved problem: Our simulation does not consider the need for vehicular networks, and we do not propose protocols or techniques for these communications.

[1] https://www.questtono.com/en/

- The custom design for vehicles that use Digital Rails is specified: We do not propose or evaluate any vehicle design nor any engineering aspect necessary for vehicles to be able to use the system.
- Platooning maneuvers and protocols are well defined: We do not develop protocols for vehicle platooning.

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. Information about DR lanes is represented on its input file, which contains a list of the streets that include the DR exclusive lane. This data is used to complement the InterSCSimulator road network metadata, where a new attribute indicates that there is a DR lane to each link on the list. Each trip defined on the trips input file is marked with an attribute indicating whether the vehicle can use Digital Rails. On links with DR lanes, the vehicles use a simplified speed model, always using the maximum street speed. Otherwise, the vehicles not able to use the DR lane, use the original InterSCSimulator speed model based on the link capacity and the road current vehicle density.

Traffic signals are a new class of agents in the InterSCSimulator. 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 cycle duration measured in ticks. The offset is generally used to coordinate various crossings 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.

METHODOLOGY

We began our evaluation considering a single road in São Paulo with high traffic: Paulista Avenue, located in a central region of the city. Later, we expanded the scope of the evaluation by selecting an area in São Paulo and measuring the impact of DR in its main arterial ways.

Benchmark scenario at Paulista Avenue

The first step to study the impact of Digital Rails at Paulista Avenue was to establish a simulation scenario to represent the current traffic conditions during peak hours. For this benchmark, we limited the simulated traffic only to Paulista Avenue. We considered the segment of the avenue that goes from Consolação Street to Oswaldo Cruz square, spanning about 2445m. All the simulated travels were in one of two possible ways: from Oswaldo Cruz square to Consolação Street (called Consolação way) or from Consolação Street to Oswaldo Cruz square (called Paraíso way, since the square is located at the Paraíso district).

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 (CET 2017) for the morning peak hour at Paulista Avenue: 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 Paulista Avenue. Figure 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.

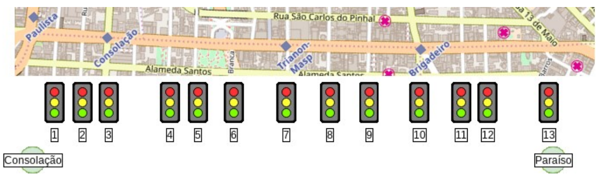

Figure 1: Selected segment of Paulista Avenue and traffic signals location

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. 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, we made the following assumptions:

- There are two phases with a green light in each intersection: One for both ways in Paulista Avenue and the other for the perpendicular way.
- The green light phase for Paulista Avenue in each intersection starts at t=0s, relative to the cycle.
- 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 latter being 150s in every intersection.

Digital Rails at Paulista Avenue

After obtaining a timing plan as described in the previous section, we developed simulation scenarios to evaluate the impact of Digital Rails at Paulista Avenue. 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 rates from 0% to 100% using increments of 5%. Since the selected traffic signal timing plan had a cycle of 90 seconds, platoons of vehicles using Digital Rails would leave their origins every 90 seconds.

The second scenario was meant to study the impact of the system for vehicles traveling on roads that cross Paulista Avenue. In this scenario, each vehicle traveled on a given crossing road for a couple of blocks before and after the crossing with Paulista Avenue. The simulation spanned one hour of 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. 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 $p_{enter} = 0.3$.

We extracted the traffic restrictions such as forbidden left or right turns from OpenStreetMap, to avoid the simulated vehicles from violating them. The scenario also spanned one hour of real-world time, and we simulated vehicles starting at Paulista Avenue as well as the crossing roads on the selected region. The starting points were the same as on the first scenario (Paulista Avenue) 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.

Finally, we wanted to measure the impact DR would have on a large region of the city of São Paulo. We selected an area spanning a large portion of what is called the expanded downtown of São Paulo, on which CET applies restriction of vehicles during peak hours, based on their license plates. 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. Figure 2 shows the selected region with the routes highlighted in green. The next step was to generate realistic traffic input for simulation scenarios in the chosen area. The starting point was the mobility trace of the city of São Paulo generated with InterSCSimulator, obtained by simulating the traffic of the city of São Paulo for a whole day.

For each of the simulated 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 400,000 trips defined. The final step in elaborating this simulation scenario was to account for all the traffic signals in the selected region, which count in the thousands. Instead of modeling each intersection, which would not fit our straightforward framework for traffic signals, we re-calibrated the original speed model of InterSCSimulator. We based the calibration on the simulations done for trips on Paulista Avenue. We prepared a simulation scenario on Paulista Avenue without traffic signals agents.

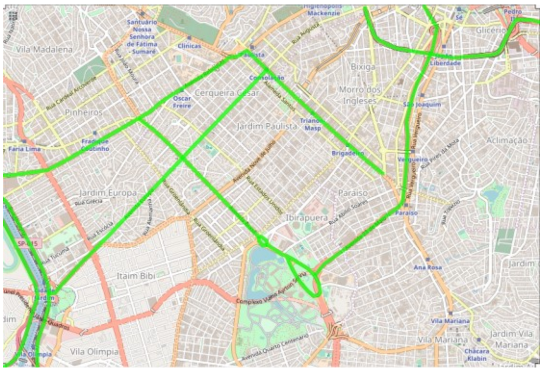

Figure 2: Region with DR lanes highlighted in green

To account for the time lost waiting 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.

RESULTS

As described in the previous chapter, we started with scenarios in the Paulista Avenue region, which were later expanded to a larger region in São Paulo. The results are presented and discussed in the same order.

Paulista Avenue

For the simulations on the Paulista Avenue region, we start presenting the results for the benchmark scenario, followed by the scenario for trips on Paulista Avenue only. We continue with the scenario for trips on crossing roads and finish with the random walk scenario. First, we ran the benchmark simulation scenario. The average travel time for vehicles to travel the extension of Paulista Avenue was 563s, with a standard deviation of

45s and an average speed of 15.62km/h (4.34 m/s), consistent with the reports from São Paulo traffic managers (CET 2017).

We proceed with the first simulation scenario with the DR. The chosen timing plan has a cycle of 90 seconds, meaning that Digital Rails support 40 platoons/h. 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 Paulista Avenue. Using DR, vehicles spend 197s to travel the whole extension of Paulista Avenue. Figure 3 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.

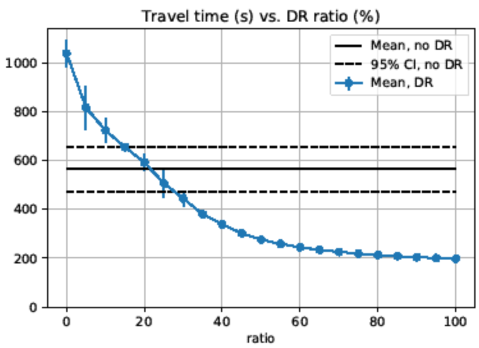

Figure 3: Travel time for vehicles outside DR vs. ratio of vehicles using DR on Paulista Avenue, compared to the average travel time on the benchmark scenario

The average travel time decreases when the ratio of vehicles using DR increases. Other remarkable results include, with 25% vehicles using DR, the average travel time is 506s, 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 4 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 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 higher than 35% is consistent with the speed model of InterSCSimulator. Since most of the considered portion of Paulista Avenue 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 to the vehicles using the remaining lanes develop greater speed than in the benchmark scenario. It is also important to remark that this result 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.

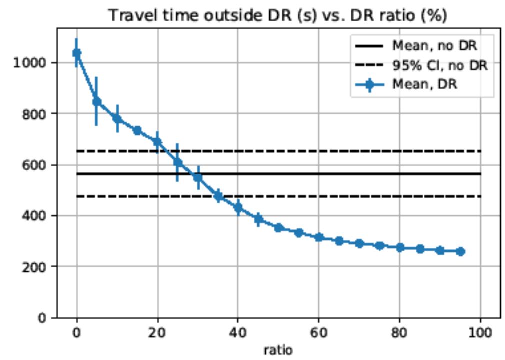

Figure 4: Travel times for vehicles on the crossing roads of Paulista Avenue, using the benchmark scenario signal timing plan used for DR.

For the second scenario, with the random walk algorithm in the Paulista Avenue and crossings, the simulated travels had lengths ranging between 56 and 2989m, with an average travel time of 98s and standard deviation of 76s. Since this range is relatively broad, we analyzed the travel times for travels in each distance quartile, as shown in Table 1.

Table 1: Travel time statistics for each quartile of random walk travels on the benchmark scenario

	Travel dist. (m)	Avg time (s)	Std dev (s)
1	(55.999, 208.0]	37	10
2	(208.0, 560.0]	65	0,05
3	(560.0, 947.0]	89	0.10
4	(947.0, 2989.0]	210	0,15

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 grows. Figure 5 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 meant 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 Paulista Avenue, which are not affected by the DR vehicle ratio.

The last scenario, simulated a broader region of the city of São Paulo, as with the scenarios for random walks on Paulista Avenue, the simulated trips in these scenarios also spanned a large range of lengths, ranging from 30m up to 33.2km. Table 2 presents the distance quartiles and their average travel times on the benchmark scenario.

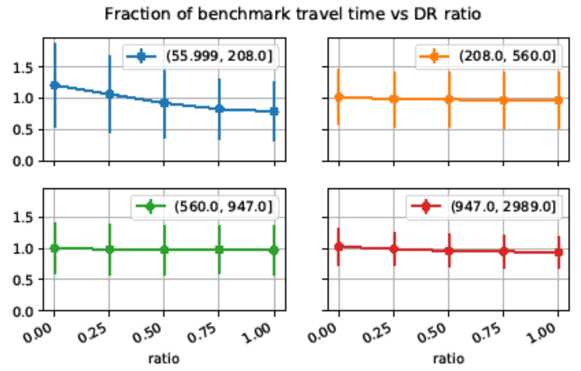

Figure 5: Evolution of travel time with DR ratio for the quartiles of travel distance on the random walk scenarios on Paulista Avenue. The legend on each plot indicates the travel distance range in each quartile

Table 2: Travel time statistics for each quartile on the benchmark scenario for the selected region in São Paulo

	Travel dist. (m)	Avg 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

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 noticeable for each quartile. Figure 6 shows the evolution of travel times as a fraction of the benchmark scenario average for each quartile.

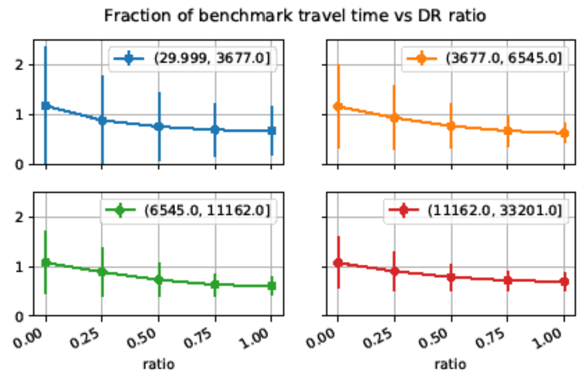

Figure 6: Evolution of global travel time with DR ratio, by distance quartiles on the scenarios with DR in multiple arterial ways.

As with the scenario with travels on Paulista Avenue, 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. 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 7 shows the evolution of travel times for them, also divided in quartiles by travel distance. We highlight the following results: With 25% of vehicles able to use DR, the average travel time is equal to or lower than in the benchmark scenario. For more 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. 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 Paulista Avenue. We expected this, mainly because the paths of the simulated trips are not always within a road with a DR lane.

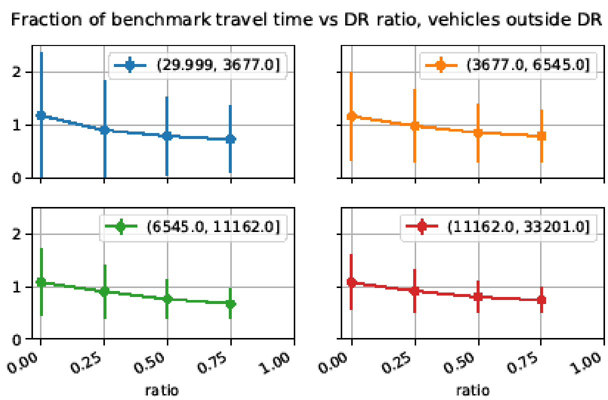

Figure: 7. Evolution of travel time with DR ratio for vehicles outside DR by distance quartiles on the scenarios with DR in multiple arterial ways. The legend on each plot indicates the travel distance in each quartile

Threats to validity

We now discuss some threats to the validity of our results. The first one has to do with the InterSCSimulator and the DR speed model, which are mesoscopic models that miss individual vehicular interactions and is unable to simulate the effects of queues and traffic shock waves in great detail, which could have a significant impact on the traffic on DR lanes. Even if the model is accurate, our calibrations may not be. For instance, we used the same parameters 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.

CONCLUSIONS AND FUTURE WORK

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 Paulista Avenue, the time reduction is substantial when comparing to the benchmark scenarios. In the general case, the decline starts when the ratio of vehicles able to use the system in the total fleet is higher 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. Regarding future work that could be done starting from ours, we highlight:

- DR exclusive lanes selection: Our criteria was very simple, based only on the vehicle counts published on the CET reports only. However, it is possible to use different data sources, such as traffic cameras or location traces from cell phones.
- Microscopic simulation models: Simulations with microscopic models can capture individual vehicular interactions, queuing and shock wave effects.
- Platooning maneuvers and strategies: Evaluate techniques for vehicle platooning inside the DR lanes should also be elaborated and evaluated with microscopic models.
- Different routing algorithms that consider DR: The routing algorithms that we used for the 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.

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 need further research.

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