An Integrated Framework for IVC Simulation under Realistic Interconnected Transport Environments

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Abstract

The performance of transport systems in the movement of people and goods has become a critical aspect in the planning process of a city. Today the advances in technology have changed the paradigms behind planning, fleet design, and optimization of massive transport systems, in a context where the dispatch and routing decisions from systems' operators as well as motorists, are based on real-time information of the whole system performance. Simulating the effects of inter-vehicle communication on transport system behavior are of paramount importance for the design of efficient Intelligent Transport Systems and related wireless communication protocols. In this sense, we recognize the importance of properly modeling the impact of applying optimization algorithms used for dynamic routing and dispatching along with the consequences of highly congested and dynamic mobility models on the communication channel. Some work has been done on bidirectionally coupled simulators for studying these effects side by side under an integrated environment, but much work remains to be done on bringing the fields of transport and wireless network simulations together.

This work presents an adaptation of the existing VEINS bidirectional simulation framework for use with Paramics, a new system we call PVEINS, bringing the framework closer to the tools already in use in the field of transportation. We present the general design of this modified framework, along with a proof-of-concept simulation scenario to illustrate its capabilities. Finally, we also provide a brief performance evaluation along with guidelines for future work.

Keywords: Bidirectionally Coupled Simulation, Intelligent Transportation Systems, Intervehicle communication, PVEINS, Routing and Dispatch

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1. Introduction

Nowadays, the performance of transport systems in the movement of people and goods within an urban context has become a critical aspect in the planning process of a city, with a high impact in the many activities performed by people in their daily schedule of events. In fact, inefficient transport systems are the reflex of disorganization in the normal functioning of the city as a whole, causing increasing travel times, delays on the dispatches of goods, people getting late and in a bad mood to work, a high rate of pollution due to long routes at low speed of circulation, among many other aspects. Moreover, today the advances in technology have changed the paradigms behind the planning, fleet design, and optimization processes associated with massive transport systems. We are moving to a world where the dispatch and routing decisions made online by systems' operators as well as ordinary people driving their car, are based on real-time information obtained from the conditions of the whole system performance. Then, the inter-vehicle communication (IVC) is an issue that now has become relevant in both directions, from the operators and decisions makers trying to convey the results of their optimization algorithms to users and vehicles for a better scheduling and routing, and from the system to decisions makers, communicating real-time information of traffic conditions, online demand, and unexpected events that could completely change the expected response of algorithms.

In the last decades, the concept of Intelligent Transport Systems (ITS) has become popular in the aforementioned sense, in which an architecture ITS appears as a response to the necessity of optimization, coordination, and improvement in several aspects of the different transport systems interacting. The objective of ITS is to offer innovative ways to provide transport services and traffic management, giving as well real-time information to the users of the different transport modes, for them to have a more pleasant, coordinated, and safer way to realize their transport needs. The types of applications that arise are different, from routing and scheduling of massive transport systems to the provision of entertainment systems on-board and the control of autonomous vehicles, for example. As we mentioned previously, a critical aspect to be considered in these applications is the necessity of extracting information in real-time from the system operation, which has to be processed to generate a response to the user, or an input required by the dispatching or routing algorithm. With this objective in mind, several wireless access technologies have been proposed to make this communication possible, with standards such as IEEE 802.11-OCB (previously 802.11p), WPAN technologies such as IEEE 802.15, or cellular access networks such as LTE [1, 2, 3, 4]. However, the complexity and dynamism of transport systems generate the necessity of evaluating communication technologies and protocols in more realistic environments of operation of transport systems, focusing on critical parameters such as the transmission delay, the conditions of the transmission channels, and the optimal distance between nodes in the communication network.

This research is the result of the necessity of modeling the behavior of wireless communication technologies for vehicular networks realistically. In addition, it is also relevant to evaluate the impact of the wireless communication in the performance of transport systems in terms of optimization algorithms used for dynamic routing and dispatching. A typical example is the current dissemination of Advanced Traveller Information Systems (ATIS), which provide real-time information of traffic conditions to drivers, allowing them to modify their routing decisions while moving toward their destination. It is clear that the immediate feedback has an impact in the performance and optimization of transport systems, and that is something worth to be analyzed in the context of both, a proper way to model the communication network coupled with the proper modeling of the movement of vehicles on a transport network.

Nowadays, in the context of transport systems, the simulation has become a very attractive tool to represent the movement of vehicles under several scenarios and traffic conditions. Simulations are performed at different scales depending on the purpose [5]: macroscopic, mesoscopic, microscopic, and nanoscopic. The macroscopic models use continuum fluid representations, and the microscopic simulation models typically rely on detailed car following and lane changing models [6]. In contrast, a mesoscopic model considers vehicles (with a specific origin, destination, departure time, and routes) individually and moves vehicles according to a number of macroscopic traffic flow relations. In the context of this work, and given that the objective is to go deep into communication issues related to the movement of specific vehicles, we focus our analysis at a microscopic level. The focus is then in the integration of a well-known simulator of wireless communication networks –OMNeT++–, with a well-known commercial package of traffic microsimulation –Paramics–. Both were chosen due to their availability, the extensive use of both in the academic and professional modeling of communication and transport networks, and the necessity of creating a common platform able to incorporate the communication issues in the microscopic simulation of transport systems.

The framework developed in this article is an extension of a previous work [7, 8, 9], in which OMNeT++ is integrated with the open source traffic microscopic simulator SUMO, where the communication between both simulators is performed through a socket, in a client-server configuration. The implementation proposed in the present work replaces SUMO by Paramics in a very transparent way to OMNeT++. As explained later, we implement a plugin using the API functions of Paramics. The framework allow us to construct a wireless communication network equivalent to the transport network in Paramics, in which each vehicle in Paramics is associated with a node containing the communication capabilities as in OMNeT++. Both simulations evolve in a synchronized way, and the nodes in OMNeT++ can modify the behavior of their respective vehicles. With this framework, it is possible to analyze the interaction in both ways: the impact of vehicular mobility on the communication channel, and the impact of the information transmission on the transport system modeling.

In what follows, we present a brief review of the state of the art for bidirectional IVC simulation. Next, we explain the proposed PVEINS simulation framework, together with a validation of the tool using several experiments in order to quantify its performance in diverse ITS scenarios. Finally, we provide some key conclusions as well as ongoing and future research.

2. Related Work

In the case of transport systems, particularly in the context of ITS applications, the microscopic simulation of traffic has become a very attractive tool [10]. Examples of simulation models that have been applied to real-life networks include DynaMIT [11], AIMSUN [12], and METROPOLIS [13]. Hybrid models proposing simulation at different levels (mostly meso and micro approaches) are also found in the literature [14]. With regard to the simulation of other vehicles different from private cars, Cortés *et al.* [15] and Fernandez *et al.* [16] developed a platform of microsimulation constructed to model transit systems; Cortés *et al.*, [17] developed also another module that microsimulates a fleet of vehicles routed according to certain dispatcher rules, where the vehicles are able to interact with other modes. The simulation schemes add the passengers (or clients) as part of the simulation engine (then, it corresponds more to the nanoscopic level of simulation, as defined by Ni [5]).

According to Sommer *et al.*, most traffic simulations of ITS are performed *unidirectionally* [8], by feeding realistic mobility traces into wireless network simulators. These traces can be generated in two ways: *offline*, in which case the trace is either obtained from a real-world source [18, 19] or generated separately in a traffic simulator [20], or *decoupled online*, in which case the network simulator simply *consumes* the traces as the traffic simulator generates them.

While these methods are useful for studying the effects of real-world mobility patterns on wireless communication networks, they are not able to replicate the effect that the communication itself may have on the underlying transportation model. Such methods are thus unsuitable for the study of systems which can be assumed to have an impact on driver behavior, such as accident information and hazard warning systems.

These kind of systems require closed-loop cooperation between the network and transport simulation environments, in which the wireless network simulator no longer acts as a mere consumer of mobility traces, but is also able to produce feedback in the traffic simulator.

The environments featured in [21, 22] are examples of this. The first of these, NCTUns, was developed from scratch by researchers from the *National University of Chiao Tung* in Taiwan. It is a completely integrated environment for ITS simulations, and as such implements both elements from traffic simulators and network simulators; it is able to simulate both predefined vehicular traces as well as dynamically generate them, and implements a complete protocol stack on top of each vehicle.

Moreover, TraNS, developed by researchers from the *École Polytechnique Fédérale de Lausanne*, Switzerland, is a framework which integrates two well-known simulators in the field of wireless communications for Intelligent Transportation Systems. SUMO [23], a microscopic traffic simulator developed from scratch by researchers from the German Institute of Transportation Systems, handles the transportation and traffic aspects of the simulation, while ns-2 [24], a popular network simulator developed by several different international agencies and companies, handles the wireless network. Both simulators operate side by side, communicating through a TCP socket using the TraCI - ***Tra****ffic* ***C****ontrol* ***I****nterface* - protocol [25].

Another example of an environment which employs this kind of architecture is the VEINS framework [9], developed by researchers at *Universität Paderborn* in Germany. This framework integrates OMNeT++, a discrete event simulator widely used in the field of ad-hoc wireless communications [26], with SUMO, also using a TCP socket and TraCI.

There exists thus a number of solutions for integrated simulation and study of Intelligent Transportation Systems. Nevertheless, a big problem still persists - all of these solutions come from the field of wireless communications, and generally do not take into consideration the standards and models used by the researchers working on Transportation and Operations Research. For instance, Joerer *et al.* identify SUMO as the most used traffic simulator in ITS simulations, appearing in about 20% of all publications [26], whereas a 2015 survey by Mubasher *et al.* found SUMO to only be fifth most popular traffic simulator in the transportation literature [27]. In contrast, the same study by Joerer *et al.* mentions that the traffic simulator VISSIM is used in a mere 6% of all ITS publications - this same simulator is noted by Mubasher *et al.* to be the *most* popular in transportation studies, with three times as many occurrences in publications as SUMO (see table 1). We can conclude then that there exists a gap between communication and transportation research topics in the field of ITS and other dispatching, routing and optimization rules (used in the field of Operations Research as well, where simulation is becoming relevant in dynamic settings), a gap that we will attempt to bridge with the work presented in this article.

Simulator	**Ocurrences in Literature**
VISSIM	15
PARAMICS	12
CORSIM	10
AIMSUN	9
SUMO	5

Table 1: Traffic simulators in transportation science literature (table adapted from [27]).

3. The PVEINS Simulation Framework

We present the PVEINS (*Paramics-VEINS*) Simulation Framework as a step towards abridging the gap that exists between ITS simulations in the fields of communication and transportation research. The framework is based upon the work done by Sommer *et al.* on the VEINS integrated simulation framework [7, 8, 9], replacing SUMO with one of the most popular traffic simulators in transportation applications: *Quadstone Paramics* (see table 1).

Our choice of frameworks and simulators is based primarily on two factors. Firstly, Paramics is the second most popular traffic simulator in academic publications according to Mubasher [27, 28], particularly due to its extensibility and adaptability through its Programmer API. This component of the Paramics software suite allows users and researchers to create extensions - *plugins* - to the functionality of the simulation environment using the C and C++ programming languages, for instance to integrate novel routing algorithms, or as in our case, to couple the simulation with external software.

Secondly, the OMNeT++ and the VEINS simulation framework haven proven themselves as one of the most popular tools for ITS simulations in the fields of communication and networks, being mentioned and used in hundreds of publications [29]. The framework is highly extensible, both in terms of simulation modules for the OMNeT++ environment and in terms of the lower-level components of the coupling between simulators. Besides, it is very well documented.

3.1. Coupling Paramics and OMNeT++

We developed a client-server framework that builds on top of the existing VEINS architecture, integrating Paramics through a plugin that contains an implementation of a TraCI server. Our plugin acts thus as an interface that allows any TraCI client to obtain traffic information from, and to also directly modify the internal state of the traffic simulator using standard TraCI commands.

Coupling of the traffic simulator and the already existing VEINS/OMNeT++ framework takes advantage of the fact that both the traffic and network simulators are based on discrete events models. This means that both simulators advance the state of their internal models in regular, non-continuous, intervals, which are used by the framework to buffer and synchronize commands.

In figure 1 we show a synthetic representation of the proposed Paramics - Vehicles in Network Simulation (PVEINS) framework.

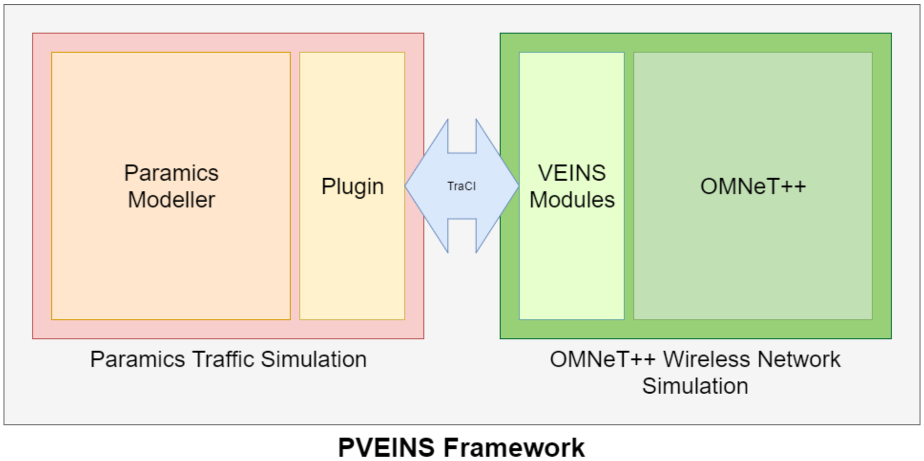

Figure 1: General architecture of the PVEINS framework.

The control of the simulation execution as a whole is handled by OMNeT++, in a *lockstep* execution model (exemplified by figure 2); what this means is that the simulators "take turns" advancing their internal states, so as to maintain complete synchronization. This design is also natively compatible with the sequential simulation models of both simulators, simplifying the total complexity of the system and reducing overhead.

Given its modular nature and client-server architecture, the framework maintains compatibility with most OMNeT++ modules, making it extensible and dynamic.

3.2. Implemented Functionality

The following functionality has been implemented in the current version of the framework:

1. **Simulation control.** Functionality for initializing, advancing, and closing the simulation from an external TraCI client.
2. **Variable extraction.** Functionality for extracting values both from the traffic simulation itself (for instance, the total number of vehicles present in the transport network at any given moment) and from its components (*e.g.,* the speed and position of a particular vehicle).

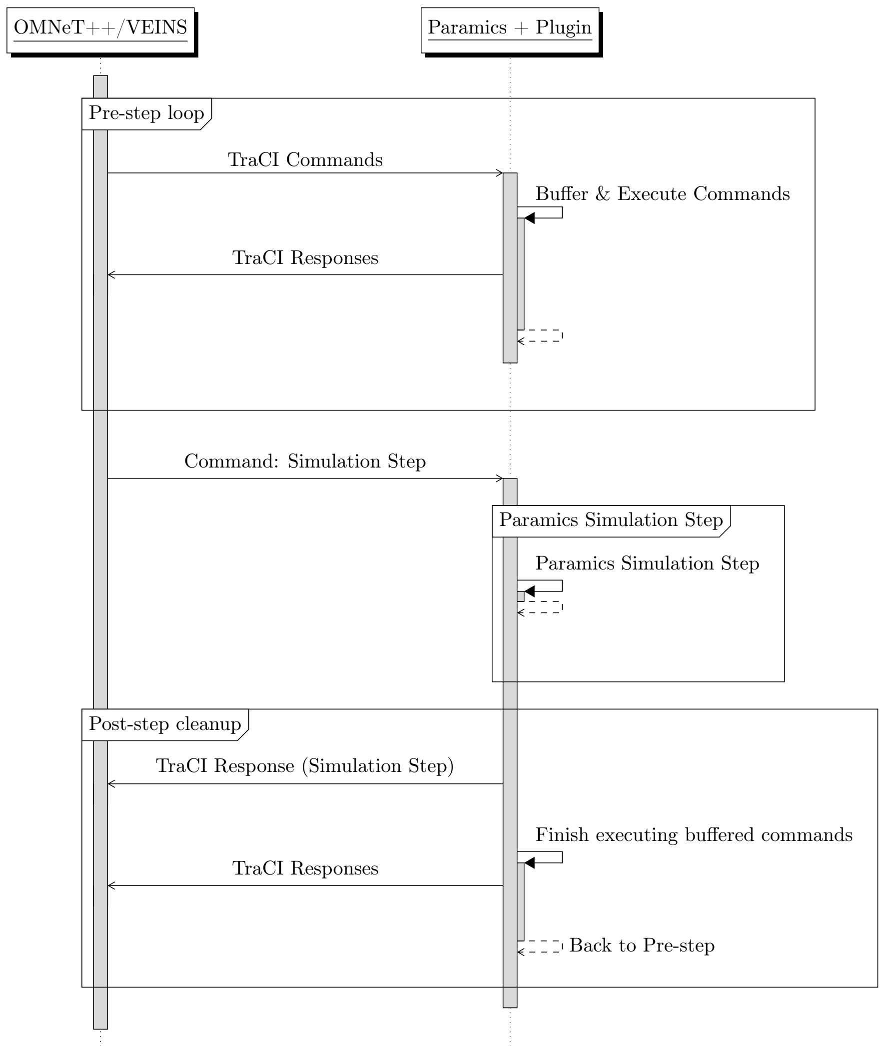

Figure 2: Execution flow of PVEINS

3. **Vehicle control.** Functionality for changing the states of vehicles in the traffic simulation, *e.g.,* changing the speed, acceleration or even the trajectory of a vehicle.

4. Validation

We designed a realistic proof-of-concept scenario to test the feasibility of studying real-world applications of Intelligent Transportation Systems with PVEINS. The scenario builds on top of a map of Providencia, a busy commercial sector of Santiago de Chile, developed by Zúñiga in 2010 [30].

The scenario consists of a simulation of rush-hour traffic during which a car is stopped by PVEINS, emulating an accident. The stopped vehicle emits a series of warning beacons (i.e., every 5 seconds) to nearby vehicles using the IEEE 802.11p wireless access technology. Neighboring vehicles react to the warning by doing a simple route-change to avoid the compromised road[1]. Six total *runs* of the scenario were executed with three different *demand factors*; 20%, 50% and 100%. The *demand factor* corresponds to a relative measure of the demand of vehicle flow in the simulation – for this particular scenario, a demand factor of 100% corresponded to an average of 1380 vehicles present in the simulation at any instance in time (see table 4). For comparison purposes, half of the *runs* of the scenario were executed without actual communication among vehicles (see figure 3 and table 2 for a synthesis of the validation scenario) in order to measure the effect of beacons reception in the behavior of traffic.

From these *runs* we then extracted statistical information regarding the performance of the transport network in the presence of an accident, with and without intervehicular communication. In specific we looked at:

- the number of vehicles that arrived at their intended destination in the simulated time;

[1] Basically, we force the vehicle to take an alternative, parallel, road if we estimate there is a possibility the vehicle will traverse the compromised road.

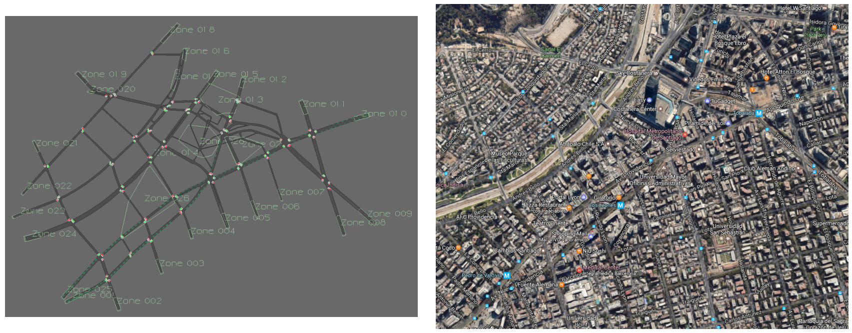

Figure 3: Side by side comparison of the Paramics map used for the simulation scenario and the corresponding sector in real life (image courtesy of Google Maps ©).

- the relationship between time and total distance covered, for each vehicle;
- and the relationship between CO^2 emission and total distance, again for each vehicle.

The results were encouraging, and in line with what we expected based on already established knowledge in the field of ITS and other dynamic transport and Operations Research applications.

To begin with, we obtained general simulation data through OMNeT++. We found a general increase in the number of vehicles that arrived at their destination in the given simulation time when the vehicles were able to communicate compared to when they could not (see figure 4 and table 3). Although the difference is marginal, it is consistent across experiments, and represents a general trend that agrees with what one could reasonably expect.

We attribute the small size of the difference to two factors. Firstly, given the size of the network, the incident itself only has a measurable effect on a small percentage of the vehicles that traverse it. Most vehicles in the network never actually come near the accident road, and thus their travel time and trajectory are almost completely unaffected. Secondly, our rerouting procedure is simple and far from a more formal optimization procedure, which may result in a less efficient response to the accident.

For our second and third validation experiments, we extracted data about the

Parameter	**Value**
pMax	20mW
sat	-89dBm
alpha	2.0
carrierFrequency	5.890e9 Hz
sendDirect	true
useServiceChannel	false
txPower	20mW
bitrate	18Mbps
sensitivity	-89dBm
useThermalNoise	true
thermalNoise	-110dBm
usePropagationDelay	true

Table 2: Simulation parameters for the 802.11p wireless access technology employed in the validation scenario

total time spent in the simulation, the total amount of CO^2 emissions and the total distance traversed, per vehicle. We then studied the correlations between these measurements, specifically the relationship between distance traveled and total time (figure 5), and between distance and carbon dioxide emissions (figure 6).

We found that although the scenarios with and without communication present very similar behaviors, the effect of the unmitigated accident can be clearly observed in the correlations for the scenario devoid of communication. In the case of distance versus time, there are evident groups of vehicles which deviate from the general behavior of the scenario, presenting lower total distances coupled with longer travel times - no doubt because of the congestion caused by the accident. In contrast, the scenario with communication presents a much more even behavior, and although there are some small groups of deviating vehicles, these are not nearly as pronounced as in the former case.

Similar conclusions can be drawn from the relationship between distance

Duration	**Comm. Disabled**	**Comm. Enabled**	△	**% improvement**
15 min	3801	3858	+57	1.5%
2 hr	11014	11488	+474	4.3%

Table 3: Comparison between the number of vehicle that reached their destinations for scenarios with and without communication (100% demand factor).

and CO^2 emissions. Once again, the scenario without communication presents groups of vehicles that deviate from the general behavior, generating higher carbon dioxide emissions for shorter distances. These results are all in concordance with what one would expect from previous established knowledge.

Thus, we can conclude from these experiments that the framework provides a robust tool for modeling realistic and dynamic scenarios of optimization from dispatchers, operators, and the behavior of drivers. Also, taking into consideration the simplicity of the scenario and basic optimization rules applied, one could expect even more precise results with proper tuning of the parameters of the communication system and the transport infrastructure, as well as the optimization methodology.

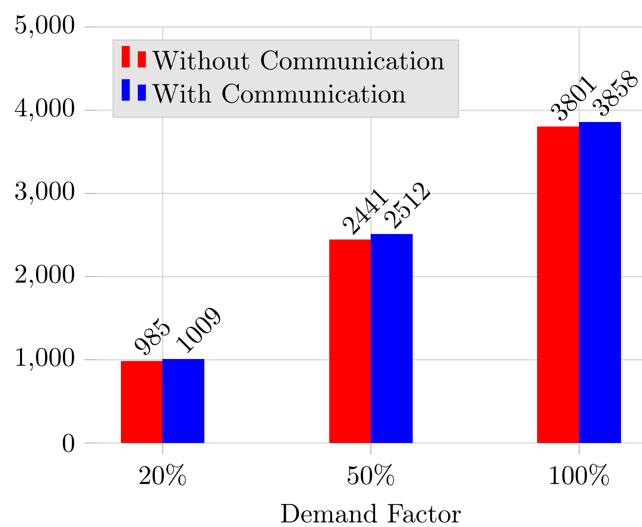

Figure 4: Comparison of the number of vehicles that arrived at their respective destinations within the simulation time.

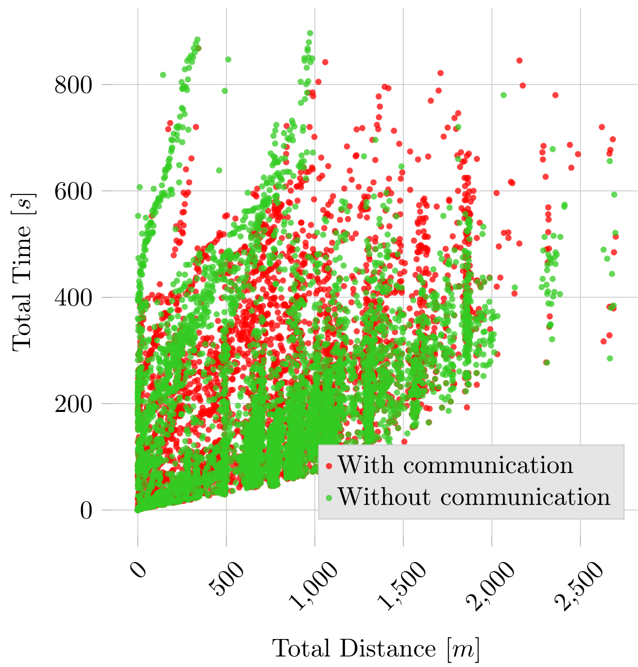

Figure 5: Distance vs. Time traveled.

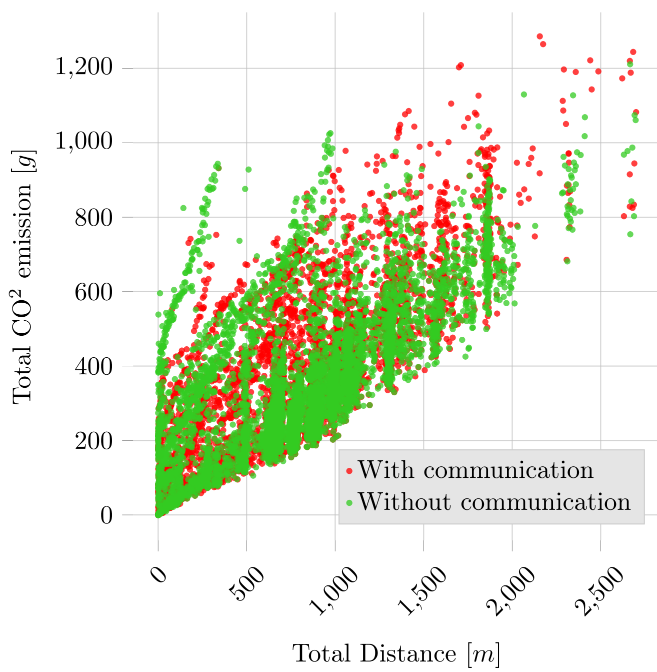

Figure 6: Distance vs. CO^2 emissions.

Demand Factor	Avg. Number of Vehicles	Mean Execution Time [s]	Ratio $\frac{\text{Exec. Time}}{\text{Simul. Time}}$
100%	1379.9	1471.5	1.64
75%	868.75	683.5	0.76
50%	514.5825	275.75	0.31
25%	246.5675	113.25	0.13

Table 4: Average number of vehicles present in simulation at any given time vs. mean simulation execution time, for a 900 second long scenario (simulated time).

4.1. Computational Performance

We also evaluated the feasibility of studying large scenarios efficiently with the framework. To this end, we measured the running times for the aforementioned scenario with four different demand factors. The results of these measurements, four for each demand factor, can be observed in table 4.

From these results, it can be concluded that the software is efficient for large networks; for this specific scenario, the framework achieved ratios smaller than 1.0 between execution time and simulation time for three of the four demand factors, meaning that the simulation executes in less time than the time it is simulating. Additionally, although the ratio for the largest demand factor was greater than 1.0, it should be noted that the load is extremely high considering the scenario is simulating extreme rush hour traffic in a busy downtown sector of Santiago.

5. Conclusions and Future Work

In this paper, we have presented a framework, called PVEINS, that integrates the widely used commercial microscopic traffic simulator Paramics with OMNeT++, a discrete event simulator commonly used in the field of performance evaluation of wireless communications and protocols. The developed framework, in general, fulfills all the requirements for a complete bidirectional simulation environment of microscopic traffic scenarios, which can be used for many applications such as dynamic optimization of transportation systems considering routing, dispatch, and scheduling, as well as other Intelligent Transportation Systems applications. We managed to simulate a realistic scenario with great success, obtaining data from the simulation that allowed us to perform meaningful analysis on the simulated system. The inclusion of the communications is a key issue in the evaluation of optimization transport algorithms and behavioral models affected by the real-time information collected from the transport network. With the bidirectional framework provided by PVEINS, researchers from the fields of transportation engineering and wireless communications will be able to simulate many interesting transport systems scenarios. The next step is to code more sophisticated rules in the APIs developed in Paramics by Cortés *et al.* [15] and Cortés *et al.* [17] for modeling public transport systems as well as fleet dispatch and routing, in an integrated way with the communication network models provided by OMNeT++.

Finally, the code for the framework can be obtained from the author's personal GitHub repository on `https://github.com/molguin92/paramics_traci`, distributed under a *BSD 3-clause revised* license [31].

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