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Powered Two-Wheelers
Extensive Simulation Study in SUMO

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Abstract

Traffic congestion and road safety is a well-known issue of the ever-growing population moving in our cities. Among the topics we are interested in, the Intelligent Transportation Systems (ITS) community is conducting studies on safety, mobility patterns, and traffic optimization. Although globally increasing in Europe, Powered Two-Wheelers (PTW) are underrepresented in these ITS studies. In the last two years, we evaluated multiple aspects of mobility and traffic efficiency while relying on PTW to reduce congestion in modern cities. Our case study is the Principality of Monaco. Despite all the efforts and enhancements to the public transports, the parking spaces, and the road infrastructure, Monaco faces recurring daily congestion due to substantial commuters traffic, mostly coming from Nice, the 5$^{\text{th}}$ biggest city in France by population. Our approach evaluates the impact of PTW in a multi-modal environment, in order to propose solutions that will shift the users from private cars to PTW, keeping into account the impact on the existing infrastructures.

In this study we show by simulation means how increasing gradually the number of PTW enhances the overall mobility and decreases the traffic congestion as expected. Although the simulation results are promising, to validate them, we require calibration data. Since the beginning of the project, there is an ongoing discussion with the Principality of Monaco to obtain them.

In the meanwhile, we studied the impact of the mode shift to PTW with other methods. We explored issues connected with our main topic, and we implemented the tools required to achieve a comprehensive study. Initially, we built the simulation scenario of Monaco and surroundings named Monaco SUMO Traffic (MoST) Scenario using freely available datasets and statistics. We made sure that the mobility model available in the chosen simulator implemented all the features required to accurately simulate PTW behavior in mixed traffic with customizable parameters. To enable the mode shift to PTW, some of the possible solutions require the presence of multimodal hubs such as parking areas and public transportation stations. While measuring the throughput of the transportation network using the Macroscopic Fundamental Diagram (MFD) for mixed traffic, we discovered the limitations of the simulation when it comes to parking management and mobility generation based on activity chains. We implemented Python Parking Monitoring Library (PyPML) and the SUMO Activity Generation to face these additional issues. All our tools are available on GitHub:

- MoST Scenario: `https://github.com/lcodeca/MoSTScenario`
- PyPML: `https://github.com/lcodeca/PyPML`
- SUMO ActivityGen: `https://github.com/lcodeca/SUMOActivityGen`

1 Introduction

Traffic congestion is a pervasive problem that the majority of people face on a daily bases. Its impact it is complex to quantify because it influences many different aspect of our lives, from the economical weight, to the social and health related components. We believe that Powered Two-Wheelers (PTW) present an important alternative in the mitigation of traffic congestion, and given that the majority of the optimization studies are confined to highways or specific intersections [5], we want to study their impact in a different setting. Our objective is to (i) evaluate PTW as a multi-modal alternative to vehicles, (ii) study them in a large city-scale multi-modal urban scenario to see if their characteristic mobility patterns have a visible impact on the large scale, (iii) and finally, identify possible drawbacks in their presence in traffic.

We chose the Principality of Monaco for our case-study because it is a touristic European capital that already implements smart growth features (such as well-connected public transports, Park & Ride (P+R) parking areas, and modern road infrastructure), but it still faces paralyzing traffic congestion[1]. We decided to investigate the issue from a different perspective: shifting a share of the traffic demand from cars to PTW to quantify their impact on traffic congestion, and on the existing infrastructure.

In Europe, 2017 market figures show an increasing trend in the sales of PTW[2]. Nonetheless, the vast majority of PTW-related studies are concentrated in Asia [2]. PTW size and maneuverability make them an ideal candidate for moving in our cities, especially in congested conditions. The majority of PTW studies focus on safety aspects or localized traffic optimization [5], but at the best of our knowledge, there is a lack of studies concerning the impact of PTW on city-scale traffic optimization. PTW move through traffic following different patterns compared to other motorized vehicles. For example, PTW are able to overtake without changing lane, and filter (creep) through traffic. These complex characteristic behaviors induce more frequent emergency braking and last-second avoidance maneuvers. Studies such as [28, 24, 36] use real traffic and trajectory data (mostly collected from videos), to define, calibrate, and validate PTW mobility models in mixed traffic. Another kind of studies provide mathematical analysis of macroscopic mixed models, and more specifically, the impact analysis of the gradual penetration of PTW in heterogeneous traffic flows [15].

[1]Institut Monégasque de la Statistique et des Études Économiques: `http://www.imsee.mc/` (Last Access: May 2019)

[2]European Association of Motorcycle Manufacturers, Market Data: `http://www.acem.eu/market-data` (Last Access: May 2019)

A 2013 report from the European Commission on road safety[3] stated that PTW fatalities constitute 18% of all road fatalities, though they represent only 11% of all motorized vehicles on the road. A lot of work has been done in Intelligent Transportation Systems (ITS) for cars and other vehicles, but we lack behind when it comes to PTW. The majority of efforts are aimed to protect riders from mistakes and reduce their vulnerability compared to other means of transportation [7]. However, deployment, adoption, and the user acceptance of new ITS services for PTW seems a complicated issue, mainly due to the differences between driving and riding tasks [13, 9].

Research Statement Our goal is to perform simulation study of PTW mobility related issues to propose traffic enhancements and ITS solutions tailored for multi-modal mobility.

2 State of the Art

PTW behavior in mixed traffic has been studied by many, from different point of views. An extensive survey on the work that has been done in the last 30 years in ITS on PTW is available at [5]. Different models have been developed to try to incorporate PTW behaviors; an exhaustive explanation and comparison of multiple microscopic driver behaviour models in mixed traffic is available in [3].

Analytical Approach For example, the authors of [23] refine a cellular automaton model they previously developed, to study the PTW (erratic) lane-changing behaviors in mixed traffic contexts. They present and demonstrate the fundamental diagrams and space-time trajectories for vehicles with various car-PTW mixed ratios. The authors of [24] decided to study PTW proposing three mathematical models able to characterize key elements of PTW mobility, and then calibrate them by using field data collected at Victoria Embankment in central London. In order to improve the simulation models for PTW, the authors of [28] analyzed speed, flow and headway through video recordings four locations in Hanoi (Vietnam). They developed the fundamental diagrams and used the empirical data to validate the characteristics of motorcycle speed and time headway in different traffic flows. On a completely different note, the authors of [6] studied the PTW behavior while overtaking with a game theoretic approach. All the drivers are assumed

[3]Eureopean Commission - Road Safety: `https://ec.europa.eu/transport/road_safety/users/motorcyclists-mopdeds_en` (Last Access: May 2019)

to be rational decision-makers that develop strategies (cooperative or not), while commuting in urban environment. They evaluate their model using trajectory data extracted from video recordings on an urban arterial in Athens, Greece. The flow optimization studies that have been conducted in mixed traffic are mainly focused on intersections. The authors of [29] focus on the effects of PTW behavior on the capacity of signalized intersections. They measured the relative positions between passenger cars and PTW, and the number of rows formed by PTW lined up behind the stop line. They used statistical tests and regression models on traffic data collected at intersections in two capital cities in South East Asia. They assessed that the relative position of PTW to passenger cars affected the mean headway. However, the characteristics of start-up lost time were too complex to describe by means of the number of rows of PTW. Correct delay estimation plays a major role in traffic signals optimization. In [27], the authors work on an analytical model to estimate delays under heterogeneous traffic conditions. They developed and validated the models for the saturation flows on multiple intersections, and compared the model with the conventional (not mixed traffic) ones.

Simulation Approach The authors of [11] analyzed the effect of PTW lane-sharing behavior on macroscopic traffic flows models, starting from the microscopic mobility provided by VISSIM[4]. They observed that the lane-sharing behavior takes place when the average speed is less than 65 km/hr, with a ratio of PTW in between 25 to 60%. The authors used a multi-modal traffic composition, and their analysis focuses on a single stretch of road. In our case, we studied the impact of PTW in a large-scale multi-modal traffic scenario using Simulator of Urban MObiltiy (SUMO) as microscopic mobility simulator. The lane-changing and overtaking strategies used by PTW highly influence the mobility patterns, with a ripple effect on the optimization efforts. The study of these strategies have been studied in many different ways. For example, the authors of [8] went in the direction of driving simulators; they focus their effort in providing and optimizing the presence of virtual lanes for PTW. They propose a model where the PTW drivers dynamically structures the road using virtual lanes built according to the surroundings, and they implement and validate a lane-changing algorithm which allows PTW to move efficiently in heavy traffic.

[4]VISSIM: `http://vision-traffic.ptvgroup.com/en-us/products/ptv-vissim` (Last Access: May 2019)

Remarks Our goal is to alleviate traffic congestion by shifting the mobility from private cars to PTW. We aim to quantify in a realistic mobility environment the impact of different percentages of PTW on safety, traffic congestion, and on the existing infrastructure. To the best of our knowledge, this has not been done before on a city-scale mobility environment.

3 Lane-changing and Sub-lane Models

The models overview presented in this Section is based on the survey: "Driving Behaviors: Models and Challenges for Non-Lane Based Mixed Traffic" [3] and the papers presented in it. The overview of the models implemented in SUMO is based on the publication "Lane-Changing Model in SUMO" [14], and on the publications from Semrau et al. [30, 32, 31].

3.1 Mixed Traffic Modelling at Glance

The vast majority of microscopic driving behavior models were developed for lane-based mobility with homogeneous vehicles. Over time, the necessity of modeling mixed traffic pushed the community to extended them with improved gap acceptance, and longitudinal and lateral movements.

Longitudinal Movement Models In the literature, the longitudinal movement describes the way a vehicle follows and reacts to a leading vehicle. Additionally, car-following models have been adapted for free-flow traffic where a vehicle does not have a leader. When it comes to mixed traffic, we need to take into account the following variations:

- The number of leaders and the reactions may vary depending on the vehicles' composition.
- The vehicles may react not only to their leader(s) but to vehicles on their sides.
- The "creeping" mechanism (where a small vehicle squeezes between two leaders) must be taken into consideration.
- In the case of unseparated bidirectional flow, the vehicles may react to the oncoming traffic.

Usually, these models are classified using behavioral assumptions. For example, the primary modeled behavior may be centered on the safety distance or the optimal speed.

Stimulus-response models focus on the existence of a relation between every action and a stimulus. Well-known models based on this are Chandler's [10], Gipps' [17], Krauss' [22], and Treiber's [35] models. A simplified example can be: $action = sensitivity * stimulus$, where the stimulus can be "the vehicle in front is braking", and the sensitivity is "the distance between vehicles".

Psycho-physical models take into account that the driver has limitations (e.g., the reaction time, and the perceived proximity of other vehicles). Among them, we find Leutzbach-Wiedemann model [25] and Bando's model [4].

An evaluation of Gipps Model, Intelligent Driver Model (IDM), and Krauss Model in mixed traffic conditions can be found in [20].

Lateral Movement Models In the literature, lane-changing models are used to describe the lateral movements and they incorporate both the intention and its execution. The change of lane may be mandatory (e.g.: to turn at an intersection or avoid obstacles) or discretionary (e.g.: to improve the current driving conditions by overtaking a slow vehicle or having a shorter queue).

Lane-changing models such as Gipps [17], SITRAS [18], and Wei et al. [37] are often based on decision rules . With the decision-based approach, drivers compare all the acceptable lanes using a hierarchy of considerations (e.g.: downstream lane blockages, vehicle restrictions, obstructions, type of vehicle already using the lane, and speed gains).

Other studies such as Yang [38], Ahmed [1] and Toledo [34], use the random utility theory. These models are commonly estimated using the maximum likelihood approach based on vehicular trajectory data to describe the lane selection behavior, and are able to capture trade-offs among the various considerations.

Several authors proposed discrete lane-change models similar to those used with homogeneous traffic conditions. The authors of [16, 26, 33] applied these concepts on a finer scale by dividing the road into a large number of narrow strips. In this case, the vehicles move laterally between these strips. Continuous lateral movement models can be applied to this strip approach, providing a more realistic description of this behavior.

3.2 Lane-changing and Sub-lane Models in SUMO

We want to study how different penetration rates of PTW impacts traffic congestion and the existing infrastructure in a multi-modal mobility environment. Hence, we need a microscopic traffic simulator able to handle PTW behavior in detail, with multi-modal traffic capabilities, and scalable to a city-wide mobility scenario. SUMO [21] is not the only microscopic simulator that meets the requirements, but it is open-source, enabling us to control (and, if necessary, modify) the models, and it has a very active community with developers ready to help.

Lane-changing Model The content of this Section is based on the publication "Lane-Changing Model in SUMO" [14] and SUMO version 1.2.0.

In SUMO the the lane-changing behavior on multi-lane roads is modelled using a 4-layered hierarchy of motivations to determine the vehicle behavior during every simulation step. During each simulation step, the following procedures are executed for every vehicle:

1. The preferred successor lanes are computed.
2. The safe velocities are computed, both under the assumption of staying on the current lane, and the possible integration with the lane-changing related speed requests from the previous simulation step.
3. The lane-changing model computes change request (left, right, stay).
4. Either the lane-changing maneuver is executed, or the speed request for the next simulation step is computed. The second possibility involves planning for multiple steps. Whether speed changes are requested depends on the urgency of the lane-changing request.

There are different motivation (with different priorities) behind requesting a lane change. **Whenever a vehicle must change its lane in order to be able to reach the next edge on its route, the lane changing is defined as strategic.** It happens whenever the current lane of the vehicle has no connection to the next edge of the route. In this case, the vehicle is on a dead lane; for example, a left-only turn lane is dead from the perspective of a vehicle that wants to go straight. If no other motivation prevents it, a vehicle can perform a strategically motivated lane change well in advance before reaching the dead lane.

In many real-world situations, **the drivers perform lane-changing maneuvers with the sole purpose of helping another vehicle with lane-changing towards their lane**. More precisely, the vehicles are informed by other vehicles about being a blocking follower. If there are no strategic reasons against changing the lane, the vehicle can change the lane to clear a gap for the blocked vehicle.

The maneuvers performed when a vehicle attempts to avoid following a slow leader is defined as tactical lane-changing. It requires the balancing of the expected speed gains from lane-changing against the effort required to change the lane. The expected speed gains must also take into account the obligation for keeping the overtaking lane free.

The compulsion to clear the overtaking lane could be framed as cooperative behavior because it helps other faster-moving vehicles. However, contrary to the optional cooperative lane-changing behavior, this behavior is mandated by traffic laws.

The motivations previously discussed are evaluated hierarchically following a decision schema.

1. If an urgent strategic change is needed: *change*.
2. If the change would create an urgent situation: *stay*.
3. If the vehicle is a blocking follower for another vehicle with an urgent strategic change request: *change*.
4. If the probability of speed gain is above a threshold and the directions match: *change*.
5. If a non-urgent strategic change is needed: *change*.

Sub-lane Model[5] The content of this Section is based on the publications from Semrau et al. [30, 32, 31] and SUMO version 1.2.0.

Traditional lanes are divided laterally into several so-called sub-lanes. In this case, each vehicle occupies many sub-lanes according to its lateral position and width. In order to implement collision-free traffic, two vehicles cannot occupy the same sub-lane when driving side by side. More precisely, it is required to take into account further model changes for longitudinal movement as well as lateral movement.

Usually, each vehicle had at most one immediate leader vehicle. With the introduction of sub-lanes, a vehicle may have multiple immediate leaders (i.e., multiple motorcycles driving side by side on the same lane). Consequently, the car-following model is applied to all leader vehicles and uses the minimum safe speed to ensure safe driving.

An extension to the previously-described lane-changing model is required to make use of the sub-lanes. Among the most significant changes, the number of possible maneuvres

[5] SUMO Wiki: `https://sumo.dlr.de/wiki/Simulation/SublaneModel` (Last Access: May 2019)

that have to be considered is increased by the number of adjacent lanes to the number of neighboring sub-lanes. Additionally, a larger number of choices requires different trade-offs to be considered. Finally, the motivations for lane-changing are no longer mutually exclusive (e.g., a strategic change to a lane does not preclude sub-lane-changes within that target lane to optimize for travel speed).

In addition to the existing lane-changing motivations, there is the possibility of achieving a desired lateral position within a lane in the absence of more critical motivations. The behavior is user configurable and includes options such as lateral alignment within a lane and compactness to maximize capacity. Finally, the lateral distance keeping aspect needs to be modeled.

Lane-changing and Sub-lane Parameters in SUMO In SUMO there are mainly three classes of parameters that influence motivation, acceptance and hard boundaries respectively[6]. The parameters that affect motivation are: `lcStrategic`, `lcSpeedGain`, `lcCooperative`, `lcKeepRight`, and `lcSublane`. The parameters that affect acceptance are: `lcAssertive` for longitudional gaps, `lcPushy` for lateral gaps. In addition, `lcImpatience` and `lcTimeToImpatience` are also for acceptance but their behavior (disabled by default) add a time-varying aspect to the lcAssertive parameter. Finally, there is an extensive set of parameters that set the hard boundaries used by the models. Parameters such as `minGapLat` and `lcAccelLat` are the more important in our context.

Remarks It is important to notice that the flexibility provided by SUMO allows the study of PTW in mixed traffic conditions in large-scale traffic simulation.

4 Preliminary Investigation

In order to make sure that the parameters available in SUMO allow reliable modeling of PTW behavior, we generated a simple grid scenario with enough variation in the number of lanes and type of intersections to achieve measurable results.

Goal In the real world, one of the perks of using PTW is the high level of mobility. The possibility of squeezing through congested traffic implies that PTW can react to traffic congestion differently from the rest of the vehicles. We hypothesize that PTW should not

[6] All the parameters are defined in the official SUMO documentation: `https://sumo.dlr.de/wiki/Definition_of_Vehicles,_Vehicle_Types,_and_Routes#Lane-Changing_Models` (Last Access: May 2019)

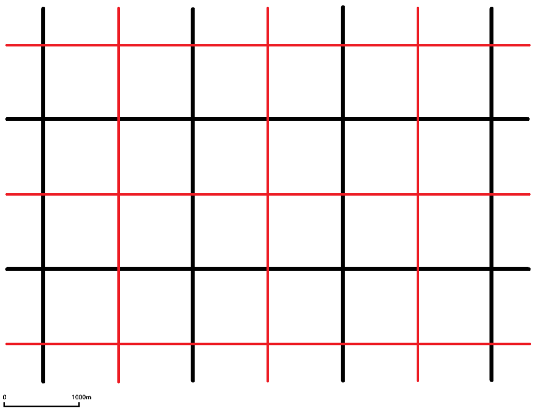
react to the measured traffic congestion, and that depending on global traffic congestion levels, PTW that will prefer the fastest route (based only road length and intersection priority), will minimize their waiting time. In a controlled simulation setting, we built a grid scenario with enough complexity to generate the target behavior while minimizing the additional behavior that we are not interested in measuring.

4.1 Experimental Setup

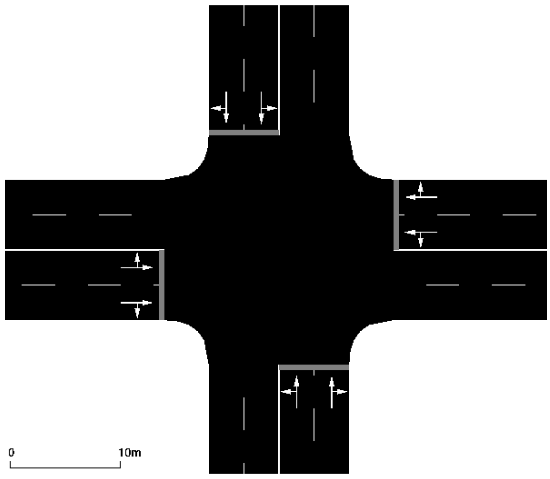
In SUMO, among other mobility features, it is possible to find the routing device. A vehicle equipped with a routing device can react to traffic congestion using configurable parameters. The delays on the networks measured by the vehicles are independent of the type. The intention is to use this feature to measure the difference in time loss between the PTW that react to traffic in the same way as the other vehicles, and the ones that are not reacting to traffic congestion, preferring the fastest route based only road length and intersections priority. In order for the vehicles to react to traffic congestion, the network topology has to provide enough meaningful alternatives.

The grid topology (and its intersections) is shown in Figure 1. Figure 1a shows the overall topology of the 7 by 5 Manhattan grid with internal edges long 1km and external edges of 500m. In black, we can see the streets with 3-lanes in each direction. In red we find the streets with 2-lanes in each direction. Figure 1b shows the topology of every intersection between two streets with 2 lanes in each direction. All the streets involved have the same priority. This kind of intersection in SUMO is defined as a `right-before-left` intersection, and the vehicles must give priority to the vehicle on their right. Figure 1c shows the topology of every intersection between a street with 2 lanes in each direction and a bigger one with 3 lanes in each direction. The streets with 3 lanes have higher priority than the streets with 2 lanes in each direction. This kind of intersection in SUMO is defined as a `priority` intersection, and the vehicles coming from smaller streets must give priority to the vehicles coming from bigger streets. Figure 1d shows the topology of every intersection between two streets with 3 lanes in each direction. All the streets involved have the same priority for the computation of the fastest route, but not at the intersection. In this case, the intersection is defined as `priority` one, where the preferred direction are north-bound and south-bound. More precisely, the vehicles coming from east or west must give priority to the vehicles coming from north and south.

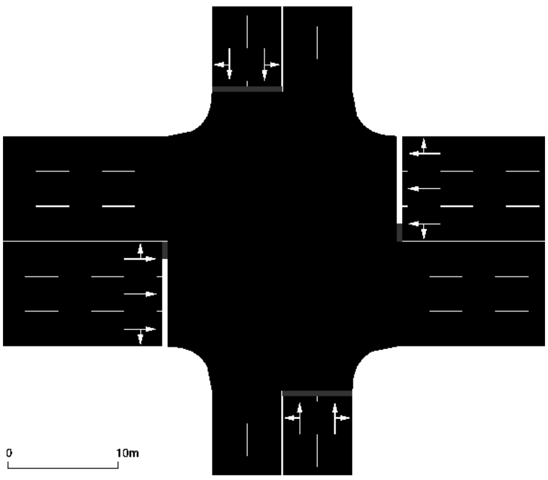
The origin and the destination of each trip are randomly selected. The traffic flow



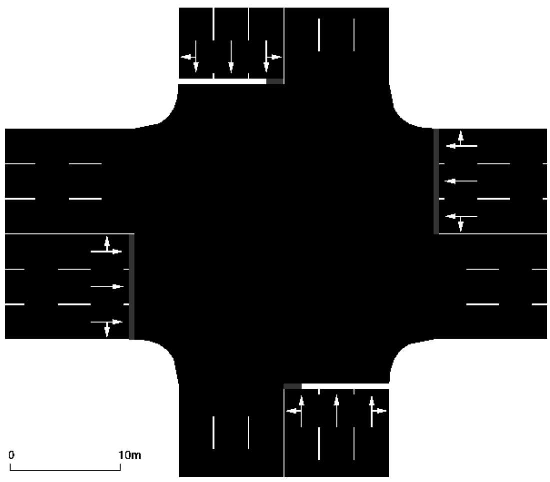
(a) Manhattan grid 7 by 5 with 1km edges. The streets in black have 3 lanes for each direction and the ones in red have 2 lanes in each direction.



(b) Intersection between two streets with 2 lanes for each direction. In intersection both street have the same priority and the vehicle respect a right-before-left priority.



(c) Intersection between a streets with 2 lanes for each direction and one with 3. This intersection is regulated, the street with 3 lanes has higher priority level and the vehicles have right of way.



(d) Intersection between two streets with 3 lanes for each direction. This intersection is regulated, the street that is north-south bound has higher priority level and the vehicles have right of way.

Figure 1: Manhattan Grid experimental setup in detail.

density varies from free-flow to gridlock, and it is achieved by generating trips with period 0.20s, 0.25s, 0.28s, 0.30s, 0.33s, 0.50s, 1s (i.e., vehicles are emitted every 0.20 seconds). The mobility is composed by 35% PTW, 50% passenger cars and 15% delivery vans. Table 1 shows the parameters that we changed explicitly. All the remaining parameters

vClass	*latAlignment*	*tau*	*speedDev*	*lcPushy*	*minGapLat*	*sigma*
motorcycle	arbitrary	0.5	0.1	1.0	0.5	
passenger	center	0.5	0.1			0.25
delivery	center	0.5	0.1			

Table 1: Values for the vType parameters.

are set to SUMO default values[7].

Based on the above-mentioned mobility definition, each setup has to variants. In the first case, all the vehicles are equipped with the device router, and every 300s they are going to react to traffic congestion. The second case uses the same behavior for passenger cars and delivery vans, but the PTW are not equipped with the device router, and their route is fixed.

4.2 Simulation Results

Among all the simulation setups we selected four representative examples to show in Figure 2. The four graphs represent the Empirical Cumulative Distribution Function (ECDF) of the time loss computed only for the PTW. The time loss is defined as "the time lost due to driving below the ideal speed"[8]. The solid red line is associated with the experiment in which the PTW are not equipped with the Routing Device (RD). The dashed blue line is associated with the experiment in which the PTW are equipped with the RD.

The first graph shows an example of free-flow traffic conditions, where the total population is 7.2K vehicles (vehicle emission period of 0.50s). This case is used as a control, 95% of the vehicles have a time loss lower than 1 minute, and given the lack of congestion, there is no difference between being equipped or not with a RD.

The fourth graph shows an example of traffic congestion close to gridlock, where the total population is 14.4K vehicles (vehicle emission period of 0.25s). This case is used once more as a control, because in gridlock conditions, there is no space for smaller vehicles to squeeze through traffic, and once more there is no difference between being equipped or not with a RD.

The interesting cases are represented in the second and third graph, where the presence

[7]The complete vType definitions in SUMO: `https://sumo.dlr.de/wiki/Definition_of_Vehicles,_Vehicle_Types,_and_Routes` (Last Access: May 2019)

[8]SUMO Wiki: `https://sumo.dlr.de/wiki/Simulation/Output/TripInfo` (Last Access: May 2019)

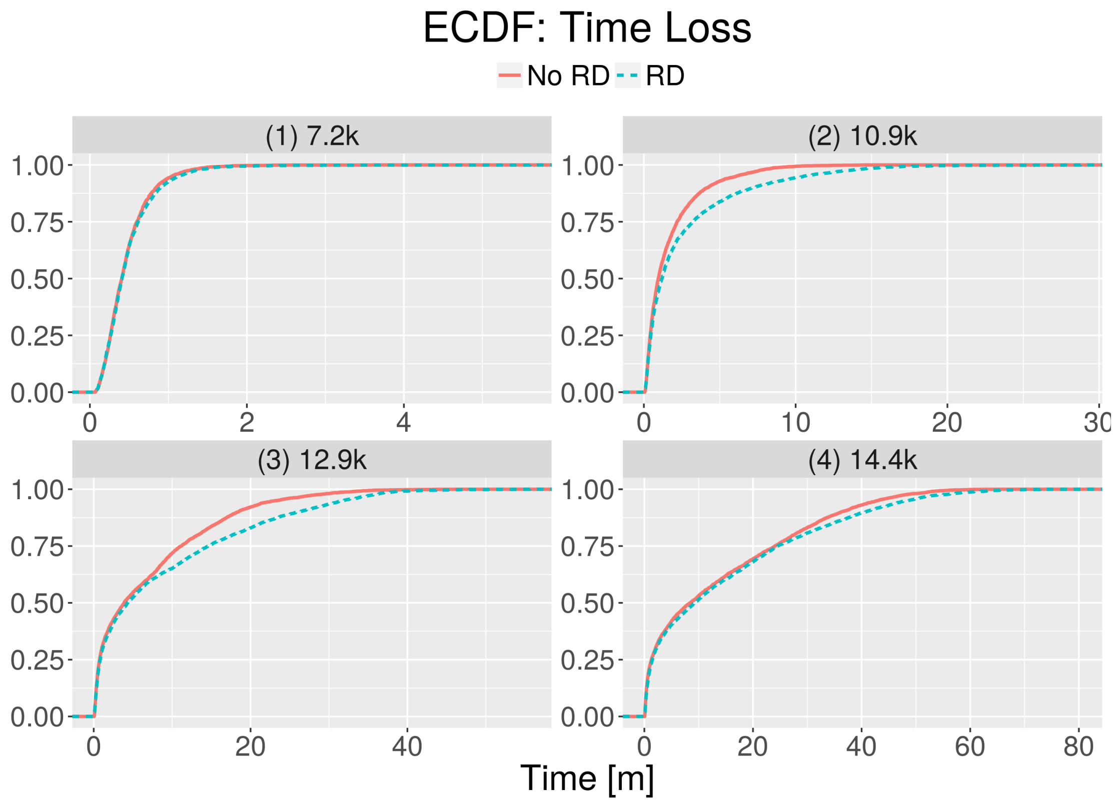


Figure 2: Empirical Cumulative Distribution Function of the time loss for four different congestion levels varying from free-flow to gridlock.

of congestion has an impact on PTW mobility. In the second graph the population is 10.9K vehicles (vehicle emission period of 0.33s). Here we can see that the PTW not equipped with the RD have consistently less time lost compared to the one equipped with the RD. The same result can be seen in a more congested scenario, presented in the third graph, where the population is 12.9K vehicles (vehicle emission period of 0.28s).

Remarks With this simulation study, we showed that the SUMO simulator is able to reproduce the behavior in which we are interested in. In the following section, we are going to study the impact of PTW on mobility in a realistic simulation scenario.

5 Simulation Framework and Results

We used the Monaco SUMO Traffic (MoST) Scenario [12] to manipulate the mobility patterns in the Principality of Monaco and in the neighboring French cities. It provides a state-of-the-art 3D playground with various kind of vehicles, vulnerable road users

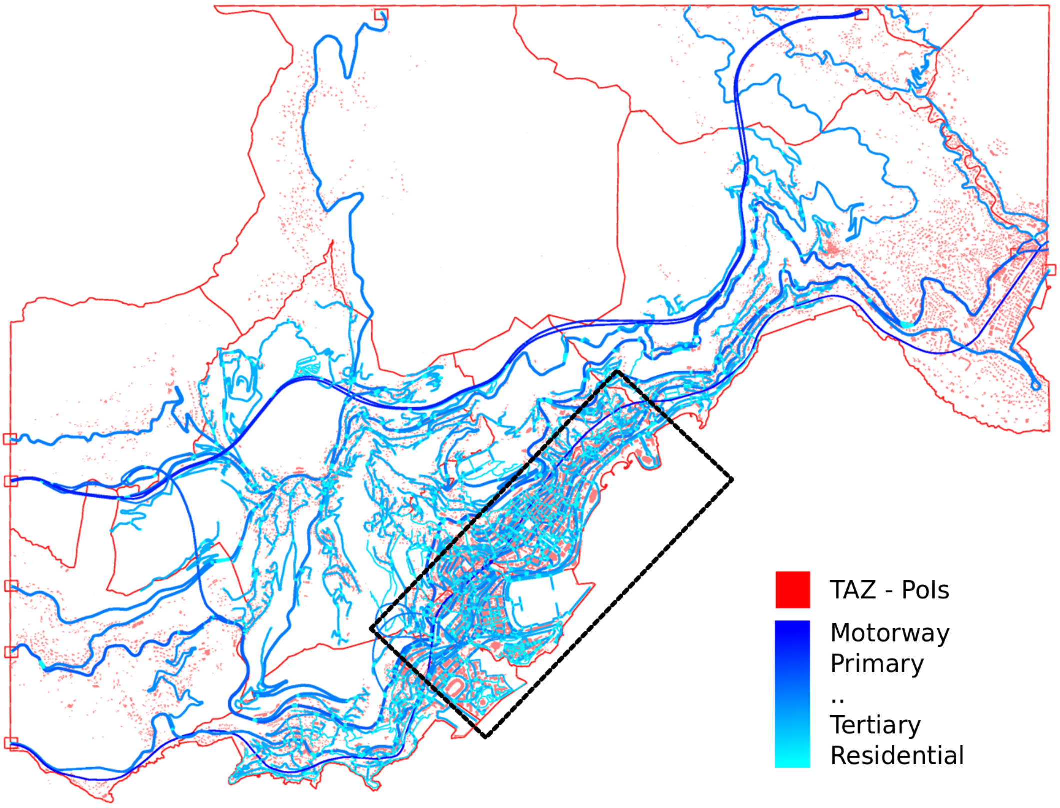


Figure 3: Monaco SUMO Traffic (MoST) Scenario.

(pedestrians and two-wheelers), and public transports. The latter are based on buses and trains, with more than 20 routes over 150+ stops. It covers the Principality of Monaco and its surroundings; it provides 20 Traffic Assignment Zone (TAZ), perfect for us to generate various reasonable mobility patterns in the scenario. The scenario is available on GitHub[9]. Figure 3 shows the MoST Scenario topology with the roads colored by priority (dark blue - high priority, and light blue - low priority), and TAZ and Points of Interest (PoIs) in red. The black rectangle is the Principality of Monaco; outside, it is French territory.

5.1 Simulation Environment

Among the many differences between PTW and other motorized vehicles, we decided to focus on the capability of PTW to creep in normal traffic flows. As presentented in Section 3, SUMO allows us to use the sub-lane mobility model to obtain realistic results during lane-changes, overtaking, and the creeping of PTW. The size of the sub-lanes was

[9]`https://github.com/lcodeca/MoSTScenario`

set to 30 cm to enable the continuous movement of the vehicles between lanes. A more detailed explanation on which parameters we decided to evaluate is available in Section 5.2.

We used the MoST Scenario in two different settings. The first one (Section 5.3) has only PTW and cars. We varied the ratio of PTW from 10% to 90% to see their impact on traffic congestion. The second setup (Section 5.4) tests the impact of different ratio of cars and PTW in a more realistic traffic composition, with public transports, pedestrian, commercial and emergency vehicles. Both scenarios are meant to represent morning rush hour traffic, where all the commuters are moving from France to Monaco; the traffic congestion is directional and the road capacity is almost saturated. The mobility generation is based on the TAZ defined in the scenario, where their weight is proportional to the concentration of PoIs in the area. This follow the reasonable idea that people are more interested to go where there are many PoIs over sparsely populated TAZ. Each trip, being a person that uses public transport, or an emergency vehicle, is computed using `duarouter`[10], a tool provided by SUMO to compute the dynamic user assignment [19], and optimized to minimize travel time.

5.2 Experimental Setup

We decided to quantify the impact of PTW in congested traffic by comparing the *time lost* for all the vehicles in the simulation. This variable is directly computed by SUMO[11] and defined as follows: *the **time lost** is due to driving slower than desired, where the desired speed takes the vehicles speed definition and the speed limits into account.*

The first two experiments are used to quantify the maximum improvement reachable in an ideal setting where we have only PTW and cars. Using this setting we evaluate the impact of *cooperation* and *pushiness* on the level of congestion. These two parameters are defined in SUMO as:

- **cooperation** is the willingness for performing cooperative lane-changing maneuvers, where lower values result in reduced cooperation.
- **pushiness** represents the willingness to approach (push) laterally other drivers. This behavior may violates the lateral minimum gap of the neighbor, triggering evasive lateral movement.

[10]SUMO Wiki: `https://sumo.dlr.de/wiki/DUAROUTER` (Last Access: May 2019)
[11]SUMO Wiki: `https://sumo.dlr.de/wiki/Simulation/Output` (Last Access: May 2019)

The third experiment evaluates the time lost using specific values for cooperation and pushiness, but with a realistic mobility composition.

5.3 Impact of PTW in Ideal Traffic

We consider *ideal traffic* a scenario in which we have only a restricted variety of vehicles, the traffic is congested, and all the vehicles are allowed to react to traffic congestion by rerouting, only if necessary, every 5 minutes[12]. For sake of comparison, both PTW and private cars have the same origin-destination probability matrix. In this experiment we shift the percentage of PTW from 10% to 90% (with 10% increments). The total population is composed by 30.000 vehicles running from 5AM to 12PM. In SUMO, the default value for cooperation is 1.0, and the default value for pushiness is 0.0. These are the values we used if not otherwise specified.

Cooperation Figure 4 shows the changes in the median time loss and the number of safety distance violations while varying the cooperation parameter from 0.0 to 1.0 (with 0.25 steps). In the figure is noticeable that with the same percentage of PTW the impact of cooperation on the time lost is marginal. However, increasing the percentage of PTW in the simulation, decreases the time lost, alleviating the traffic congestion in the system. More precisely, the time loss for the private cars sees a 55% improvement from 10% to 90% of PTW, and for PTW themselves, the improvement is about 45%.

Pushiness Figure 5 shows the variation of the median time loss while investigating the pushiness parameter from 0.0 to 1.0 (using steps of 0.25). In the figure we see that with the same percentage of PTW, increasing the pushy behavior improves the median time lost, particularly at higher PTW penetration rates. Similarly to the cooperation experiment, the time loss improvement from 10% to 90% of PTW for the private cars is about 55%, and 45% for PTW.

Remarks These two experiments showed that although both cooperation and pushiness parameters require calibration data to be sure which simulation setup is closer to real world behaviours, the major factor in the decrease of congestion is the increase ratio of PTW over cars. Obviously, pushiness can be associated with aggressive driver behavior, and it may be considered unsafe. Unfortunately, microscopic mobility simulators such SUMO provides reports on the number of safety distance violations, but this number

[12]SUMO Wiki: `https://sumo.dlr.de/wiki/Demand/Automatic_Routing` (Last Access: May 2019)

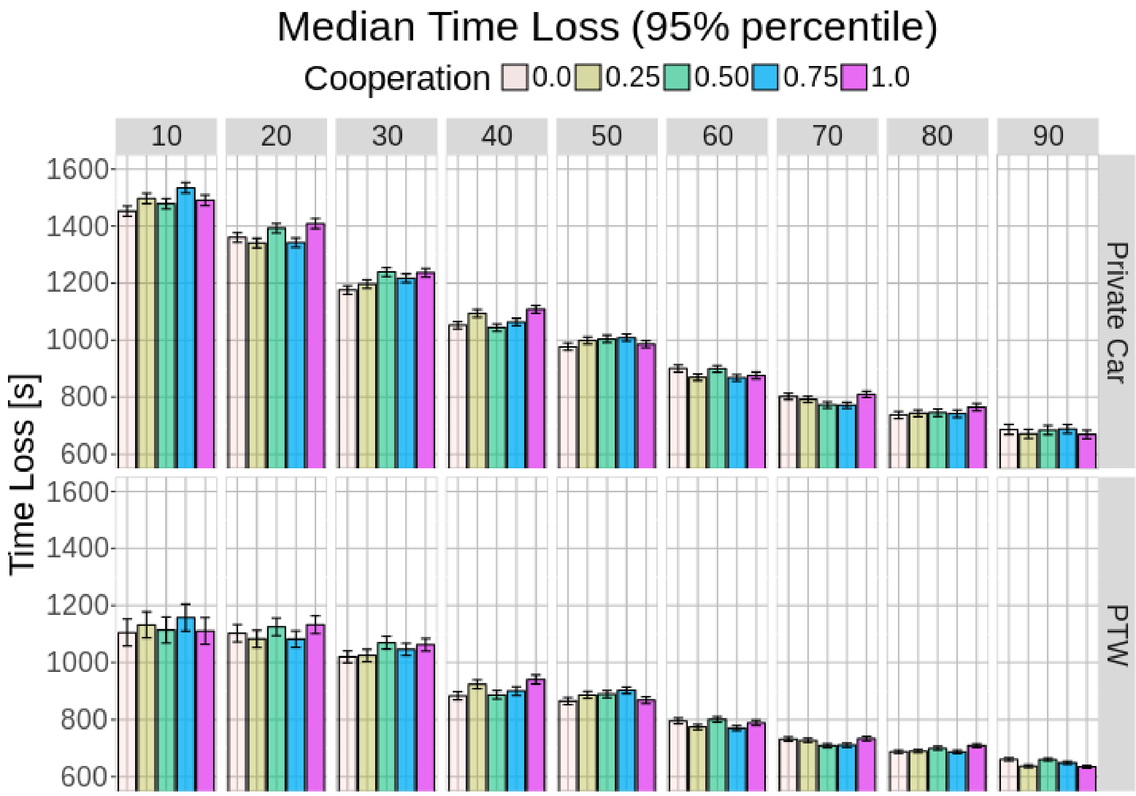


Figure 4: Time loss evaluation in ideal traffic while varying the cooperation parameter from 0.0 to 1.0, where 0.0 means no cooperation. The vertical bars over the histogram represent the 95% percentile.

cannot be used to accurately investigate the issue, due to the car following models used. Anyhow, the ideal scenario does not reflect a realistic composition of the mobility in a city, and further investigations are required.

5.4 Impact of PTW in Multi-modal Traffic

Given the promising results from the previous experiments, we decided to set cooperation to 0.75 and pushiness to 0.25, and then measure the impact of the shift from cars to PTW in a more realistic environment, with multi-modal traffic.

We define as base mobility the share of vehicles and pedestrian that are the same for each simulation. The base mobility is composed by 1% emergency vehicles, 4% commercial vehicles (e.g. delivery trucks), and 40% eco-friendly mobility (pedestrian, bicycles, electric/hybrid vehicles, shared rides, taxi, and public transportation). The remaining 55% is shared between PTW and private cars, varying the penetration rate of PTW from 5% to 50%. Figure 6 shows an example of the complete traffic demand with a population

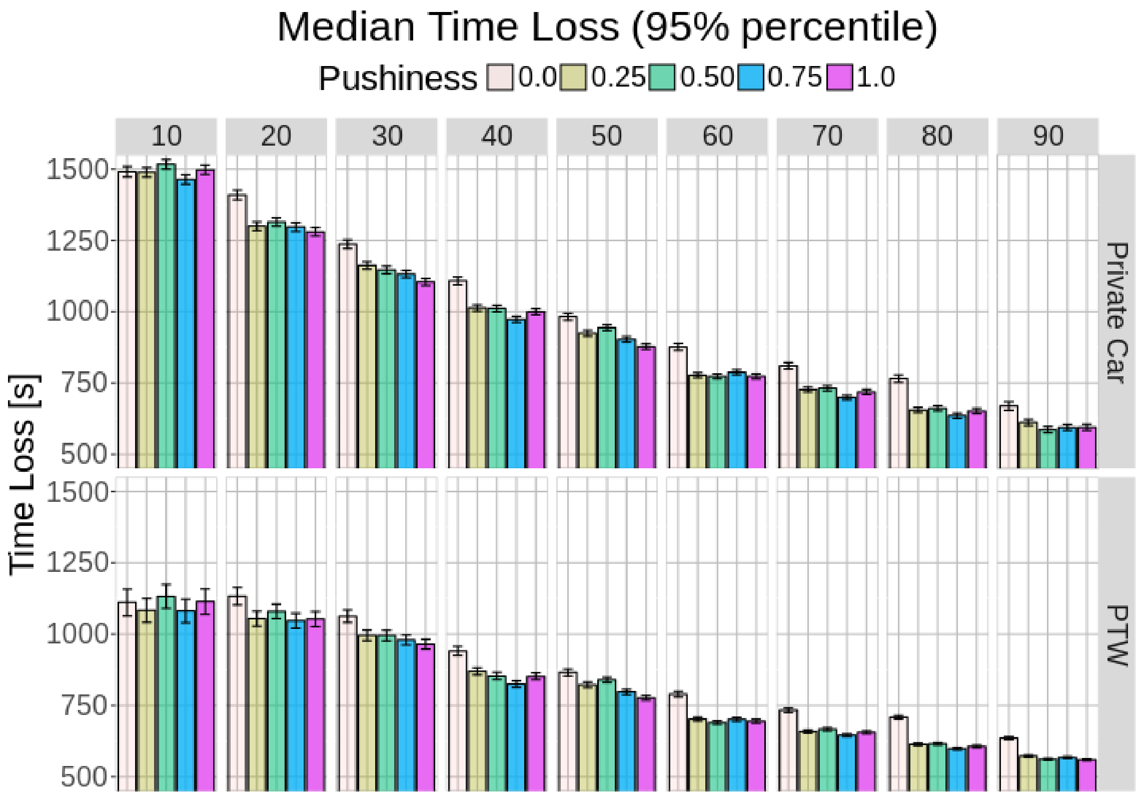


Figure 5: Time loss evaluation in ideal traffic while varying the pushiness parameters from 0.0 to 1.0, where 0.0 means no pushy behavior. The vertical bars over the histogram represent the 95% percentile.

of 30.000 entities; in this specific case we have 30% of private cars and 25% of PTW. The precise proportion of classes of mobility is not possible to validate due to the lack of real data available[13]. However, it is important to keep into account that a share of the mobility cannot be reasonably converted to PTW; additionally, public transport are an efficient solution to move large amount of people, and classes such as delivery and emergency are always going to be present in a city.

Figure 7 shows the median time loss variation and the number of collision in the simulations with multi-modal traffic. The first consideration interests the level of congestion. In the previous experiments the maximum median time lost was on the order of 1500s, now we are on the order of 1000s. Obviously, the use of public transports and shared rides allows the same amount of entities to move in the scenario generating less traffic congestion. With the aim at showing the additional benefit of PTW, the graph shows that increasing their penetration rate, the improvement for the private cars reaches a

[13]Institut Monégasque de la Statistique et des Études Économiques: `http://www.imsee.mc/` (Last Access: May 2019)

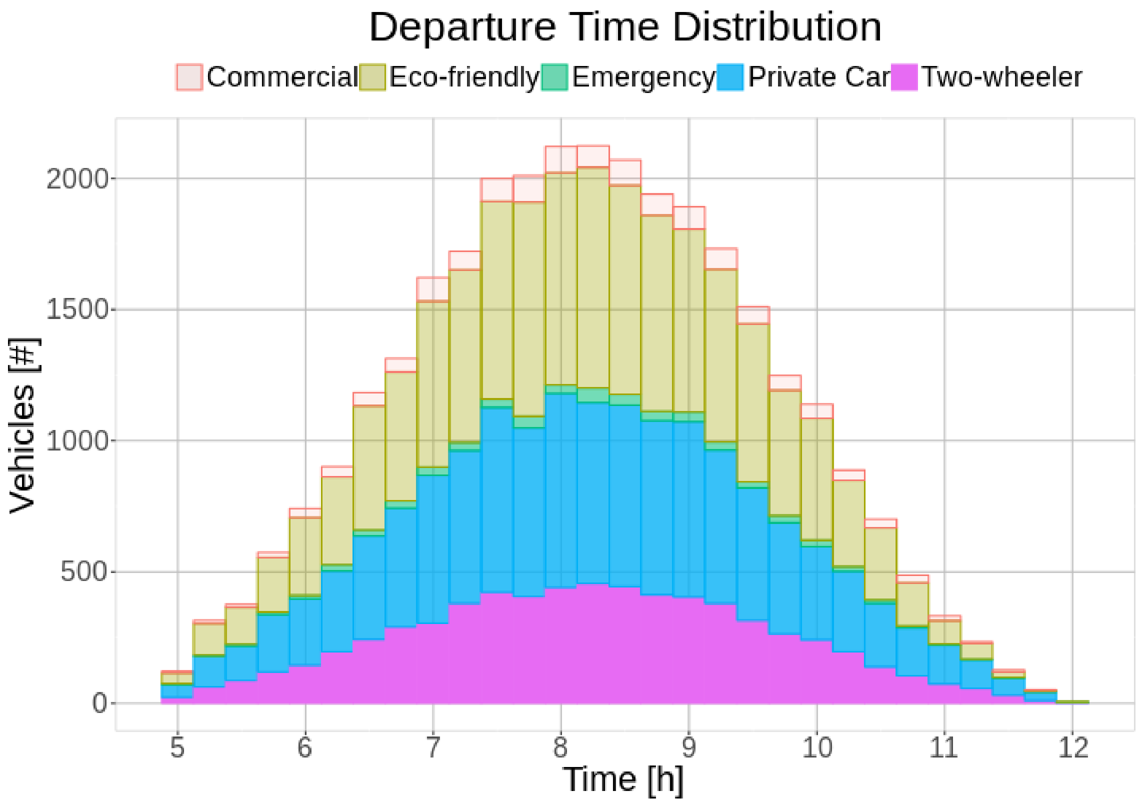


Figure 6: An example of traffic demand definition for the multi-modal traffic experiment.

maximum of 39% (blue), followed by PTW with 34% (purple), commercial (red) and emergency vehicles (green) with 28%, and finally eco-friendly with 20% (olive green).

Remarks The three experiments showed that changing the means of transport from private cars to PTW effectively improves the traffic congestion, both in a controlled environment and in a more realistic multi-modal traffic scenario. With high congestion in the ideal environment, due to the complexity of the interactions, elevated levels of cooperation seem disruptive, while in low congestion, their impact is not quantifiable. Concerning the pushy behavior, it enables fast reduction of delays even in elevated congestion.

6 Conclusions and Future Work

In this study, we evaluated we evaluated how parameters such as cooperative lane-changing and pushiness behavior affect traffic fluidity; first in a more controlled environment, and then with multi-modal traffic. We selected as case-study the Principality of Monaco, a well-organized small independent city-state on France's Mediterranean coast-

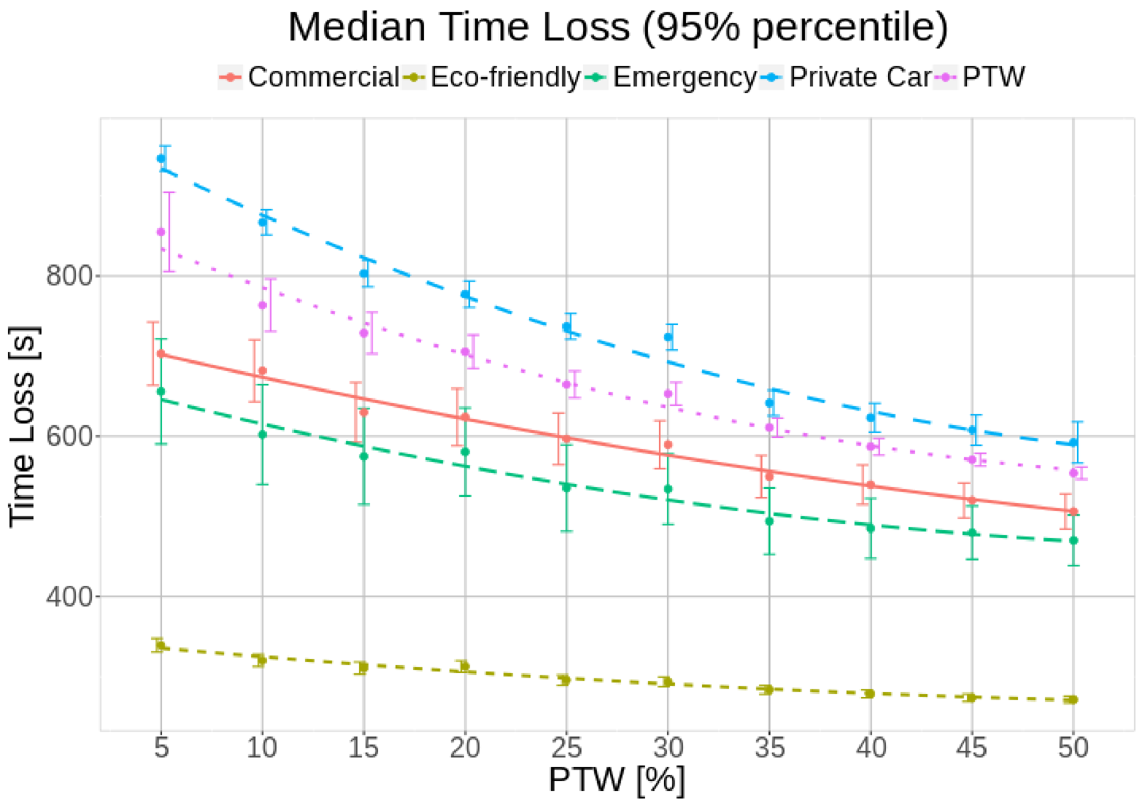


Figure 7: Impact of PTW in multi-modal traffic, time loss evaluation. The vertical bars over the histogram represent the 95% percentile. The fitting curve is a second degree polynomial function.

line. We used Simulator of Urban MObiltiy (SUMO) with the Monaco SUMO Traffic (MoST) Scenario to simulate and analyze the multi-modal environment.

The results confirmed that increasing the percentage of Powered Two-Wheelers (PTW) always alleviates traffic congestion. Elevated levels of cooperation seem more disruptive in highly congested scenarios (due to the complexity of the interactions), while in low congestion their impact is not visible. On another note, the pushy behavior enables the fast reduction of delays. We then analyzed these behaviors in the multi-modal environment. The improvement in the traffic congestion is gradual while increasing the percentage of PTW compared to the private cars. The final evaluation shows that moving from 5% of PTW to 50% the improvement for the private cars reaches a maximum of 39%, followed by PTW with 34%, commercial and emergency vehicles with 28%, and finally eco-friendly with 20%.

6.1 Future Work

We need to calibrate the parameters required to reproduce PTW behaviour specific to the South of France, and we need to validate the mobility from the MoST Scenario with current live data from the Principality of Monaco in order to know the initial proportions of vehicles in the environment. From there, we plan to propose solutions that involve smart commuting, PTW sharing, and the use of peripheral parking lots to enable a new version of Park & Ride (P+R) paradigm.

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