Comparing Multi-Modal Traffic Assignments in Large-Scale Simulations using the Macroscopic Fundamental Diagram: Mode Shift from Cars to Powered Two Wheelers

Lara CODECÁ[*], Francesco VITI[†], Vinny CAHILL[*], and Jérôme HÄRRI[‡§]

***Abstract*— The Macroscopic Fundamental Diagram (MFD) relates traffic flow (vehicles/hour) and density (vehicles/km), and can be used to support decisions on how to mitigate traffic congestion in some region. The MFD is usually computed over an area characterized by a homogeneous traffic pattern. For this reason, when considering multiple traffic assignments for the same transportation infrastructure, the different patterns of traffic densities arising result in MFDs computed over different areas, which cannot be meaningfully compared. In order to allow the use of MFDs to compare the impact of different traffic assignments, partitioning of the region needs to be done based on an infrastructure metric that will not change the resulting area. This paper assesses the use of the administrative boundaries of a city to partition the area in a way that satisfies this requirement. Using this partitioning method, we show how MFDs can be used to quantify the impact of a mode shift from cars to powered two wheelers on traffic congestion in a city-scale multi-modal mobility simulation of Monaco. Our results show that it is possible to use administrative boundaries to generate MFDs, and to use them to evaluate the impact of multiple traffic assignments on the same transportation infrastructure.**

I. INTRODUCTION

The Macroscopic Fundamental Diagram (MFD) establishes the relationship between aggregated measurements representing traffic flow (e.g., number of vehicles flowing out of an area) and density (e.g., number of vehicles accumulated in the same area). Other combinations of metrics that have been related with the MFD are (i) the number of accumulated vehicles in an area with the average trip length, and (ii) the number of accumulated vehicles in an area with the average speed in the same area. It is often used to provide an indication of the traffic state in the network at a relatively high level [1], [2], [3], [4], and it is used to inform decisions on how to mitigate traffic congestion in given areas using various traffic control methods [5], [6], [7], [8]. To compute the MFD, various clustering and partitioning methods have been proposed in the past, based on density similarity or on average speeds [2], [9], [10], [11]. The methodology used to compute the MFD can be summarized in the following iterative steps [9]: (i) the data are partitioned based on homogeneous values, (ii) the resulting parts are clustered to minimize variance while achieving spatial compactness of the cluster, and (iii) the boundaries of the clusters are reshaped to obtain a regular shape while minimizing variance.

When comparing MFDs for traffic assignments with different transportation mode shares, homogeneous partitions need to be created based on transportation metrics that will not change the resulting area, enabling meaningful comparison of states of the system. In particular, when considering multiple traffic assignments for the same transportation infrastructure, the different patterns of traffic density arising result in MFDs computed over different geographical areas, which cannot be meaningfully compared. Typically, we rely on information collected at the level of administrative units to estimate the traffic demand, and the MFD is an useful model for traffic-demand estimation. This allows comparing the results of different traffic assignments, which exposes a likely equilibrium between demand and supply systems [12], [13]. For this reason, we propose to use the existent administrative boundaries of a city to use them to partition the area and compute the MFDs. This choice is also motivated by a recent study [14], where the authors observed a possible correlation between the clusters generated with state-of-the-art methods for MFD analysis, and the administrative neighborhoods in the City of Luxembourg, while comparing the traffic patterns arising from the mobility modelled by the Luxembourg SUMO Traffic (LuST) simulation. Following this idea, starting from the Monaco SUMO Traffic (MoST) Scenario, we used the administrative boundaries provided by OpenStreetMap (OSM) [15] to partition the data corresponding to the different mobility patterns associated with different traffic assignments, to assess the comparability of the resulting MFDs.

In this paper, we show that MFDs computed using administrative boundaries provide a significant asset to evaluate the impact of multiple traffic assignments on the same transportation infrastructure. More precisely, this partitioning method allows quantifying the impact of a mode shift from cars to powered two wheelers (PTW) on traffic congestion levels and the transportation infrastructure. The evaluation was carried out by means of simulation using Simulation of Urban MObiltiy (SUMO) [16] and the MoST Scenario [17], a representative multi-modal mobility scenario for Monaco and its surroundings.

The reminder of the paper is structured as follows: Section II describes related work on the use of MFDs in multi-modal traffic, and Section III discusses our proposed partitioning method. The simulation environment is presented in Section

[*]Lara CODECÁ and Vinny CAHILL are affiliated with Trinity College Dublin, School of Computer Science and Statistics, Dublin, Dublin 2, Ireland. E-mails: Lara.Codeca@tcd.ie, Vinny.Cahill@tcd.ie

[†]Francesco VITI is affiliated with the University of Luxembourg, Department of Engineering, L-4364 Esch-sur-Alzette, Luxembourg. E-mail: Francesco.Viti@uni.lu

[‡]Jérôme HÄRRI is affiliated with EURECOM, Communication Systems Department, 06904 Sophia-Antipolis, France. E-mail: Jerome.Haerri@eurecom.fr

IV, with the experimental results in Section V. Finally, conclusions and future work are discussed in Section VI.

II. Related Work

In this section we discuss the latest developments in the computation of MFDs for multi-modal networks, the commonly used partitioning and clustering methods, and the problems associated with traffic assignment.

A. MFDs in Multi-modal Traffic Networks

Recently, substantial research has been conducted on the use of MFDs in multi-modal traffic networks. The majority of the studies cover the interaction between cars and public transportation. Based on simulation data, the authors of [4], [18], [19], [20] developed multiple methodologies to compute a MFD able to relate the accumulation of cars and buses with the total vehicle flow in the network. In [19], the authors discuss a passenger-based MFD, and their results show that a metric such as the bus-car equivalent is not able to describe the influence of buses on the infrastructure correctly. Additionally, the authors of [18] analyzed the impact on traffic congestion of changing traffic demand for cars, and the bus schedule. Building on the conclusions of papers such as [4], [19] and [20], several traffic management strategies have been proposed, such as redistribution of urban space among different modes, perimeter signal control with preferential treatment of buses, and bus priority.

The authors of [21] study network-level car-bicycle interactions by quantifying the impact of bicycle traffic on empirical MFDs. Their results show that, regardless of separation and road type, the presence of both cars and bicycles on the same road can have a negative marginal effect on network capacity. They finish by proposing various traffic management strategies such as redistributing road space among different modes and extending bicycle priority in certain areas.

B. Partitioning and Clustering

All the papers mentioned above implemented a version of the three-step method initially proposed in [9] and then refined and extended in [10]. The three-step methodology is based on the fact that traffic congestion is spatially correlated, and it propagates spatiotemporally with finite speed. Hence, it is possible to describe the main pockets of congestion with a limited number of clusters. Initially, the roads are clustered based on homogeneous metrics, iteratively expanding the associated area. Then, based on the sequence of roads from the first step, for each pair of roads is defines a similarity measure able to put more weight on neighboring roads and facilitate connectivity of the clusters. Finally, the roads are reassigned to proper clusters with high intra-similarity and low inter-similarity. Additionally, extensions for this methodology have been proven capable of dealing with networks that have sparse measurements, and where the information for some links is missing [10].

C. Traffic Assignment Problem

Solving the dynamic traffic assignment problem in a transportation network is computationally expensive. It requires to find the *best* route from origin to destination in the given transportation infrastructure.

The authors of [13] use MFDs to provide a comparison between the convergence rate of multiple algorithms to solve trip-based dynamic traffic assignment problems. Most of the available algorithms are based on iterative methods aimed at solving a fixed-point problem. In the generic framework presented in the paper, the authors assess the computational performance of these iterative methods on different network sizes and traffic demand levels. Additionally, they present some extensions to significantly reduce the number of iterations to obtain a good convergence rate and drastically speed up the overall simulations.

Alternatively, the authors of [12] proposed a numerical solution based on Monte Carlo simulations using the method of successive averages to solve the network equilibrium. With this method, they propose a dynamic traffic assignment framework for computing MFD multi-region models. Starting from test scenarios, they show that the variability of trip lengths inside the regions cannot be neglected. Finally, they discuss the implementation of the proposed dynamic traffic assignment framework in the sixth district of the Lyon network. The results highlight the influence of the variability of trip lengths on the predicted traffic states.

Remarks: To the best of our knowledge, we present the first study that uses MFDs to discuss the interaction between PTWs and cars in a multi-modal network. We do it by varying the traffic assignments and comparing the resulting MFDs on the same infrastructure. Using the partitions provided by the administrative boundaries, the iterative process of clustering is not necessary, because every road is already associated with a given area. Additionally, in networks with sparse measurements, the lack of information has no impact on the partitioning. The multiple traffic assignments used in this study are generated based on the findings of [22]. Using the capability provided by the SUMO simulator for dynamic vehicle routing, the initial traffic assignment is computed based on the fastest journey on the empty transportation infrastructure. At simulation time, the vehicles are allowed to reroute once every five minutes based on the current traffic congestion.

III. Approach

As previously discussed, state-of-the-art clustering methodologies use metrics that are correlated with traffic flow, density, and speed. Although these methods provide an invaluable tool in the analysis of real datasets collected over time, they are not directly applicable to the comparison of different traffic assignments where the traffic density may vary from case to case.

Given that the MFD provides significant insight into the impact of mobility on the transportation infrastructure, we identified an alternative partitioning method directly tied to the geographical area and its the administrative boundaries.

Starting from the observations made in [14], we investigated the use of administrative boundaries as a partitioning method to compute the MFD. In that paper, the authors propose a model to link mobile network signaling data to the state of the underlying transportation infrastructure. They evaluated the model in a simulation study of Luxembourg city and validated it using real-world data extracted from the LTE network. Although their reason to compute the MFDs using the three-step method was to validate their model and show that mobile signaling data can potentially be used to estimate the state of traffic, the resulting partitions resembled the neighborhoods in the city.

Following this idea, starting from the definition of Traffic Assignment Zones (TAZ) provided by the MoST Scenario, we used the administrative boundaries defined by OSM to partition the data corresponding to the different mobility patterns associated with the traffic assignments, enabling the meaningful comparison of the resulting MFD diagrams. The administrative boundaries defined in OSM[1] follow the United Nations standard[2], making them a world-wide standard. By definition and usage, most of the administrative boundaries present internal consistency. Administrative boundaries are used in urban planning, and although the various administrations may use different strategies, the resulting infrastructure tends to be internally homogeneous [23].

The generation of Origin-Destination (OD) matrices starting from the administrative boundaries, or TAZ composed by administrative units, is common practice since demand data is usually available at that level of granularity. Hence, having MFDs computed at the same level of detail keeps consistency between demand and supply systems, enabling the comparison of different assignment processes. Finally, the use of administrative boundaries allows the application of regional assignment methods such as [12].

IV. Simulation Environment and MoST Scenario

For our mode-shift study, we based our hypothesis on the assumption that PTWs are usually smaller than cars, and the average car trip is made with only one or two passengers[3]. The expected observed behavior when increasing the percentage of PTWs compared to cars is two-fold. Initially, the traffic congestion should decrease due to the additional space available on the streets; eventually, due to the hectic line-changing behavior of the PTWs, an increase in the traffic disruptions would increase the measured traffic congestion.

To test our hypothesis through simulation, we require a sophisticated modeling of driver behavior. The state-of-the-art for representing driver behavior in non-lane based mixed traffic is discussed in detail in [24] and the papers presented there. The SUMO simulator is capable of modeling mixed traffic lane-changing behavior [25], and additionally, it uses the sub-lane mobility model described in [26]. The use of these models allows the creation of virtual-lanes, where smaller vehicles such as PTWs are enabled to creep through traffic (e.g.: filtering through standing vehicles, and crowding in front of cars before the traffic light). More precisely, among the parameters provided for the different vehicles, we find the lateral alignment. This parameter is used to define the primary behavior that the vehicle/person will follow[4]: (i) `center` means that the vehicle will try to stay in the center of the lane; (ii) `compact` implies that the person or vehicle will try to maximize the number of entities in parallel, disregarding the marked lane; and (iii) `arbitrary` indicates that the vehicle will change its lateral position in order to maximize other parameters (e.g., speed).

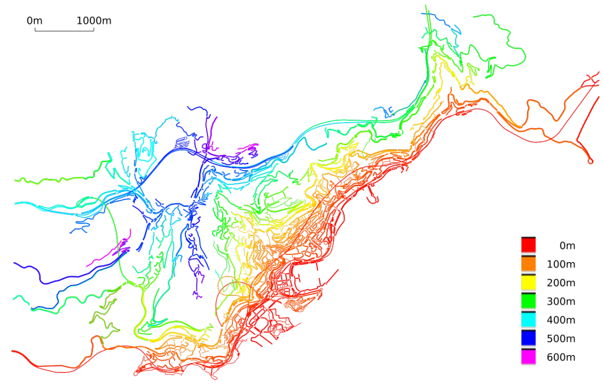

Fig. 1: Transportation infrastructure colored by elevation.

A. *Monaco SUMO Traffic (MoST) Scenario*

The MoST Scenario is a representative multi-modal mobility scenario that covers an area of approximately 50 km^2 that includes three logical areas and 16 TAZs. It provides the locations of Points of Interest (PoIs), more than 100 parking areas, the shape and location for the buildings, and the elevation of buildings and streets. The public transport network has 150+ stops served by more than 20 routes ranging from buses to trains. In the MoST Scenario there are 91 bridges and a total of 84 tunnels. The transportation infrastructure is quite complex and precisely modelled. The elevation map has been extracted from Institut Géographique National (IGN) BD TOPO® database[5], and averaged out in the tunnels and where the information was missing. Figure 1 shows the elevation of the streets in the scenario. Streets near the coast are at sea-level (in red), but the elevation changes rapidly from 0 to 600 meters. The mobility scenario is available on GitHub[6], and detailed information can be found in [17].

[1] Administrative boundaries definition in OSM: `https://wiki.openstreetmap.org/wiki/Tag:boundary\%3Dadministrative` Last access: March, 2021

[2] United Nations standard for administrative boundaries: `https://www.unsalb.org/` Last access: March, 2021

[3] European Environment Agency: Occupancy rates of passenger vehicles `https://www.eea.europa.eu/data-and-maps/indicators/occupancy-rates-of-passenger-vehicles/occupancy-rates-of-passenger-vehicles` Last access: March, 2021

[4] SUMO Wiki: Sub-lane model `https://sumo.dlr.de/docs/Simulation/SublaneModel.html` Last access: March, 2021

[5] IGN BD TOPO® documentation: `https://geoservices.ign.fr.` Last access: March, 2021

[6] MoST Scenario on GitHub: `https://github.com/lcodeca/MoSTScenario` Last access: March, 2021

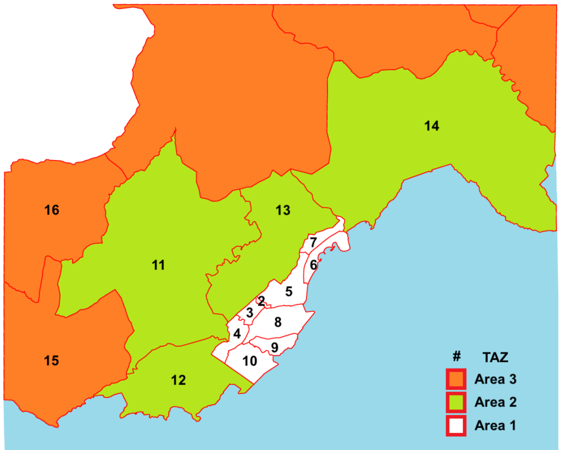

Fig. 2: TAZ in the MoST Scenario.

TABLE I: TAZ enumeration and associated areas.

Area	TAZ	TAZ Name	PoIs	Area [m^2]
1	1	Monaco	21,034	3,150,797
1	2	Sainte-Dévote	275	29,696
1	3	Les Monegetti	1,454	137,458
1	4	Jardin Exotique	2,486	304,780
1	5	Monte-Carlo	5,289	568,848
1	6	Larvotto	1,204	385,032
1	7	La Rousse	2,935	263,333
1	8	La Condamine	2,056	589,846
1	9	Monaco-Ville	1,648	242,837
1	10	Fontvieille	2,304	438,647
2	11	La Turbie	35,414	10,457,135
2	12	Cap-d'Ail	15,774	2,905,470
2	13	Beausoleil	27,272	3,711,430
2	14	Roquebrune-Cap-Martin	47,356	13,046,471
3	15	Èze	12,807	5,388,225
3	16	La Trinité	3,740	4,229,135

Administrative Boundaries: The MoST Scenario is divided into various TAZs coinciding with the administrative boundaries of the Principality of Monaco and the surrounding French region. In Figure 2 the TAZ are numbered from 2 to 16, as per Table I. Additionally, the table presents the number of PoIs extracted from the datasets associated with each TAZ and the area it covers, providing a measure of urban density. In Area 1 (in white), we find Monaco with all its neighborhoods (numbered from 2 to 10). In Area 2 (in green), we find the French villages situated on the border. Both areas 1 and 2 are modeled with a high level of detail, with all the available roads and pedestrian areas. Area 3 (in orange) is fundamental to modelling the traffic patterns, but its level of detail is limited. Only the main roads are represented to allow the correct inflow (outflow) to (from) the inner areas and the proper definition of the public transportation. Due to Area 3 not being fully modeled in the scenario, the internal consistency of the region composed by Roquebrune-Cap-Martin, Èze, and La Trinité is not representative. Nonetheless, the remaining 13 TAZ are fully modeled and usable for our partitioning purposes.

Traffic Demand: The traffic demand provided by MoST Scenario represents the morning rush hour, where the mobility patterns are characterized by inbound traffic congestion directed to Monaco. This traffic demand is based on statistical information on the population, and a simplified activity-based mobility generation model [27].

V. Experimental Setup and Results

Using SUMO and the transportation infrastructure provided by the MoST Scenario, we generated and compared multiple traffic assignments based on the same population of 50k people, starting from an OD-matrix without the transportation mode specified.

A. Experimental Setup

With the goal in mind of evaluating the impact of a mode-shift on traffic congestion, we then generated the eight different setups presented in Table II where each transportation mode is associated with a specific percentage of the population. The setups are artificially created to cover a wide range of mode shares. The public transportation used in the simulation is composed of buses and coaches, both with a capacity set to 50 people and centered lateral alignment. The passenger cars are defined using a distribution of vehicles with a capacity ranging from four to six passengers and centered lateral alignment. The PTWs are composed of motorcycles with a capacity of two people and mopeds with a capacity of one. The lateral alignment is set to arbitrary for both. Commercial vehicles are composed of taxis, trailers, delivery, and trucks with capacity ranging from five to 50 (in this case, the capacity differs from people to containers) and centered lateral alignment. Finally, the other category represents the army, emergency, and public authority vehicles. In this case, the capacity is not set, and the lateral alignment is set to be compact. Finally, based on the resulting mobility pattern associated with each setup, we used the MFD to evaluate whether the city and each neighborhood are functioning correctly without reaching elevated congestion levels.

B. Results

For each setup we ran 10 simulations and extracted the complete Floating Car Data (FCD) output[7]. We then split the simulation into 15 minute intervals, and based on the administrative boundaries, we computed both accumulation (number of vehicles that are present in the area during the interval) and output (number of vehicles that left the area) for every class of vehicles and the aggregated one. This process results in the generation of 48 MFDs for each of the 16 areas[8].

[7] SUMO Wiki: FCD Output `https://sumo.dlr.de/docs/Simulation/Output/FCDOutput.html` Last access: March, 2021

[8] All the graphs generated are accessible at `https://github.com/lcodeca/results/tree/master/MFD-mixed-traffic`. Last access: March, 2021

TABLE II: Mobility shares for the different setups.

Modes	Setup 1	Setup 2	Setup 3	Setup 4
	Mobility by mode share			
Public Transport (PT)	50%	40%	30%	20%
Passenger Car	20%	25%	30%	35%
PTW	15%	20%	25%	30%
Commercial	10%	10%	10%	10%
Other	5%	5%	5%	5%
PT Frequency (s)	300	900	1200	1800

Modes	Setup 5	Setup 6	Setup 7	Setup 8
	Mobility by mode share			
Public Transport (PT)	10%	20%	10%	10%
Passenger Car	40%	30%	35%	30%
PTW	35%	35%	40%	45%
Commercial	10%	10%	10%	10%
Other	5%	5%	5%	5%
PT Frequency (s)	2700	1800	2700	2700

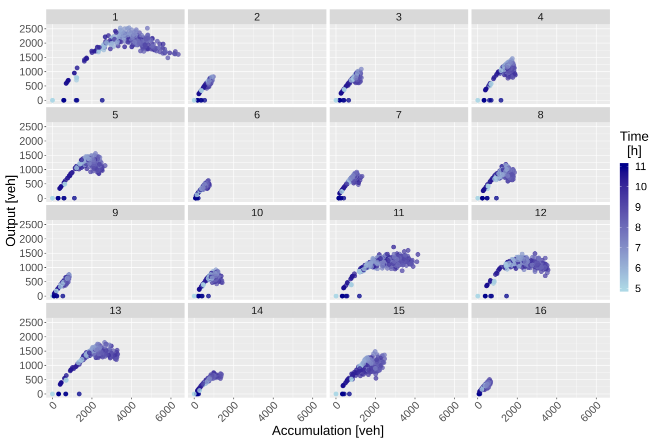

Fig. 3: Aggregated MFD for mixed traffic in Setup 5 compared by partitions.

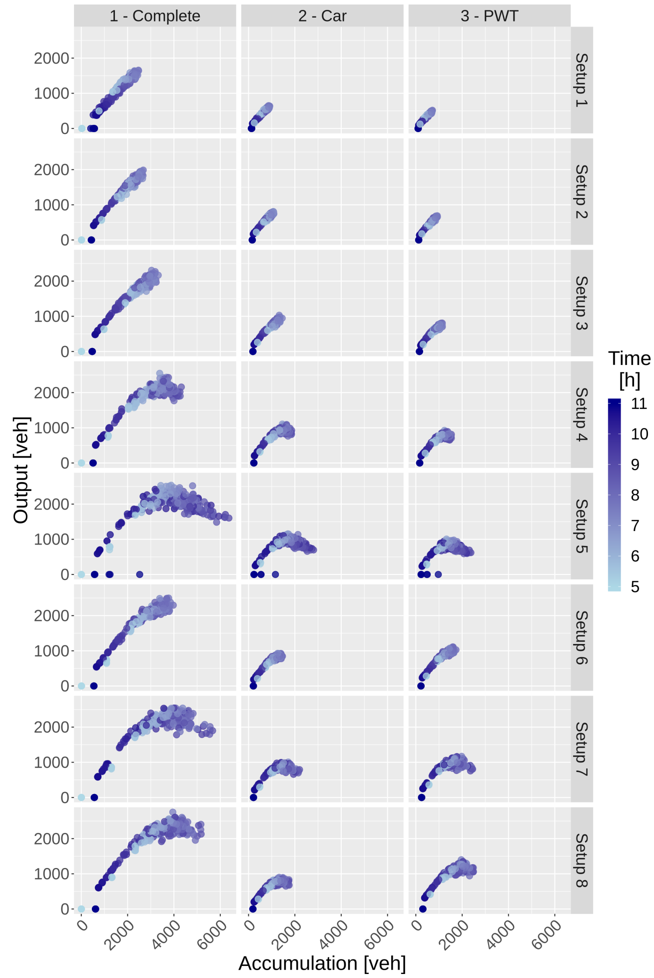

Fig. 4: Direct comparison of the eight setups for the complete mobility, cars, and PTW in the Principality of Monaco.

Comparison by TAZ: Figure 3 shows the MFDs for mixed traffic extracted from Setup 5. We selected Setup 5 as it being one of the most congested setups (as discussed in the following section) enables us to discuss the major accesses to Monaco. Given that we are using the traffic demand for the morning rush hour, the majority of the traffic is directed to Monaco (TAZ 1), showing signs of significant traffic disruption in the MFD, and similarly, in the principal gateways to the city (TAZ 11, 12, and 13) coming from Nice, one of the largest French cities west of Monaco. Although TAZ 15 presents some perturbations, we cannot be sure about the reason due to being part of Area 3 and not fully modeled (note that TAZ 16 is also part of Area 3). The presence of the gateways to Monaco is visible in the neighborhoods too, where TAZ 11 is connected with TAZ 8 through a tunnel, TAZ 12 is connected to 4, and finally, TAZ 13 is connected to 5. Thus, Figure 3 shows that the results are representative of and fully explained by the mobility patterns, and that the administrative boundaries can be used to compute the MFD.

Comparison by Setup: Figure 4 shows the MFDs of the complete mobility compared with the cars and the PTWs for eight setups in TAZ 1 (Monaco). In all setups, the percentage of commercial and other vehicles is constant. The usage of public transportation and their frequency decreases from Setup 1 to Setup 8. The PTW share steadily increases from 15% (Setup 1) to 45% (Setup 8) while the percentage of cars varies from 20% to 40%. The setup with the higher ratio of cars is Setup 5 and presents significant traffic congestion. Setup 4 mirrors Setup 6, inverting the shares between cars and PTW, and the same for Setup 5 and 7. Setup 8 presents the highest share of PTWs. The setups from 1 to 3 do not show signs of traffic disruptions, and the output is steadily increasing. Setup 4 shows the initial signs of congestion, where although the output is higher than before, there is an increase in the accumulation. Setup 5 presents the highest level of congestion, with the highest levels of accumulation. Setup 6 is well balanced and shows one of the highest outputs without traffic disruptions. Interestingly, in both Setups 7 and 8, although not being as bad as 5, both output and accumulation are very high, showing signs of traffic disruption. This observed behavior is representative of an increase of PTWs and the hectic lane changing associated with their creeping through other vehicles.

VI. Conclusions and Future Work

In this paper, we show that it is possible to use administrative boundaries to generate MFDs, and we used them to evaluate the impact of multiple traffic assignments on a transportation infrastructure. The evaluation is carried out through simulation using SUMO and the MoST Scenario, a representative multi-modal mobility scenario for Monaco and surroundings. By comparing the resulting MFDs, we showed the potential impact of a mode-shift from cars to PTW on traffic congestion and the transportation infrastructure. The results from the mode shift are as expected; there is an initial improvement in traffic congestion while increasing the percentage of PTWs, and the final decrease in efficiency of the system due to their disruptive creeping behavior.

As future work, we aim to test this partitioning method on other cities, and we are interested in finding other partitioning methods, similar to the use of the administrative boundaries, and strongly correlated to the transportation infrastructure. Additionally, we intend to obtain traffic counters from Monaco, compare them with the different setups, to know where they stand in relation to reality, and fine tune the mode shift in a deployable direction.

Acknowledgments

This work was partially funded by the French Government (National Research Agency, ANR) through the "Investments for the Future", ref. #ANR-11-LABX-0031-01. EURECOM acknowledges the support of its industrial members, namely BMW Group, IABG, Monaco Telecom, Orange, SAP, ST Microelectronics and Symantec.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 713567. ENABLE is funded under Science Foundation Ireland (16/SP/3804) and is co-funded under the European Regional Development Fund.

References

[1] Buisson, Christine and Ladier, Cyril, "Exploring the impact of homogeneity of traffic measurements on the existence of macroscopic fundamental diagrams," *Transportation Research Record*, 2009.

[2] Gayah, Vikash V and Dixit, Vinayak V, "Using mobile probe data and the macroscopic fundamental diagram to estimate network densities: Tests using microsimulation," *Transportation research record*, 2013.

[3] Ampountolas, Konstantinos and Kouvelas, Anastasios, "Real-time estimation of critical values of the macroscopic fundamental diagram for maximum network throughput," in *TRB 94th Annual Meeting Compendium of Papers*. Transportation Research Board, 2015.

[4] Loder, Allister and Ambühl, Lukas and Menendez, Monica and Axhausen, Kay W, "Empirics of multi-modal traffic networks–Using the 3D macroscopic fundamental diagram," *Transportation Research Part C: Emerging Technologies*, 2017.

[5] Keyvan-Ekbatani, Mehdi and Kouvelas, Anastasios and Papamichail, Ioannis and Papageorgiou, Markos, "Exploiting the fundamental diagram of urban networks for feedback-based gating," *Transportation Research Part B: Methodological*, 2012.

[6] Haddad, Jack and Ramezani, Mohsen and Geroliminis, Nikolas, "Cooperative traffic control of a mixed network with two urban regions and a freeway," *Transportation Research Part B: Methodological*, 2013.

[7] Ramezani, Mohsen and Haddad, Jack and Geroliminis, Nikolas, "Dynamics of heterogeneity in urban networks: aggregated traffic modeling and hierarchical control," *Transportation Research Part B: Methodological*, 2015.

[8] Keyvan-Ekbatani, Mehdi and Gao, Xueyu and Gayah, Vikash V and Knoop, Victor L, "Traffic-responsive signals combined with perimeter control: investigating the benefits," *Transportmetrica B: Transport Dynamics*, 2019.

[9] Ji, Yuxuan and Geroliminis, Nikolas, "On the spatial partitioning of urban transportation networks," *Transportation Research Part B: Methodological*, 2012.

[10] Saeedmanesh, Mohammadreza and Geroliminis, Nikolas, "Clustering of heterogeneous networks with directional flows based on "Snake" similarities," *Transportation Research Part B: Methodological*, 2016.

[11] Lopez, Clélia and Krishnakumari, Panchamy and Leclercq, Ludovic and Chiabaut, Nicolas and Van Lint, Hans, "Spatiotemporal partitioning of transportation network using travel time data," *Transportation Research Record*, 2017.

[12] Batista, SFA and Leclercq, Ludovic, "Regional Dynamic Traffic Assignment Framework for Macroscopic Fundamental Diagram Multi-regions Models," *Transportation Science*, 2019.

[13] Ameli, Mostafa and Lebacque, Jean-Patrick and Leclercq, Ludovic, "Cross-comparison of convergence algorithms to solve trip-based dynamic traffic assignment problems," *Computer-Aided Civil and Infrastructure Engineering*, 2019.

[14] Derrmann, Thierry and Frank, Raphaël and Viti, Francesco and Engel, Thomas, "How Road and Mobile Networks Correlate: Estimating Urban Traffic Using Handovers," *IEEE Transactions on Intelligent Transportation Systems*, 2020.

[15] Mooney, Peter and Minghini, Marco and others, "A review of OpenStreetMap data," 2017.

[16] Pablo Alvarez Lopez and Michael Behrisch and Laura Bieker-Walz and Jakob Erdmann and Yun-Pang Flötteröd and Robert Hilbrich and Leonhard Lücken and Johannes Rummel and Peter Wagner and Evamarie Wießner, "Microscopic Traffic Simulation using SUMO," in *The 21st IEEE International Conference on Intelligent Transportation Systems*. IEEE, 2018.

[17] L. Codeca and J. Härri, "Monaco SUMO Traffic (MoST) Scenario: A 3D Mobility Scenario for Cooperative ITS," in *SUMO 2018, SUMO User Conference, Simulating Autonomous and Intermodal Transport Systems*, Berlin, GERMANY, 05 2018.

[18] Geroliminis, Nikolas and Danés, Jordi and Estrada, Miquel Ángel, "Multimodal Macroscopic Fundamental Diagram for "Car-Bus" Mixed Traffic Signalized Corridors: Application in City of Barcelona, Spain," Tech. Rep., 2013.

[19] Geroliminis, Nikolas and Zheng, Nan and Ampountolas, Konstantinos, "A three-dimensional macroscopic fundamental diagram for mixed bi-modal urban networks," *Transportation Research Part C: Emerging Technologies*, 2014.

[20] Loder, Allister and Dakic, Igor and Bressan, Lea and Ambühl, Lukas and Bliemer, Michiel CJ and Menendez, Monica and Axhausen, Kay W, "Capturing network properties with a functional form for the multi-modal macroscopic fundamental diagram," *Transportation Research Part B: Methodological*, 2019.

[21] Huang, Yizhe and Sun, Daniel J and Li, Aoyong and Axhausen, Kay W, "Impact of bicycle traffic on the macroscopic fundamental diagram: Some empirical findings in Shanghai," *Arbeitsberichte Verkehrs-und Raumplanung*, 2019.

[22] L. Codecá, R. Frank, S. Faye, and T. Engel, "Luxembourg SUMO Traffic (LuST) Scenario: Traffic Demand Evaluation," *IEEE Intelligent Transportation Systems Magazine*, 2017.

[23] Hijazi, Ihab and Li, Xin and Koenig, Reinhard and Schmit, Gerhard and El Meouche, Rani and Lv, Zhihan and Abune'meh, Mohammed, "Measuring the homogeneity of urban fabric using 2D geometry data," *Environment and Planning B: Urban Analytics and City Science*, 2017.

[24] Asaithambi, Gowri and Kanagaraj, Venkatesan and Toledo, Tomer, "Driving behaviors: Models and challenges for non-lane based mixed traffic," *Transportation in Developing Economies*, 2016.

[25] Erdmann, Jakob, "Lane-changing model in SUMO," *Proceedings of the SUMO2014 modeling mobility with open data*, 2014.

[26] Semrau, Marc and Erdmann, Jakob and Friedrich, Bernhard, "Multi-Level-Validation of Chinese traffic in the ChAoS Framework," *SUMO 2018-Simulating Autonomous and Intermodal Transport Systems*, 2018.

[27] M. Balmer, K. Axhausen, and K. Nagel, "Agent-based demand-modeling framework for large-scale microsimulations," *Transportation Research Record: Journal of the Transp. Res. Board*, 2006.