Towards a Personalized Multi-objective Vehicular Traffic Re-routing System

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Abstract. *Vehicular traffic re-routing is the key to provide better vehicular mobility. However, considering just traffic-related information to recommend better routes for each vehicle is far from achieving the desired requirements of a good Traffic Management System (TMS), which intends to improve mobility, driving experience, and safety of drivers and passengers. In this scenario, context-aware and multi-objective re-routing approaches will play an important role in traffic management, considering different urban aspects that might affect path planning decisions such as mobility, distance, fuel consumption, scenery, and safety. There are at least three issues that need to be handled to provide an efficient TMS, including: (i) scalability; (ii) re-routing efficiency; and (iii) reliability. In this way, this thesis contributes to efficient and reliable solutions to meet future TMSs. The proposed solutions were widely compared with other related works on different performance evaluation metrics. The evaluation results show that the proposed solutions are efficient, scalable, and cost-effective, pushing forward state-of-the-art traffic management systems.*

1. Introduction

Urban mobility became an evident problem in large cities around the world due to the high number of vehicles on the roads and also by the traffic jams produced by them [de Souza 2021]. One effective way to deal with such problems is the implementation of vehicular traffic re-routing services [de Souza et al. 2020a], which aim to improve the overall traffic efficiency by recommending faster routes (e.g., paths that avoid traffic jams) to the vehicles. However, considering traffic-related information to recommend better routes for each vehicle is far from achieving the desired requirements of future Traffic Management Systems (TMS). In this sense, context-awareness and multi-objective re-routing will play an essential role in vehicular traffic re-routing, improving the vehicular experience and enabling a whole new set of services. Hence, improving traffic mobility and driving experience, the energy consumption of electric vehicles, as well as the safety of drivers and passengers [de Souza et al. 2017b]. This new vehicular experience will ultimately have a profound impact on society and the daily lives of billions of people worldwide, changing the way we live, work, and play.

Context-awareness in vehicular re-routing is essential since different drivers can have different preferences to perform their journey [de Souza 2021]. These preferences are related to urban factors, including travel time, distance, fuel consumption, scenery, and even safety, which can lead to different routes to reach the same location [de Souza et al. 2020a]. However, considering a single preference to re-route vehicles can directly lead to other significant concerns. For instance, [(CNN) 2015] shows a real example, where a couple got shot, and the woman died after taking the directions recommended by a vehicular navigation system (VNS), which guided them towards a dangerous neighborhood in Rio de Janeiro, Brazil, aimed to provide the fastest route. Another example shows a vehicle (which took the directions recommended by a VNS) passing through shooting in Boston [Online 2016]. These issues could have been possibly avoided using safe route recommendation systems [de Souza et al. 2018]. Navigation systems that focus on optimal safety can lead to stressful paths since the recommendation algorithm can include congested roads to provide the safest way, and these roads are more likely to be avoided in drivers' criteria during their route planning [Taha and AbuAli 2018]. In this scenario, multi-objective optimization of traffic efficiency and safety is desirable to increase the appeal and the effectiveness of the re-routing strategy.

In this scenario, advances in wireless communication and processing such as the fifth-generation (5G) networks [Dong et al. 2017], vehicle-to-everything (V2X) [Wedel et al. 2009] communication and multi-access edge computing (MEC) [Liu et al. 2017] will enable TMSs to sense and act in the urban environment in different ways, interacting not only with vehicles, but also with intelligent devices, subsystems, and even people in order to provide better solutions [de Souza et al. 2020a, de Souza et al. 2020b, de Souza et al. 2019a]. In other words, TMSs will understand a set of different urban factors and build various pieces of knowledge to help traffic management decisions, including detecting areas with recurrent traffic congestion and limited safety, improve re-routing effectiveness, and avoid dangerous neighborhoods. Besides, with the help of machine learning techniques [Ye et al. 2018], TMSs can predict future urban dynamics and know in advance when some areas can become congested or dangerous to improve their effectiveness. However, how to predict these urban dynamics accurately and explore their spatiotemporal correlation is still an open issue. In this scenario, deep learning techniques such as recurrent neural networks (RNN) [Ye et al. 2018] can play an essential role by providing accurate predictions about urban dynamics such as traffic conditions and safety risks while exploring their spatial and temporal information.

This extended abstract summarizes the goals and contributions of the thesis entitled: **Towards a Personalized Multi-objective Vehicular Traffic Re-routing System** [de Souza 2021], developed at University of Campinas, Brazil with joint-supervision at University of Bern, Switzerland. The results produced by this research pushed forward the state-of-the-art in traffic management systems by: *(i)* proposing a scalable and cooperative architecture for traffic re-routing systems; *(ii)* proposing a multi-objective non-deterministic re-routing algorithm that consider spatial and temporal correlation of urban aspects during the re-routing; *(iii)* proposing a reinforcement learning-based re-routing algorithm that adapts to future changes in urban dynamics to provide better routes considering users preferences.

The rest of the abstract is structured as follows: Section 2 summarizes the limitations of literature solutions for dealing with traffic re-routing. Section 3 details the main goal of the thesis and also present the research questions built to guide the research towards the goals. Section 4 lists the publications and achievements of the thesis. Finally, Section 5 concludes the paper.

2. Related Work

Several solutions have been proposed to enable context-awareness and multi-objective re-routing, such as Weighted-Sum, Resource-Constrained Shortest Path (RCSP) and Evolutionary algorithms [de Souza et al. 2020a]. However, these solutions are deterministic and are not suitable for traffic management applications since many vehicles with the same origin and destination can take the same route, potentially degrading traffic efficiency [de Souza et al. 2020b]. Besides, most of the TMSs proposed to perform vehicular traffic re-routing have issues related to scalability as a result of the network overhead produced by them, and also due to computing efforts related to the complexity time of the re-routing algorithm and their architecture [de Souza et al. 2017b].

In this scenario, the major limitations presented by literature solutions to enable multi-objective vehicular traffic re-routing can be listed as follows:

High network overhead: To enable efficient vehicular traffic re-routing, the TMS needs to have accurate knowledge about traffic conditions on the roads. In this way, vehicles need to report their position and velocity to the system periodically to enable traffic condition estimation. However, if all cars communicate their traffic-related information, it potentially overloads the network in dense scenarios, consequently introducing an undesired latency, which might degrade the overall system performance [de Souza and Villas 2016, de Souza et al. 2017].

High computational efforts: The vehicular re-routing task of a TMS consists of finding better paths connecting an origin and destination pair. Therefore, the complexity time of a personalized re-routing algorithm is directly related to its preferences (e.g., the number of additional urban factors that will be considered to plan the path) and the number of vehicles that need to be re-routed. Consequently, depending on the TMS architecture, such complexity can dramatically increase, especially under heavily congested scenarios [de Souza et al. 2019b].

Lack of knowledge about future urban dynamics and their spatiotemporal correlation: Different urban factors might have different conditions depending on the region, day, and time, which means that the same area can provide a set of different situations throughout the day for each urban factor (e.g., spatiotemporal correlation). For instance, some areas are more likely to present traffic congestion during rush hours than on business days. Also, some regions can provide different opportunities for criminal activities along the day, either increasing or decreasing the safety risk in that area. Therefore, the lack of knowledge about such a correlation can directly reduce the effectiveness and the reliability of the re-routing algorithm due to dynamic changes [de Souza et al. 2018].

Non-adaptable multi-objective re-routing: The multi-objective re-routing algorithm itself is not enough to enable personalized re-routing since the TMS needs to be able to understand the relative preferences of each driver to provide methods to allow efficient and customized re-routing. For instance, considering safety risk as a preference, there are a set of events (e.g., criminal actives) that can provide different threats to the safety of drivers and passengers according to their relative preferences. In other words, different drivers can also have different relative choices to each type of crime (e.g., narcotics, assault, shooting, kidnapping, sexual attack, etc.) that can increase or decrease the risk to them. Those relative preferences can also vary according to age, gender, and social characteristics. Thus, enabling each driver its relative choices is essential to achieve trust and reliable TMS [De Souza et al. 2018].

For more details regarding the related work, please refer to Chapter 3 of the thesis [de Souza 2021], which provides ta detailed analysis and classification for literature solutions. However, based on the limitations presented by related work it is possible to conclude that an efficiency TMS for traffic management needs to have: *(i)* a scalable architecture to enable an efficient and real-time re-routing; *(ii)* a multi-objective non-deterministic re-routing algorithm to enable the personalization according to the preference of each user to improve the traffic management considering several urban aspects without degrading the efficiency of each other; and *(iii)* a re-routing algorithm that cares about future changes in urban dynamics to improve the reliability of the route computed by the system.

3. Goals and Contributions

Motivated by the limitations of literature solutions and the high safety risks to drivers and passengers produced by public safety issues, the thesis proposed a context-aware vehicular re-routing system to improve traffic efficiency and the safety of drivers and passengers. The system implements mechanisms to extract knowledge about traffic conditions and public safety issues. Thus, personalized path planning is applied, enabling the drivers themselves to choose which safety risk (e.g., criminal events) they want to avoid. Besides, to facilitate decision-making (e.g., compute an alternative route) in advance, the system exploits the spatiotemporal information of each criminal activity, consequently understanding the future safety dynamics of each area. In this context, the goals of the thesis were achieved by answering the following research questions:

How to ensure system scalability with low overhead and reasonable traffic management?

To enable a scalable system and efficient traffic management a distributed traffic-aware data sharing protocol is proposed, in which the vehicles estimate the traffic conditions on the roads locally within their communication range based on the traffic information shared by them. Thus, the best vehicles are chosen to report their local estimations to the TMS by employing a selection mechanism. To enable real-time traffic management (i.e, re-routing) an offloading mechanism is employed to distribute the re-routing task in several processing units. Therefore, by offloading the re-routing computation in each vehicle, the TMS will overcome the limitation of high latency produced by computational efforts related to the vehicles' density, consequently enabling real-time re-routing and improving system scalability. Finally, a cooperative re-routing approach is proposed to allow that the distributed approach achieves similar performance to the centralized one in terms of traffic balancing effectiveness. The detailed description of these solutions are presented in Chapter 4 of [de Souza 2021] which introduces a system named SIC (Sharing is Caring). The results have shown that the SIC provides a suitable architecture for traffic re-routing, producing a low overhead, complexity and CPU time (which enables a real-time system), consequently enabling a highly scalable system cooperative re-routing algorithm. In particular, it reduces the overhead and CPU time in up to 90% *and* 99% *when compared to centralized approaches, while providing a suitable traffic management.*

How to enable an efficient and personalized multi-objective re-routing without cre-

ating different congestion spots?

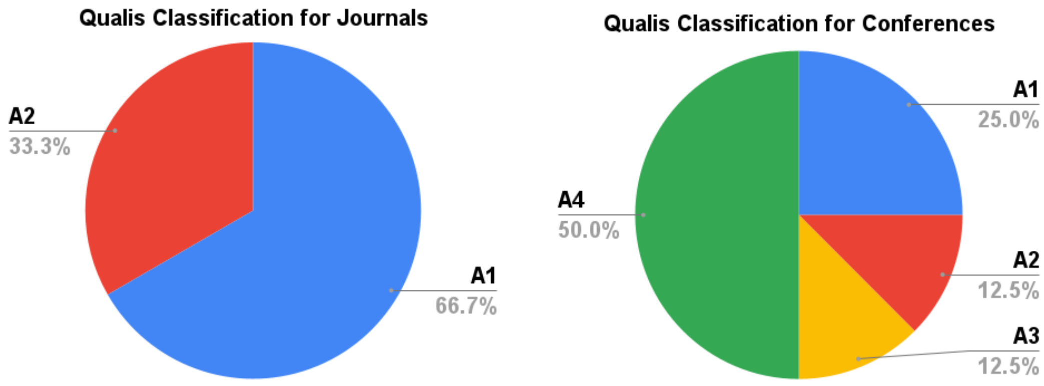
To allow a personalized multi-objective re-routing, an architecture was designed that enables the estimation of different urban dynamics, such as, travel time, green house emissions, and safety. Then, by extracting knowledge about city dynamics, the system can implement multi-objective re-routing. For instance, by extracting information about traffic conditions and safety risks, the system re-routes vehicles through the fastest and safest route. Also, supported by the offloading mechanism to enable real-time re-routing, vehicles can decide which information they want to re-route themselves. Therefore, the system provides the vehicles the info they are interested in. However, to achieve the desired effect of traffic re-routing and avoid creating different congestion spots (due to many vehicles with the exact origin and destination take the same route). A non-deterministic re-routing algorithm is proposed to compute the set of paths that improve mobility of the vehicle and safety considering its preferences and then distribute the traffic flow over the collection of routes previously computed. The detailed description of these solutions to deal with personalized multi-objective re-routing for TMS is presented in Chapter 5 of [de Souza 2021] which describes the system named as SNS Safe and Sound. Simulation results revealed that when compared to state-of-the-art approaches, SNS decreases the average safety risk for drivers and passengers in at least 30% *while keeping efficient traffic mobility.*

How to consider future changes in urban dynamics during re-routing to plan more efficient and reliable routes?

To pave the way for a more efficient and reliable traffic re-routing a prediction model is proposed, which predicts future changes in the urban dynamics to understand the environment and to know when and where some changes will happen. Thus, a recurrent neural network has been implemented to predict the future dynamics (considering a time window) based on past events and historical data. Hereafter, a routing algorithm that considers the predicted dynamics during the route planning is proposed. In summary, the algorithm learns the most efficient path by iterating with the environment considering the future changes using a trial-and-error approach, which is suitable for reinforcement learning-based solutions. In other words, a reinforcement learning-based route planning algorithm is proposed. The detailed description of the prediction model and the reinforcement learning-based algorithm are presented in Chapter 6 of [de Souza 2021] which introduces the system named VTq (Vehicular Traffic re-routing with Q-learning). The results have shown substantial improvements for in the planned routes provided by VTq when compared to state-of-the-art solutions for traffic management considering mobility and safety.

4. Publications

The solutions presented in the thesis were published in relevant conferences and prestigious journals on computer networks and communication. The conferences in which the solutions were published include *IEEE International Conference on Communications (ICC), ACM International Conference on Modeling Analysis and Simulation of Wireless and Mobile Systems (MSWIM), IEEE Vehicular Technology Conference (VTC), IEEE Intelligent Transportation System Conference (ITSC), IEEE Distributed Computing in Sensor Systems (DCOSS), and Brazilian Symposium on Computer Networks and Distributed Systems (SBRC)*. On the other hand, the published journals: *IEEE Transactions on In-*



(a) Journals (b) Conferences

Figura 1. Percentage of scientific production published in journals and conferences according to the Qualis classification.

Tabela 1. List of Publication with Qualis classification, impact factor, H5, and number of citations.

	Year	Published in	Title	Qualis	Impact Factor/H5	Citations
Journals	2020	IEEE T-ITS	Safe and sound: Driver safety-aware vehicle re-routing based on spatiotemporal information	A1	6.49	5
	2020	IEEE ITSM	Enhancing sensing and decision-making of automated driving systems with multi-access edge computing and machine learning	A1	3.41	2
	2019	Elsevier Ad hoc Networks	Vehicular software-defined networking and fog computing: Integration and design principles	A1	4.11	55
	2019	MDPI Sensors	An interest-based approach for reducing network contentions in vehicular transportation systems	A1	3.73	4
	2019	Springer JISA	Better safe than sorry: a vehicular traffic re-routing based on traffic conditions and public safety issue	A2	1.88	11
	2017	DSN	Traffic management systems: A classification, review, challenges, and future perspectives	A2	1.64	118
Conferences	2020	SBC SBRC	Vem Tranquilo: Rotas Eficientes baseado na Dinâmica Urbana Futura com Deep Learning e Computação de Borda	A4	7	0
	2018	IEEE ITSC	Efficient Context-aware Vehicular Traffic Re-routing based on Pareto-Optimality: A Safe-Fast Use Case	A2	32	6
	2018	IEEE VTC	Itssafe: An intelligent transportation system for improving safety and traffic efficiency	A1	44	16
	2018	IEEE DCOSS	Fns: Enhancing traffic mobility and public safety based on a hybrid transportation system	A3	22	3
	2018	SBC SBRC	Por aqui é mais seguro: Melhorando a mobilidade e a segurança nas vias urbanas **(Honorable mention award)**	A4	7	6
	2017	ACM MSWIM	A fully-distributed traffic management system to improve the overall traffic efficiency	A4	18	38
	2017	IEEE ICC	A fully-distributed advanced traffic management system based on opportunistic content sharing	A1	56	18
	2017	SBC SBRC	GTE: Um Sistema para Gerenciamento de Trânsito Escalável baseado em Compartilhamento Oportunista **(Honorable mention award)**	A4	7	4

telligent Transportation Systems (T-ITS), IEEE Intelligent Transportation System Magazine (ITSM), Springer Journal of Internet Applications and Services (JISA), Elsevier Ad hoc Networks, MDPI Sensors, and International Journal of Distributed Sensor Networks

(DSN). Table 1 shows the list of publications organized by year, type of publication, Qualis classification, impact factor, H5 and number of citations.

It is worth noticing the quality of the venues in which the papers were published according to the Qualis system. Figure 1 shows the scientific production published in journals (Figure 1(a) and articles published in conferences (Figure 1(b)). As can be seen, all papers were published in journals and conferences classified in the top levels of the CAPES systems (i.e., Qualis A1, A2, A3 and A4).

Finally, the achievements received by research presented in thesis [de Souza 2021] includes: a best thesis award in the computer institute of the University of Bern in 2021 (university where the *"Cotutela"* agreement of this thesis was established). Two honorable mentions awards in previous editions of SBRC (e.g., SBRC 2017 [de Souza et al. 2017a] and SBRC 2018 [de Souza et al. 2018]), and several citations (281 citations according to *Google Scholar*[1]) in top-tier venues in the area of traffic management, computer networks and distributed systems.

5. Conclusion

This extended abstract sums up the contributions of the thesis in [de Souza 2021] which addresses the issues to provide an efficient TMS, including: *(i)* scalability; *(ii)* re-routing efficiency; and *(iii)* reliability, which paved the way for development of efficient and reliable traffic management solutions. The main contributions of the thesis includes: the proposal of a scalable and cooperative architecture for traffic re-routing systems; a multi-objective non-deterministic re-routing algorithm considering spatial and temporal correlation of urban aspects; and a reinforcement learning-based re-routing algorithm that adapts to future changes in urban dynamics to provide better routes considering users preferences. Finally, the knowledge produced during research has been featured in several top-tier venues in the area, in terms of scientific publications or in short course.

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