Ramp metering in lane-free vehicular traffic via variable speed limits

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1 INTRODUCTION

Highways and main roads in big cities worldwide face persistent traffic congestion phenomena, causing substantial delays, higher fuel consumption, unnecessary environmental harm, and compromised safety. The proficient utilization of control actuators in the frame of real-time traffic management strategies may result in the reduction of traffic delays or complete prevention of congestion. Furthermore, it is beneficial to harness the potential of the rapidly evolving vehicle automation and communication technologies to create cutting-edge solutions that can be implemented in a smart road infrastructure. In recent years, vehicle manufacturers, along with IT companies and research institutions, have dedicated significant resources to develop and deploy vehicle automation and communication systems, completely changing what vehicles can do.

Recently, a new traffic concept known as TrafficFluid has emerged, offering a revolutionary approach to vehicular traffic in the context of highly automated vehicles and advanced communication systems. The TrafficFluid concept proposes a traffic system without designated lanes, unlike traditional traffic where vehicles are restricted to drive on lanes. Additionally, the concept of vehicle nudging involves the ability of vehicles to exert a "nudging" effect on nearby vehicles, thereby influencing their movement, especially those in front and on their sides.

Creating a strategy for effectively and safely navigating traffic in the lane-free paradigm is a challenging task, and there are multiple methods that are striving to achieve this objective (Yanumula *et al*., 2023; Karafyllis *et al*., 2022; Troullinos *et al*., 2021). With the aim of efficiently verifying and demonstrating the TrafficFluid concept, a preliminary ad-hoc strategy was formulated for the movement of vehicles on lane-free roads (Malekzadeh *et al*., 2022). Extensive research has been conducted and documented on this particular model, encompassing its capability for safe movement in lane-free road scenarios (Malekzadeh *et al*., 2022), calibration of macroscopic models that reproduce its macroscopic effects (Papamichail *et al*., 2023), and application of internal boundary control (Malekzadeh *et al*., 2024). These investigations revealed that the proposed moving strategy still entails the conventional traffic issue of capacity drop, caused by congestion in merging areas, as confirmed by the flow results from microscopic simulations. A commonly suggested solution to tackle this problem is the implementation of ramp metering control measures. This study explores a novel approach by implementing ramp metering in a lane-free context, providing novel aspects on traffic management.

The implementation of Variable Speed Limits (VSL) has been studied in multiple cases as a means to control traffic flow and maximize throughput at bottlenecks (Papageorgiou et al., 2008). Conventionally, the main application of this approach is aimed at the mainstream of the road. However, at high penetration rates of connected autonomous vehicles (CAVs), which is required in the TrafficFluid paradigm, it is possible to apply ramp metering via appropriate determination of the speed of the vehicles on the on-ramp, considering the traffic density in the merging area.

In summary, this work explores the application of local ramp metering in the novel context of lane-free traffic and lane-free merging relying on VSL as a control actuator at the on-ramp. A new lane-free extension of SUMO, known as TrafficFluid-Sim, was developed by Troullinos *et al*. (2021) to facilitate research on TrafficFluid-related investigations and is used in this study to test and demonstrate the developed concept.

2 RAMP FLOW CONTROL EMPLOYING VSL

An active motorway bottleneck refers to a specific location where the upstream flow exceeds the downstream capacity. There are multiple factors that can contribute to bottlenecks, however, the primary focus of this study is on on-ramp merging. The illustration in Figure 1 showcases activation of a ramp merging bottleneck, characterized by congestion and capacity drop in absence of traffic control. More precisely, the total demand $q_{in} + q_r$ from mainstream plus on-ramp, respectively, at the ramp merging area exceeds the capacity q_{cap} there. As a result, the outflow q_{out} of the merging area becomes lower than the capacity, where $q_{cap} - q_{out}$ is referred to as the capacity drop of the merging bottleneck.

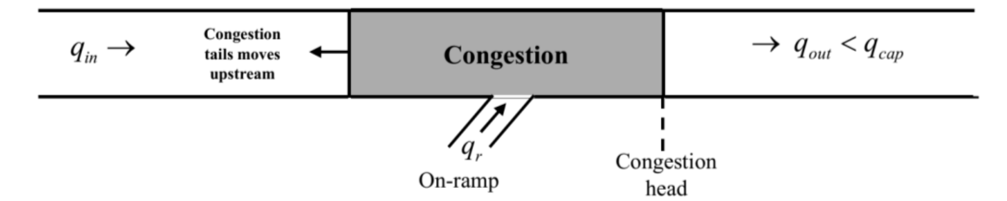

Figure 1 – *Freeway ramp merge without traffic control*

A widely recognized solution for mitigating capacity drop in merging area is ramp metering. To implement ramp metering, it is important to keep an eye on the density of the merging area. When the measured density approaches the critical density, beyond which speed break down and congestion may set in, it is time to activate ramp metering (Papageorgiou *et al*., 2002). The actuator in conventional ramp metering is a traffic light at the on-ramp, which is operated such that the metered on-ramp flow yields a merge area density close to the critical density, thus avoiding congestion and maximizing the mainstream throughput. The implementation of ramp metering can be improved with the integration of cutting-edge CAV technologies in the near future. Specifically, rather than having vehicles stop-and-go due to the traffic light operation, something that causes increased fuel consumption and emissions, it becomes possible to apply VSL to meter the ramp flow in a smooth way. To control the density around the critical value, the vehicles on the ramp receive the calculated desired speed depending on the merging area's density. So, the measured density at the merging area $\rho(k)$ is compared with a desired set point ρ_d (selected around the critical density) in each sample time k and the ramp outflow $f_d(k)$ is decided by an I-type regulator as in the well-known ALINEA strategy (Papageorgiou et al., 1991) as follows:

$$f_d(k) = f_d(k-1) + K_I(\rho_d - \rho(k)) \tag{1}$$

Eventually, assuming that the density of the on-ramp $\rho_r(k)$ is measurable, the desired speed, to be used as a VSL, is calculated using the density-flow equation:

$$v_d(k) = f_d(k) / \rho_r(k) \tag{2}$$

Both the flow in (1) and the speed in (2) are truncated if they exceed certain limits. The speed $v_d(k)$ resulting from (2) is used as a desired speed for vehicles of the ad-hoc microscopic vehicle movement strategy according to (Malekzadeh *et al*., 2022).

3 SIMULATION RESULTS

The stretch presented in Figure 2 is considered for the simulation of lane-free traffic with TrafficFluid-Sim. The mainstream entering and on-ramp demands are depicted in Figure 3. These demands lead to congestion in the merging area, which spills back to section 3, as illustrated in Figure 4. The figure also shows that congestion is practically avoided with the presented VSL-based ramp metering.

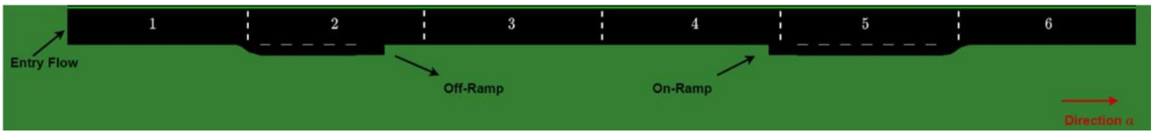

Figure 2 – *The considered stretch of highway*

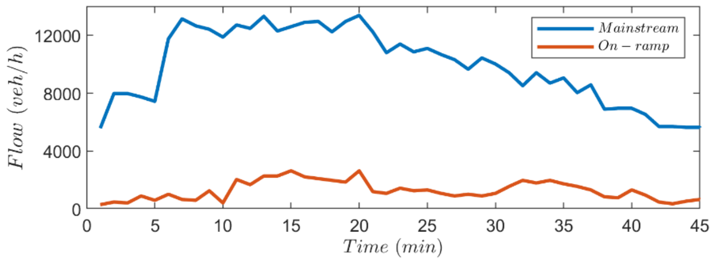

Figure 3 – *The upstream and on-ramp demands*

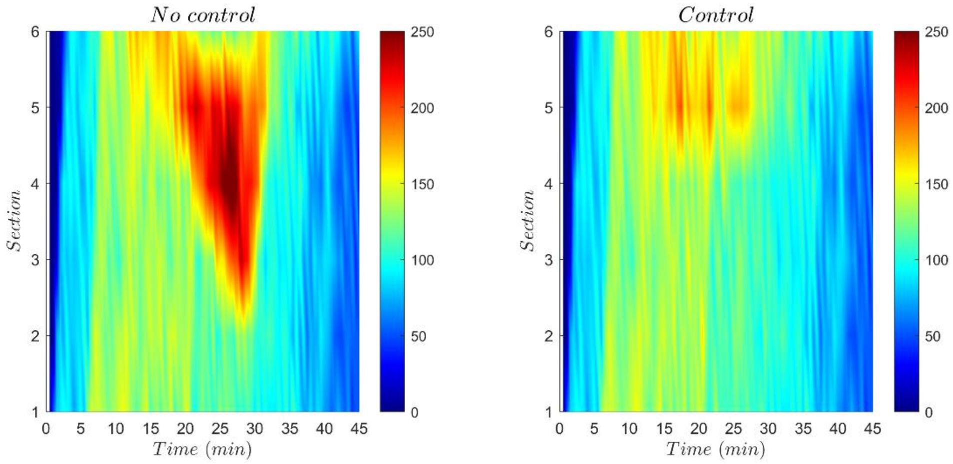

Figure 4 – *Spatio-temporal density evolution*

The performance of the controller is further explored in Figure 5, which illustrates the flow decided by the controller and its transformation to the desired speed. The dashed lines in black represent the bounds of admissible on-ramp flow and speed. Density and out-flow trajectories at the merging area are depicted in Figure 6. The controller effectively maintains the density around the selected set-point (dashed line), resulting in a significant improvement by avoiding congestion and capacity drop, compared to the case without control. This is reflected in a corresponding decrease of the total delay, which, in the average of ten replications, amounts to 42%.

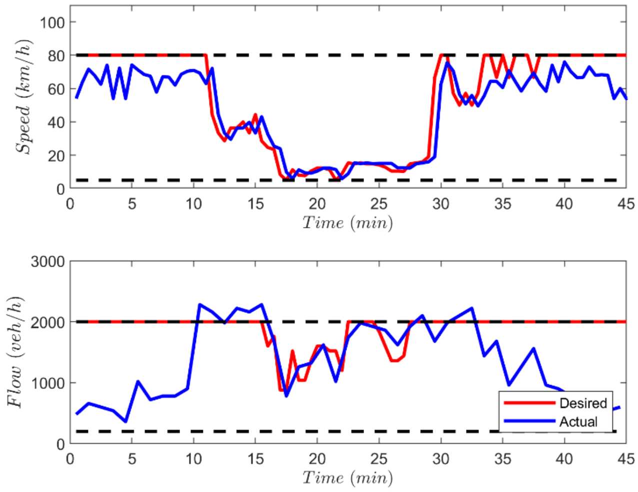

Figure 5 – *Desired and actual on-ramp flow and speed*

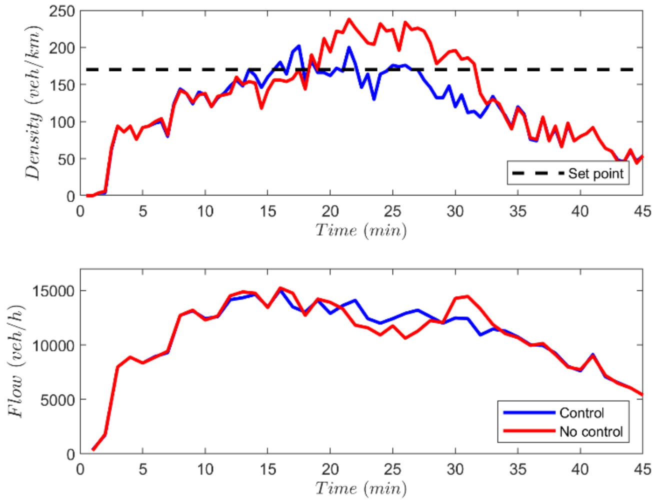

Figure 6 – *Density and flow trajectories at the merging area*

4 REFERENCES

Karafyllis, I., Theodosis, D. and Papageorgiou, M., 2022. Constructing artificial traffic fluids by designing cruise controllers. *Systems & Control Letters*, **167**, Article 105317.

Malekzadeh, M., Manolis, D., Papamichail, I. and Papageorgiou, M., 2022. Empirical investigation of properties of lane-free automated vehicle traffic. In *2022 IEEE International Conference on Intelligent Transportation Systems (ITSC)* (pp. 2393-2400).

Malekzadeh, M., Troullinos, D., Papamichail, I., Papageorgiou, M. and Bogenberger, K., 2024. Internal boundary control in lane-free automated vehicle traffic: Comparison of approaches via microscopic simulation. *Transportation Research Part C*, **158**, Article 104456.

Papageorgiou, M., Hadj-Salem, H. and Blosseville, J.M., 1991. ALINEA: A local feedback control law for on-ramp metering. *Transportation Research Record*, **1320**(1), pp. 58-67.

Papageorgiou, M. and Kotsialos, A., 2002. Freeway ramp metering: An overview. *IEEE Transactions on Intelligent Transportation Systems*, **3**(4), pp. 271-281.

Papageorgiou, M., Kosmatopoulos, E. and Papamichail, I., 2008. Effects of variable speed limits on motorway traffic flow. *Transportation Research Record*, **2047**(1), pp. 37-48.

Papamichail, I., Schoenn-Anchling, N., Malekzadeh, M., Markantonakis, V. and Papageorgiou, M., 2023. Macroscopic traffic flow model calibration for lane-free automated vehicle traffic. In *2023 IEEE International Conference on Intelligent Transportation Systems (ITSC)* (pp. 3485-3492).

Troullinos, D., Chalkiadakis, G., Papamichail, I. and Papageorgiou, M., 2021. Collaborative multiagent decision making for lane-free autonomous driving. In Proc. *20th International Conference on Autonomous Agents and MultiAgent Systems* (pp. 1335-1343).

Troullinos, D., Chalkiadakis, G., Manolis, D., Papamichail, I. and Papageorgiou, M., 2021, September. Lane-free microscopic simulation for connected and automated vehicles. In *2021 IEEE International Intelligent Transportation Systems Conference (ITSC)* (pp. 3292-3299).

Yanumula, V.K., Typaldos, P., Troullinos, D., Malekzadeh, M., Papamichail, I. and Papageorgiou, M., 2023. Optimal trajectory planning for connected and automated vehicles in lane-free traffic with vehicle nudging. *IEEE Transactions on Intelligent Vehicles*, **8**(3), pp. 2385-2399.