Meng Wang, Birgit Jaekel, Martin Lehnert, Runhao Zhou, Zirui Li (Hg.)
Proceedings of the 4th Symposium on Management of Future Motorway and Urban Traffic Systems 2022

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Preface

The 4th Symposium on Management of Future Motorway and Urban Traffic Systems (MFTS) took place between 30 November and 2 December 2022 in Dresden. As the symposium chair, Prof. Meng Wang had the pleasure to welcome 119 participants from 20 countries. Prof. Regine Gerike, Dean of the “Friedrich List” Faculty of Transport and Traffic Sciences of TU Dresden, and Mr. Michael Stritzke, Department Head of Mobility Strategy of the Saxony State Ministry for Economic Affairs, Labor and Transport gave welcome addresses to the audience.

The event is timely due to the urgency to tackle the challenges and explore the opportunities in our transportation systems. On the one hand, there are pressing challenges to protect our climate and shift to more sustainable transport systems. But the increasing urbanization and congestion, and the ever-lasting high number of road fatalities are jeopardizing the safe and efficient operations of our transport systems. Moreover, both natural and man-made disasters have occurred in the past years that lead to disruptions to our life and consequently our mobility behaviour. It is crucial to understand the characteristics and the impact of these challenges. On the other hand, opportunities emerge due to intelligent transportation system technologies (ITS) and novel mobility concepts. Communication systems have enabled vehicles, infrastructure, and traffic participants to connect to each other. Autonomous systems are gradually taking over human drivers in controlling our vehicles. Vehicles are being electrified and shared mobility systems are entering into services.

Combining the two sides leads to the intriguing question of how can public authorities, road and transport operators, industry and academia work together to tackle the challenges while leveraging the opportunities. Therefore, the MFTS 2022 conference sets its main theme as **Cooperative Management of Multimodal Traffic** to echo the importance of joint efforts towards the future sustainable motorway and urban traffic systems characterized by connected & automated vehicles (CAVs) and multi-modality. The symposium provided an excellent opportunity to bring together scientists and practitioners to share state-of-the-art of traffic management and discuss the research agenda.

The organizer of MFTS2022, Chair of Traffic Process Automation (VPA), is part of the “Friedrich List” Faculty of Transport and Traffic Sciences of TU Dresden. The chair sets its vision as an internationally recognized group in **ITS research and education**, in particular on leveraging information and communications technology and emerging mobility concepts to optimize the system operations of multimodal transport under multiple objectives of efficiency, safety, and sustainability. The focal area of research of the chair includes traffic state estimation, prediction and control; cooperative and automated traffic systems; public transport priority, and safety of vulnerable road users. The chair maintains the VAMOS system, i.e. the operational traffic management system of the city of Dresden. VAMOS data centre collects measurements from more than 1800 traffic sensors on urban and state roads in the region and we are integrating public transport data into it. Interested researchers are welcome to visit and collaborate with the chair to explore the potential of the data centre to tackle challenges in our transport and mobility systems.

The conference ran over three days. Three renowned professors in transport and mobility gave keynote presentations about their work. Prof. Serge Hoogendoorn from TU Delft presented the research activities on Multimodal Active Traffic Management. Prof. Ludovic Leclercq from the Université Gustave Eiffel talked about the recent development of trip-based macroscopic fundamental diagram (MFD) models and their applications to urban traffic and mobility services management. Prof. Marc Timme from Center for Advancing Electronics Dresden delivered a keynote on shared and biking infrastructure network problems from a complex and collective system perspective. The keynote presentations were well received by the conference participants.

There were 45 presentations in 14 MFTS sessions. They cover hot topics of traffic management in conventional and connected and automated traffic, autonomous vehicles, demand management, shared mobility, and digitalization. Apart from regular sessions, a few special events were organized, including a pre-conference workshop on **“How to integrate human aspects into traffic modeling and simulations? – Social contextualization of motorway and urban traffic systems”**, a spotlight session on **“Challenges of traffic and transport management in practice”** and a workshop on **“Learning from Covid: How can we predict mobility behaviour in the face of disruptive events?”**

The conference concluded with fruitful scientific exchanges and, hence, success. We look forward to seeing you again in Dresden.

Meng Wang (conference chair), Birgit Jaekel, Martin Lehnert, Runhao Zhou, and Zirui Li
The editors, Dresden, 2023

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Traffic-based Control of Truck Platoons on Freeways

Alessandro Bozzi[1], Tommy Chaanine[1], Simone Graffione[1], Cecilia Pasquale[1], Roberto Sacile[1], Simona Sacone[1], Silvia Siri[1]
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Abstract

This abstract deals with the control of truck platoons traveling in freeways. In order to improve their travel performance, in terms of travelling times and comfort and to guarantee safety, a hierarchical control scheme is proposed for each platoon. At the high level, the reference speed is computed according to a PI-based control rule with the main aim of reducing the time spent by the platoon in the congested area. This reference speed is communicated to the low control level which implements a Linear Quadratic Tracking policy and determines the optimal speed for each truck in the platoon. The application of these hierarchical controllers to a case study shows the effectiveness of the proposed scheme.

Keywords: autonomous, connected, control, freeway, platoons

1 Introduction

Connected and autonomous vehicles (CAVs) offer a chance to change the world by introducing new ways to move people and goods. Increasing safety and efficiency [Dia15], reducing pollution, fuel consumption and congestion and creating the possibility of transporting very young and old people are all promised benefits of introducing this type of vehicles into traffic. Different studies are being conducted nowadays to learn what will be the true impact of autonomous vehicles.

Currently, one of the most promising applications of CAVs is the implementation of truck platooning, which consists of creating a group of at least two trucks that can travel very closely together, safely at high speeds. Cooperative adaptive cruise control (CACC) technologies, radar equipment and wireless communication systems allow the vehicles to travel less than one second apart and to communicate with each other. As mentioned before, truck platooning can reduce the fuel consumption by reducing the air drag of the trucks driving within the platoon [Jan15].

Although fuel consumption is strongly related to the traffic conditions encountered during the route, only a few works in the literature include traffic state in defining planning and control scheme for platoons. This paper studies the control of truck platoons in freeways to improve their performance, as in travelling time, comfort and safety. For this purpose, a hierarchical two-level control scheme is proposed for each platoon, but unlike previous works [Pas18; Sac21], the control depends on the individual vehicles composing the platoons in addition to the surrounding traffic conditions.

2 Methodology

In this work, traffic conditions and the presence of platoons in the mainstream are represented by the Micro-Macro METANET (M3-net model) model previously introduced in [Pas18] and derived from the well-known METANET model [Kot02]. Here, the model is applied to a highway stretch, which is divided into sections and discretized in time, and the presence of platoons traveling on the freeway is explicitly considered. The model has been designed to track the presence of platoons on the freeway in order to understand what traffic conditions they will encounter on their route and how to adjust their speed accordingly.

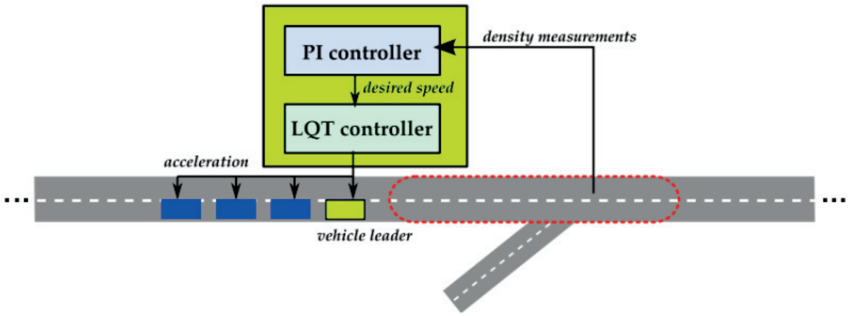


Figure 1: Sketch of the proposed control scheme.

Platoons require specific control techniques because the optimality of the control regards the whole set rather than the individual truck. Analysing the traffic flow from the microscopic point of view, platoons represent the main bottleneck of the system. This happens due to the higher number of constraints that involve many vehicles at a time. The control of each platoon is implemented by means of a two-level control architecture located in the leader vehicle of each platoon. At the high level, the reference speed is computed according to a PI-based control rule to reduce the time spent by the platoon in the congested area. The PI controller defines this speed based on the traffic conditions detected in a portion of freeway downstream of the considered platoon. Then, the low-level controller, which is a Linear Quadratic Tracking (LQT) controller, receives this reference speed profile and defines the accelerations that each vehicle in the platoon must actuate in order to reach the desired speed, while keeping the defined inter-vehicular distances for safety conditions. Each element must continuously monitor the distance from its neighbours and adapt its behaviour consequently. Without these constraints, the control of the platoon translates into a control of the individual vehicle.

To achieve all the above, the control scheme takes advantage of smart communication technologies and the capabilities of CAVs to receive real-time traffic information to define the speed that platoons should take in order to reach the defined objectives.

3 Results and Discussion

The freeway stretch adopted to test the control framework, that is depicted in Figure 2, is 20 km long and is divided into $N = 40$ sections each of which has a length of 0.5 km. The stretch has three on-ramps, located respectively at kilometers 11, 13 and 15, and an exit ramp at kilometer 14. The stretch under consideration has three lanes except for one kilometer where only two lanes are present. Specifically, the narrowing is located from kilometer 11.5 to kilometer 12.5. The presence of four platoons, composed of 5 trucks each, is considered. The arrival of the platoons at the freeway is scheduled at minutes 75, 97, 107 and 117 respectively.

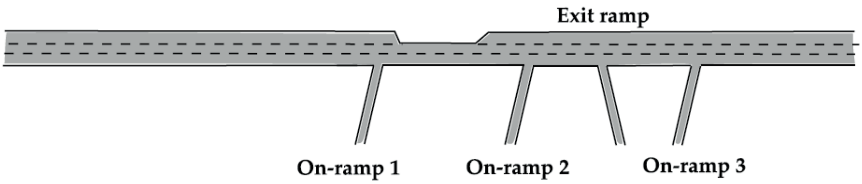
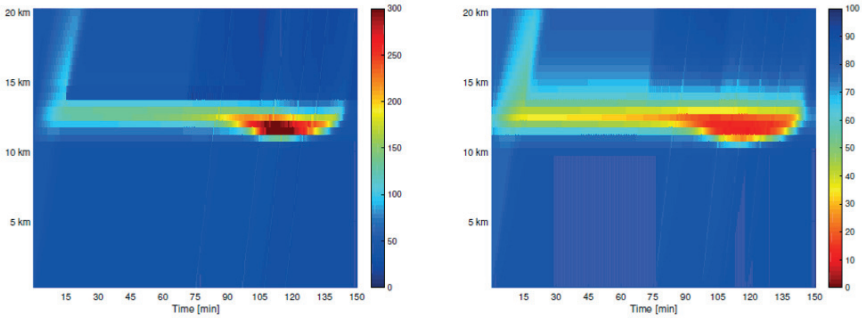


Figure 2: Sketch of the freeway network adopted for this study case.

The simulation has been conducted over a time horizon of two and a half hours. The sample time adopted for the traffic simulation model and to compute the reference value of speed of each platoon has been set equal to 10 s, which gives a total of 900 time steps. By using the simulation model, it is possible to reproduce the traffic behavior in the stretch. As it is possible to observe in Figure 3, which shows the time and space evolution of traffic density and speed, the platoons encounter a state of congestion mainly due to the lane drop at kilometer 11.5.

As for the microscopic representation of platoons, there is the need of a shorter sampling time, taken to be 50 ms, to ensure the responsiveness of vehicles to unexpected events. This allows the platoons to evolve coherently between two consecutive Micro-Macro METANET time intervals and allows the low-level controller to work with a reasonable control horizon, which is 5 in this case study, to pursue the desired speed. At the end of a Micro-Macro METANET sampling time interval, the average speed of the leader within the 10 seconds is provided to the Micro-Macro METANET and the new state of the platoon, considering



(a) (b)

Figure 3: Traffic density (3a) and speed (3b) in the freeway stretch.

the evolution of the traffic, is retrieved to start again the LQT control algorithm. Moreover, the following values of the traffic model parameters have been adopted: the maximum speed a platoon can take is 85 km/h, the free-flow speed is 100 km/h, the jam density is 200 veh/km/lane, the critical density is 50 veh/km/lane, the maximum traffic volume entering section 1 from the mainstream during one sample time is 6000 veh/h, and the maximum on-ramp traffic volume entering a section during one sample time is 1800 veh/h for all on-ramps.

Figures 4 – 7 show the evolution of each platoon overtime, with respect to their entrance and exit time in the main flow. In the above chart it can be noted that the optimal intervehicle distances are broadly maintained through the whole time of simulation without endangering passengers' safety. In other words, the inter-distances do not become too low with respect to the optimal one. Moreover, the desired speed is well-followed even in case of abrupt changes. The zoom in the speed profile denotes the slight differences among elements of the platoon. This suits the expectation of having a set of vehicles moving at a similar speed.

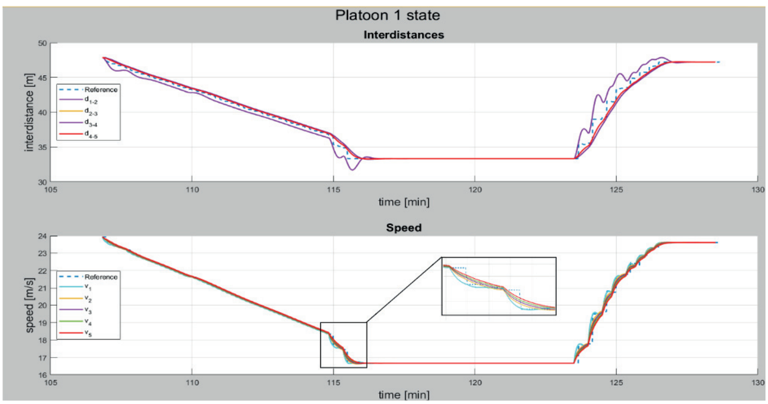


Figure 4: Evolution over time of platoon #1.

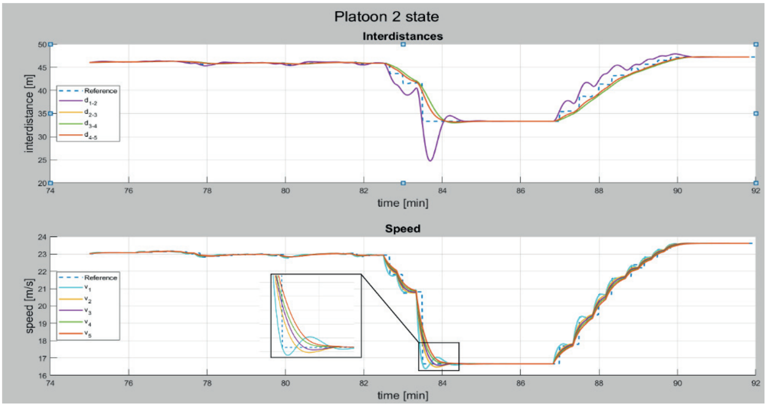


Figure 5: Evolution over time of platoon #2.

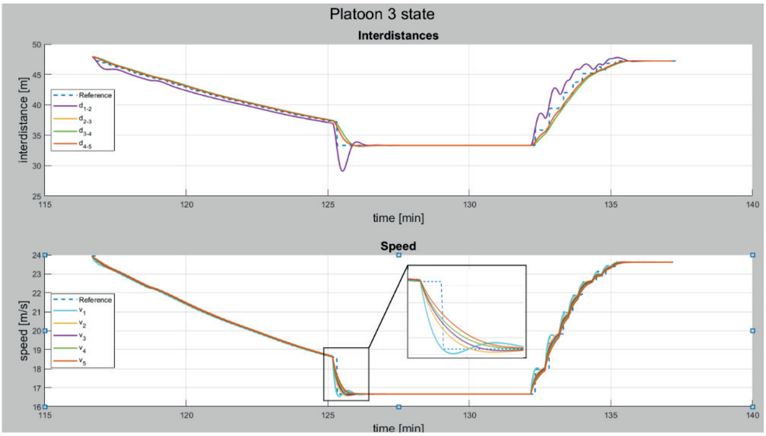


Figure 6: Evolution over time of platoon #3.

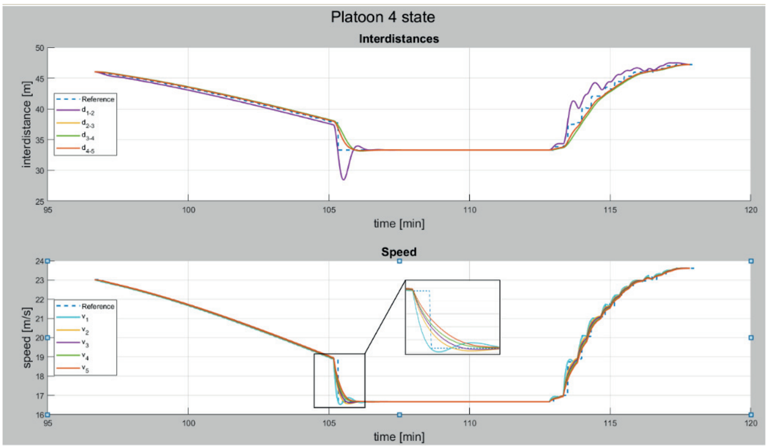


Figure 7: Evolution over time of platoon #4.

As the goal of this control architecture is to improve the operation of truck platoons, in terms of time spent in the congested area and in terms of speed variations, two suitable performance indices are introduced to quantify the performance of the controller. These indices are defined based on the Micro-Macro METANET model and described as follows:

- The time spent in the congested area by platoon z is denoted as τ^z and given by:

$$\tau^z = T \sum_{k=0}^{K} \eta^z(k), \tag{1}$$

  where η^z is equal to 1 if platoon z is, at time step k, in a section in which the traffic density exceeds the critical value, and K is the number of time steps of the considered horizon.

- The second performance index computes the smoothness of the speed profile of platoon z, that is strongly related with comfort levels. This index is denoted as σ^z and is given by:

$$\sigma^z = \sum_{k=1}^{K} \left(v^z(k) - v^z(k-1)\right)^2, \tag{2}$$

  where $v^z(k)$ is the speed of platoon z at time step k (expressed in kilometres per hour).

The effectiveness of the platoon speed controller can be computed considering the entity of the reduction of τ^z and σ^z compared with the uncontrolled case. Analysing the overall performance of the controller in improving these two indexes, and depending on the traffic conditions encountered by the platoons, we can see in Table 1 that the control acts by improving the performance indices, as is the case of platoons $z = 1, 3, 4$, or by keeping the conditions of the uncontrolled case unchanged, as is the case of $z = 2$ platoon.

Table 1: Performance parameters.

Platoon	τ^z **no-control**	τ^z **control**	**% of improvement**
$z = 1$	6.33	6	5.3
$z = 2$	1.83	1.83	0
$z = 3$	5.33	4.83	9.4
$z = 4$	5.83	5.5	5.7
Platoon	σ^z **no-control**	σ^z **control**	**% of improvement**
$z = 1$	17584	16892	3.9
$z = 2$	15548	15530	0.1
$z = 3$	17659	16741	5.2
$z = 4$	16702	16158	3.3

4 Conclusions

In this paper, a hierarchical control system is proposed to control the speed of platoons on highways. The objective of the control system is to improve the driving performance of each platoon by reducing the time it spends in congestion, and to improve driving safety by limiting the abrupt change of speed due to congestion. The main feature of this system is the combination of a high level of control, based on the traffic conditions detected in a defined environment around the instantaneous position of each controlled platoon, and a low level of control, based instead on the state of the individual vehicles in the platoon. The results obtained in a case study show the efficiency of the proposed control scheme and suggest the application of this approach also to more sophisticated control frameworks, where platoons can be used as actuators for control actions that benefit the overall traffic flow.

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A Lateral Positioning Strategy for Connected and Automated Vehicles in Lane-free Traffic

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Abstract

An optimal-control based path planning algorithm has been developed recently for Connected and Automated Vehicles (CAVs) driving on a lane-free highway, including vehicle nudging. That vehicle movement strategy considers, in the lateral direction, a lateral desired speed that had been set to zero in previous works; in other words, vehicles avoid lateral movement if this is not helpful in achieving some of their goals, e.g. achieving a longitudinal desired speed by overtaking slower vehicles. In this work, a lateral positioning strategy for the vehicles is proposed, aiming to improve the vehicles' longitudinal speeds and the traffic flow, mainly at intermediate densities, by distributing laterally the vehicles based on their longitudinal desired speeds. The intention is to leverage the existing optimal control formulation to move the CAVs to appropriate lateral positions, while respecting other, higher-priority sub-objectives, such as avoiding crashes. First, the longitudinal desired speed of each vehicle is mapped to a lateral desired position under the premise "faster vehicles drive farther left". Then, the value of the desired lateral speed is updated in real-time in dependence on the vehicle's current versus the desired lateral position, letting the optimal control problem, with the given sub-objective priorities, decide on the actual vehicle path. The proposed strategy is demonstrated via traffic simulations, involving various traffic densities, on a ring-road. Several quantities, such as the reached average flows and statistical measures of the error in the lateral position are computed for evaluation and comparison purposes.

Keywords: automated vehicles, lane-free traffic, lateral control strategy

1 Introduction

Automation has enhanced production and reduced errors in a wide range of applications. Automation in vehicular traffic comprising Connected and Automated Vehicles (CAVs) is predicted to provide similar outcomes [Dia15; Sjo17]. In this context, some road safety rules designed for human drivers with limited perception and decision capabilities, such as driving strictly on traffic lanes or driving based only on downstream perception, may be questioned. Technologies, like vehicle automation, as well as vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication, have the potential to improve road safety and traffic flow greatly, by relaxing such constraints designed for human drivers.

Road driving is moving in the direction of complete automation and cooperation of CAVs. According to a recently proposed, novel traffic paradigm [Pap21], there is no need, in the era of CAVs to duplicate the human lane-based and forward-looking driving. Based on appropriate movement strategies, in combination with advanced vehicle sensors and communications, CAVs may navigate securely and efficiently on the two-dimensional road surface, accounting for other vehicles all around them, the latter leading to the notion of vehicle nudging.

Alongside various strategies [Tro21a; Kar22], the work by [Yan21; Yan23] formulated a nonlinear Optimal Control Problem (OCP) for CAV path planning in lane-free traffic with nudging. The OCP considers minimization of an objective function that involves fuel consumption, passenger comfort, moving obstacle avoidance, and desired speeds. A feasible direction algorithm is used for its computationally efficient numerical solution [Pap16]. This paper leverages the OCP approach to enable consideration of a target lateral position for each vehicle.

The developed strategy aims to improve longitudinal vehicle speeds and thereby the traffic mean speed and flow, mainly at under-critical traffic densities, where vehicle maneuvering is easier. This is to be achieved by distributing laterally the vehicles, based on their longitudinal desired speeds, so that vehicles with higher desired speed tend to drive further left (and vice versa). This work leverages the OCP formulation to include an additional sub-objective for moving the CAVs to a desired lateral position on the road, while respecting other sub-objectives with higher priority, such as avoiding collisions. The proposed approach is demonstrated to give good results in a simulation environment, for a range of under-critical traffic densities on a lane-free ring-road and can be considered for use in future advancements linked to lane-free CAV traffic.

2 Methodology

The movement of the q^{th} vehicle in the two-dimensional plane is described by the double-integrator kinematic equations in both longitudinal and lateral directions, whereby the control inputs are the accelerations in both directions. The state equations are the following:

$$x_1^q(k+1) = x_1^q(k) + Tx_3^q(k) + \frac{1}{2}T^2u_1^q(k), \quad (1)$$

$$x_3^q(k+1) = x_3^q(k) + Tu_1^q(k), \quad (2)$$

$$x_2^q(k+1) = x_3^q(k) + Tx_4^q(k) + \frac{1}{2}T^2u_2^q(k), \quad (3)$$

$$x_4^q(k+1) = x_4^q(k) + Tu_2^q(k), \quad (4)$$

where the state variables $x_1^q, x_2^q, x_3^q, x_4^q$ represent the longitudinal position, the lateral position, the longitudinal speed, and the lateral speed, respectively, while the control variables u_1^q, u_2^q represent the longitudinal and the lateral accelerations, respectively. T is the time step, and k is the discrete-time index, which relates to the continuous time through $t = kT$. The CAVs are essentially advancing in the longitudinal direction within the lateral road boundaries.

Preventing road departures and negative longitudinal speeds and avoiding collisions in some "emergency situations" are defined as state-dependent inequality constraints on accelerations, to be considered in the OCP. The objective function to be minimized is composed of several sub-objectives. Fuel consumption [Typ20] and passenger comfort, reaching desired speeds in both directions, obstacle avoidance in regular situations, coupling of longitudinal and lateral speeds and smooth longitudinal acceleration between planning horizons are the sub-objectives composing the total objective function; see [Yan21; Yan23] for details.

In summary, the OCP minimizes the overall objective function, subject to the state equations (1) – (4) and all constraints. The OCP can be transformed into a nonlinear programming problem in the reduced space of control variables. Using an efficient feasible direction algorithm [Pap15; Pap16], the OCP is solved repeatedly for short time horizons within a model predictive control (MPC) framework, while the vehicle advances.

In [Yan21; Yan23], the OCP objective includes a lateral desired speed that is set to zero to discourage unnecessary lateral movements of the vehicle. We consider this to be the base case strategy (BCS) for comparison purposes. In the present work, a new lateral positioning strategy (LPS) is proposed that pursues the premise "faster vehicles drive farther left", similarly to conventional traffic, albeit without the presence of traffic lanes.

Note that the admissible lateral positions for a vehicle in lane-free traffic are within the road boundaries, i.e. within the range $[W_v/2, W_r - W_v/2]$, where W_v is the width of the vehicle and W_r is the width of the road, as illustrated in Figure 1.

For the present investigations, each vehicle features a longitudinal desired speed (x_{3des}^q) from the range $[a, b]$ m/s, assigned with a uniform random distribution. Other desired speed distributions are currently under investigation. In the case of homogeneous distribution, we may use a linear mapping that returns a desired lateral position (x_{2des}^q), proportional to the desired speed, by the following equation

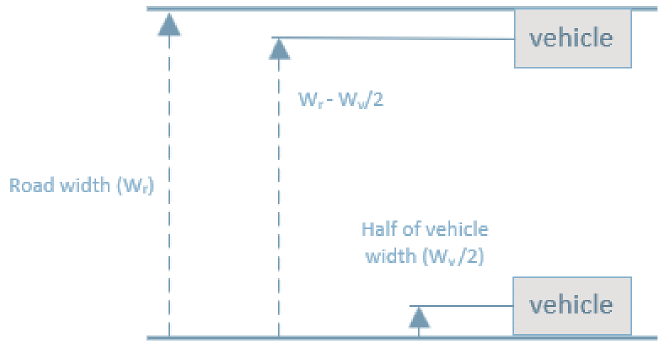

Figure 1: Lateral road boundaries and admissible vehicle positions.

$$x^q_{2des} = \left(W_r - \frac{W_v}{2} - \frac{W_v}{2}\right)\left(\frac{x^q_{3des} - a}{b - a}\right) + \frac{W_v}{2}, \ \forall x^q_{3des} \in [a, b]. \tag{5}$$

Equation (5) is performing a one-to-one mapping between the two intervals:

$$[a, b] \rightarrow \left[\frac{W_v}{2}, W_r - \frac{W_v}{2}\right].$$

This way, each vehicle is assigned a desired lateral position, and it should tend to approach that position, as it drives on the road. Although we could formulate this task as an additional sub-objective in the OCP objective function, we prefer, for the sake of simplicity and generality, to address this task by leveraging the existing lateral desired speed term in the objective function. This implies that, at each optimization run, we need to update the desired lateral speed to conform with the lateral position task. This is done by computing the lateral desired speed proportionally (according to (6)) to the vehicle deviation from the desired lateral position at the start of each OCP run. More precisely, the lateral speed, that should be applied to the vehicle over a time-period S to reach its desired position, is simply given by $(x^q_{2des} - x^q_2(0))/S$ (where $x^q_2(0)$ is its initial lateral position) and is used as its desired lateral speed

$$x^q_{4des} = \frac{x^q_{2des} - x^q_2(0)}{S}. \tag{6}$$

3 Results and Discussion

An unfolded ring-road of 1 km length and 10.2 m width is considered for simulations in a lane-free environment. Multiple scenarios have been simulated using a custom-made extension, namely TrafficFluid-Sim [Tro21b], which is built for the SUMO simulator [Lop18]. Eight classes of regular vehicles are included, each class with its own length and width, as follows (in m): (3.2,1.6), (5.15,1.84), (4.25,1.8), (4.55,1.82), (2.6,1.77), (3.9,1.7), (3.4,1.7), and (5.2,1.88). The longitudinal desired speeds are set randomly, following the uniform distribution, in the range [25,35] m/s. Initially, each vehicle is placed randomly, in lateral direction, within the range $[W_v/2, W_r - W_v/2]$; while longitudinal initial positions are roughly homogeneously distributed; and initial speeds are 0. The optimization horizon is set to 8 sec with a simulation step of 0.25 sec. A time-period S of 32 sec is used in (6) so as to reach the desired lateral position in four optimization horizons.

To evaluate the scenarios, the average flows achieved during the last ten minutes of half-hour simulations and the statistics of the lateral-position error throughout the simulation period are calculated. The average Mean Absolute Error (Average-MAE) between the current lateral position and the desired lateral position for all time steps and for all vehicles is calculated using the following formula

$$\text{Average} - \text{MAE} = \frac{1}{n}\sum_{q=1}^{n}\left(\frac{1}{tnss}\sum_{i=1}^{tnss}|x_2^q(i) - x_{2des}^q(i)|\right), \tag{7}$$

where $tnss$ is the total number of simulation steps and n is the number of vehicles. The standard deviation of the MAE (stdv-MAE) is calculated based on the following formula

$$\text{stdv} - \text{MAE} = \sqrt{\frac{1}{n}\sum_{q=1}^{n}\left[\frac{1}{tnss}\sum_{i=1}^{tnss}\left[|x_2^q(i) - x_{2des}^q(i)| - \text{Average} - \text{MAE}\right]^2\right]}. \tag{8}$$

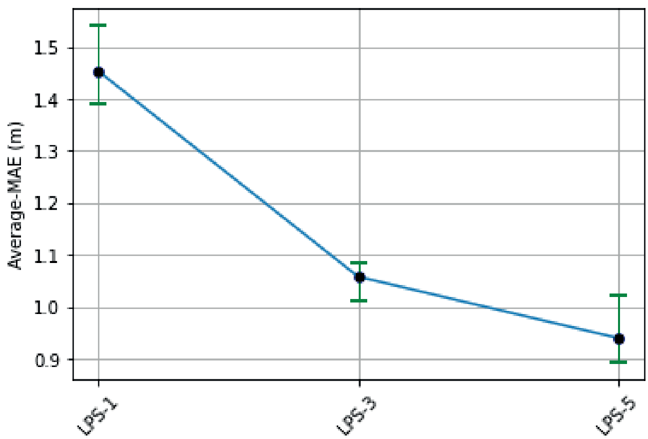

Figure 2: Average-MAE for three different values of the weight applied on the lateral desired speed term. The bars represent the range of values over the 5 different replications.

First, an investigation has been conducted using different values for the weight applied on the penalty term corresponding to the squared deviation from the lateral desired speed. Different values have been considered for this weight to explore its impact on the flow and on the deviation from the desired lateral position via the metrics (7) – (8), while also looking at its impact on other sub-objectives. As expected, an increase of the weight results in a decrease of the Average-MAE. This is shown in Figure 2, which displays the average and the range of values achieved over 5 different replications for the case of a density equal to 150 veh/km and for three different values (1, 3 and 5) used for the weight. Figure 3 shows the stdv-MAE value for the same density and again for the three different values used for the weight. In all cases, the flow achieved with the proposed LPS is improved, compared to the flow achieved for the BCS (see Figure 4 and Table 1). On average, this improvement is higher for higher values of the weight. However, according to Figure 4, the deviation from the average flow value that is observed over the 5 replications is much higher for the case of a weight equal to 5. Therefore, the value of the weight considered in the following investigations with different densities is selected to be equal to 3.

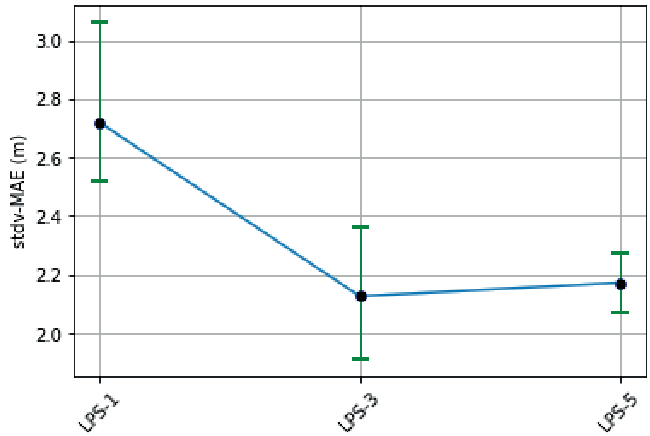

Figure 3: stdv-MAE for three different values of the weight applied on the lateral desired speed term. The bars represent the range of values over the 5 different replications.

Table 1: Flow Improvement achieved over the BCS for different values of the weight applied on the lateral desired speed term.

Weight	1	3	5
Flow Improvement (%)	4.45	4.73	4.89

The average flows achieved during the last ten minutes of half-hour simulations for different densities and 5 replications per density are used to plot the resulting fundamental diagram given in Figure 5. The same diagram includes the flows achieved for the BCS, i.e. when using the policy of zero lateral desired speed, utilized by [Yan21; Yan23]. The bars represent the range of values over the 5 replications. We observe that the critical density is 200 veh/km, while the proposed LPS improves flows around the critical density area (see Table 2 for the improvements achieved). Note that the proposed strategy has virtually no ef-

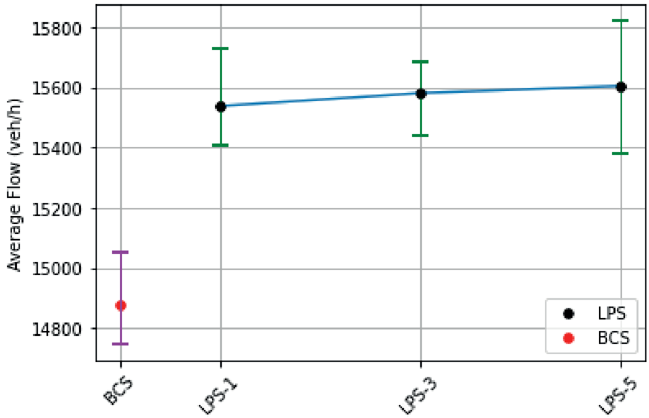

Figure 4: Average flow for the BCS and the LPS for three different values of the weight applied on the lateral desired speed term. The bars represent the range of values over the 5 different replications.

fect for very low and overcritical densities. For the case of very low densities, this is because the vehicles have anyway the space necessary to overtake slower vehicles and, as a result, they are able to achieve their desired speed. On the other hand, for overcritical densities, there is little space for maneuvers, hence the new strategy does not offer any visible advantage. Finally, for very high densities, a flow decrease is observed when using the proposed strategy. This is due to a high number of emergency situations occurring in higher densities, probably due to the additional lateral movements caused by the new sub-objective. Thus, one may consider applying LPS only around the critical density, where improvements are pronounced.

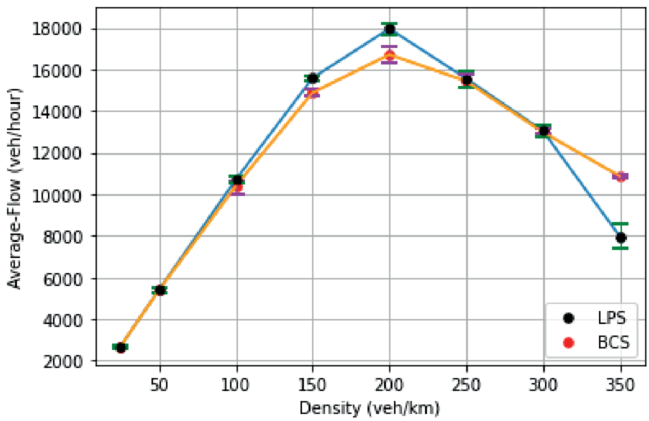

Figure 5: Fundamental diagram for the BCS and the LPS. The bars represent the range of values over the 5 different replications.

Table 2: Flow improvement achieved over the BCS per density.

Density (veh/km)	25	50	100	150	200	250	300	350
Flow Improvement (%)	-0.04	0.27	3.65	4.73	7.47	0.81	0.47	-26.60

4 Conclusions

A lateral control approach is developed for CAVs to reach a desired lateral position according to the desired longitudinal speed, with an aim to segregate similar longitudinal speed vehicle in the lateral space. It is demonstrated via SUMO on a ring-road for various densities that, when the proposed LPS is applied, the traffic flow is increased for densities around the critical area. The impact of the weight of the lateral desired speed term is also investigated. Future work is focused on having a non-homogeneous distribution in the road (including trucks), and introducing on-ramps, off-ramps, where lateral desired speeds have also a major role to enable merging and exiting of vehicles.

Acknowledgements

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Simulation Methods for Mixed Legacy-Autonomous Mainline Train Operations

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Abstract

We introduce and demonstrate a simple and efficient method for simulating mixtures of legacy and autonomous trains. The method generalises an earlier simulation that we developed for legacy-only operations, in which trains run according to fixed-block signalling rules. Autonomous trains, which use moving-block signalling rules, are incorporated into this framework by employing an overlapping set of short virtual fixed-blocks. Safe occupancy is then maintained by using shadowing rules that link the two sets of blocks. The paper gives relevant rail background, details of the proposed simulation rules, and demonstrates exemplar solution trajectories. The simulation technique is validated both in terms of (i) maintaining safe occupancy and (ii) providing a close approximation of the true continuous-space dynamics of autonomous leader-follower pairs. At the Dresden meeting, a variety of interesting mixed-fleet capacity results will also be presented.

Keywords: mainline rail capacity; fixed-block signalling rules; modelling and simulation

1 Introduction

This paper forms the latest part of a body of work [Mor22a; Mor22b] in which (i) we have taken ideas from traffic flow theory to modelling the capacity of mainline train operations, and (ii) we have examined the potential gains that might arise from more digitalised, connected, and autonomous systems.

In [Mor22a], we proposed a simplified analysis of legacy fixed-block rail operations, which resulted in fundamental diagrams that relate the speed, density, and flow rates in terms of pertinent system parameters such as signal aspects and block lengths. This theory was then modified [Mor22b] to demonstrate the increased capacity that might be achieved in a moving-block set-up, that, for example, might be achieved with level 3 of the European Train Control System (ETCS) [Sta11]. See Section 2 for a brief account of these ideas.

Unfortunately, the full gains of moving blocks might only be achieved when connected and/or autonomous trains (CATs) follow each other in sequence – because legacy driver operated and/or guided trains (DOGs) will continue to observe fixed-block rules and will not share continuous position information with their neighbours. Therefore DOG-DOG, CAT-DOG, and DOG-CAT leader-follower pairs cannot achieve the reduced headways of CAT-CAT pairs. Thus there is a pressing need to simulate mixed traffic systems and to understand both their equilibrium (smooth running) capacity and potential undesirable dynamics (stop-and-go waves etc).

In [Mor22a] we proposed and demonstrated a simple time-step simulator for legacy fixed-block mainline operations. However, the difficulty in simulating mixed running is that for CAT-CAT pairs, the follower is governed by a continuous space train-following model (TFM), analogous to a car-following model (CFM) – for example, we have shown [Mor22b] that an appropriately parameterised Gipps's model [Gip81] might be suitable. Unfortunately, the resulting mix of discrete-space and continuous-space interactions becomes quite awkward to simulate.

Therefore in this paper, we propose (Section 3) a mixed-traffic simulation method which is built upon our legacy simulation, using fixed blocks only. The basic trick is to suppose that the CATs are modelled to run on a virtual track of short fixed blocks, with two-way "shadowing" rules that link these and the (longer) fixed blocks of the legacy system. We show (Section 4) that this method allows the rules for all four leader-follower pair combinations to be represented correctly, and for the continuous-space interactions of CAT-CAT pairs to be closely approximated.

2 Fixed-block and Moving-block Operations

In [Mor22a], we investigated the line capacity of mainline rail operations that use legacy fixed-blocked signalling rules, summarised by [Pac20] and the multi-author volume edited by [The20]. In summary, the safety-critical principles are that (i) track is partitioned into fixed blocks; (ii) each block should only be occupied by at most one train at any time; (iii) each train must be able to come to a stop safely within the blocks ahead (known as the "aspects") whose occupancy the signals report, see Figure 1(a); and (iv) each train must be able to come to a stop safely ahead of any block that the signals report to be occupied by another train, see Figure 1(b).

Simple constant acceleration rules were then applied to derive the maximum safe speed for a follower train in terms of the integer-valued aspect parameter α, block length L_{B}, safety margin L_{M}, and the train's braking rate b and net-spacing s. Via density $\rho := 1/(s + L_{\mathrm{T}})$, where L_{T} is the train length, we may thus derive fundamental diagrams (FDs) that relate the

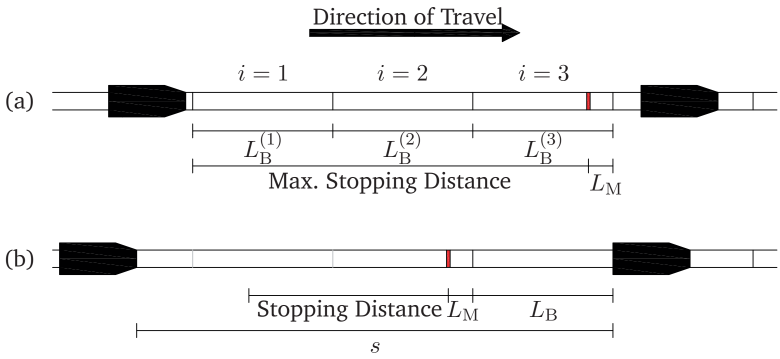

Figure 1: Safety limit cases [Mor22a]: here $\alpha = 3$ (four-aspect) fixed-block signalling is shown. (a) Each train must be able to stop safely within the blocks that the signals report upon. (b) The net spacing, s, must be sufficient for the follower train to come to a stop before the leader's block.

speed, density, and flow of mainline operations. See [Mor22a] for mathematical formulae and Figure 2 for plots of the resulting FDs.

In contrast to legacy operations, it is assumed that CATs will use a moving-block system. Thus in a pure-CAT system, the trains have continuous-space knowledge of each other's displacement. As we showed in [Mor22b], this is equivalent to a fixed-block system with an infinitesimal block size $L_B \to 0$, but infinite spatial foresight $\alpha L_B \to \infty$. This analysis gives rise to a new set of FDs indicated by the blue lines in Figure 2, quantifying the capacity gains – suggesting that a doubling of capacity might be possible in pure moving-block operations [Mor22a]. Furthermore, we showed that these moving-block capacity calculations match an analysis based on Gipps's car-following model, where we assume that the leader train is capable of a *brick-wall* instantaneous stop – this is a pessimistic but appropriate assumption given the safety tradition of rail.

3 Simulation Methodology

In [Mor22a], we described and demonstrated a simple time-step simulator for legacy fixed-block operations. This is because we found commercial simulators, such as [Ope21], are not sufficiently adaptable for our purposes – for example, they do not allow one to perform "ring-road" experiments as are standard in the traffic flow theory literature.

In our simulator, at any instant, each train is assumed to be in one of four discrete states, namely (i) at maximum (goal) speed, (ii) accelerating to goal speed, (iii) halted, waiting for the block ahead to become free, and (iv) braking to come to a stop ahead of a block that is not known to be safe for the train to enter. Each train then advances down the track according to standard 1D kinematics, registering its presence with the block(s) that it occupies, and updating its state as appropriate – for example, switching to the braking state at the instant that a "watch point" which precedes the train by its instantaneous stopping

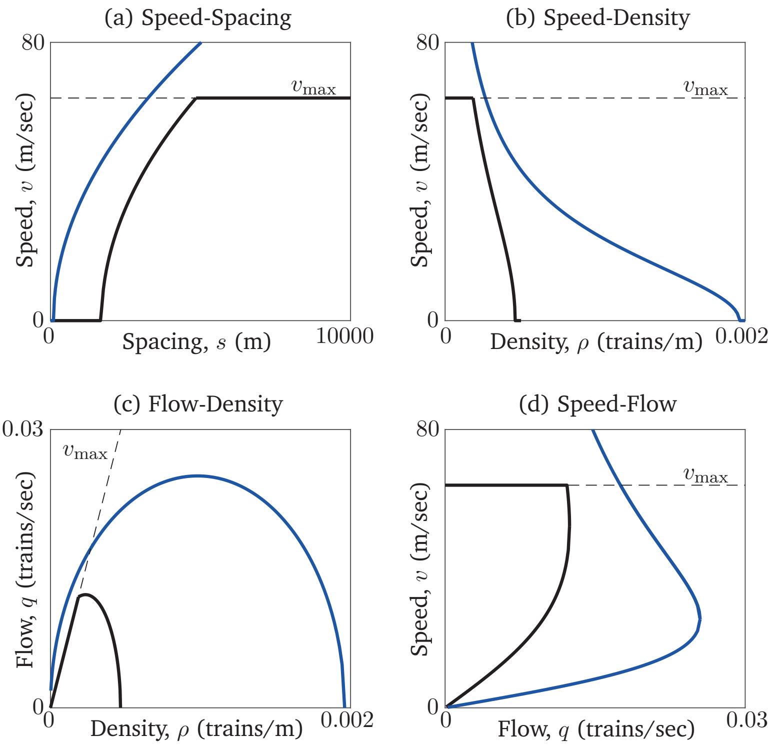

Figure 2: Fundamental diagrams (FDs) for mainline rail traffic. Black lines show legacy operations and blue lines show the improved performance of connected and/or autonomous trains. (a) Speed v versus net spacing s. (b) Speed v versus density ρ. (c) Flow q versus density ρ. (d) Speed v versus flow q. Here we implement standardised parameter choices $L_{\mathrm{T}} = 400\,\mathrm{m} < L_{\mathrm{B}} = 1,600\,\mathrm{m}$, $L_{\mathrm{M}} = 100\,\mathrm{m}$, $\alpha = 2$, $b = 0.65\,\mathrm{ms}^{-2}$ and $a = 0.4\,\mathrm{ms}^{-2}$, justified in [Mor22a].

distance first enters a block which is not known to be free. It is important to note that legacy trains do not interact with each other directly, but only via their occupancy of the discrete fixed-block infrastructure.

In contrast, CATs should ideally follow each other with (e.g.) Gipps's CFM, in which consecutive trains use continuous-position knowledge of each other (and employ a continuous range of ac/decelerations rather than just the four states described above). The mixed-traffic simulation is thus challenging to code up, since each train must maintain a pointer to its leader to determine the appropriate following behaviour, discrete or continuous. In track layouts with merges and diverges, the relative ordering of trains might change and the pointer syntax will become particularly complicated.

We have developed a rather simple solution to these problems, illustrated in Figure 3. The idea is that *all trains*, both CATs and DOGs, drive on fixed blocks according to the four-state rules of our legacy simulator. However, the CATs drive on a virtual set of blocks which are

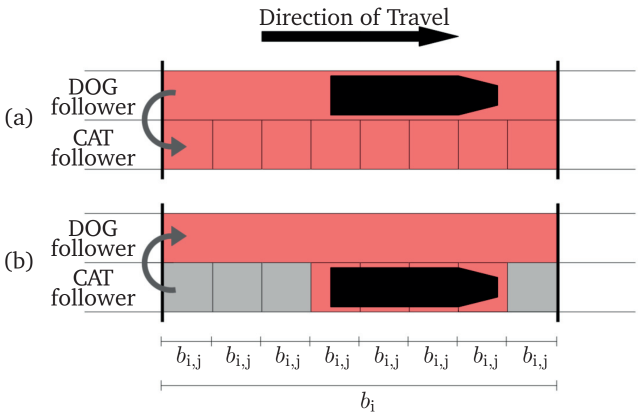

Figure 3: Block shadowing rules for mixed operations. DOGs run on the original coarse fixed blocks, whereas CATs run on shorter virtual fixed blocks. Occupancies signalled by (a) DOG leader; (b) CAT leader, where red blocks are signalled as occupied and grey blocks are signalled as free.

much shorter than the legacy blocks, to capture the idea that moving blocks are equivalent to block length $L_B \to 0$.

To ensure the correct following behaviour for all four possible leader-follower combinations, the virtual and legacy blocks shadow each other in the following ways. Firstly, see Figure 3(a), a DOG leader blocks out all of the virtual blocks that overlap with it, so that a CAT follower must act conservatively (as the legacy DOG train does not broadcast continuous-position information). In contrast, see Figure 3(b), a CAT leader blocks out only a short sequence of virtual blocks (enabling close-following by a CAT follower), but also blocks out any legacy block with which its virtual blocks overlap – thus a DOG follower must act conservatively as it only has access to the legacy signalling system, and not to the continuous-position information that the CAT broadcasts.

4 Demonstration

Using the new simulation framework, we have performed a range of experiments with different mixtures of DOGs and CATs, using a variety of different track topologies. The aim is to examine how realised capacities of mixed running compare to the theory in Figure 2. For more complex track topologies, we have also made comparisons with the emerging Macroscopic Fundamental Diagram (MFD) ideas for rail [Far17]. Full details will be given at the Dresden meeting.

Here we focus, very briefly, on displaying some of the dynamics via trajectory plots, see Figures 4 and 5. The basic set-up is a “ring-road” into which we inject DOGs and CATs via two distinct input tracks, in such a way to randomise the resulting order, with density controlled by the length of the “ring-road”.

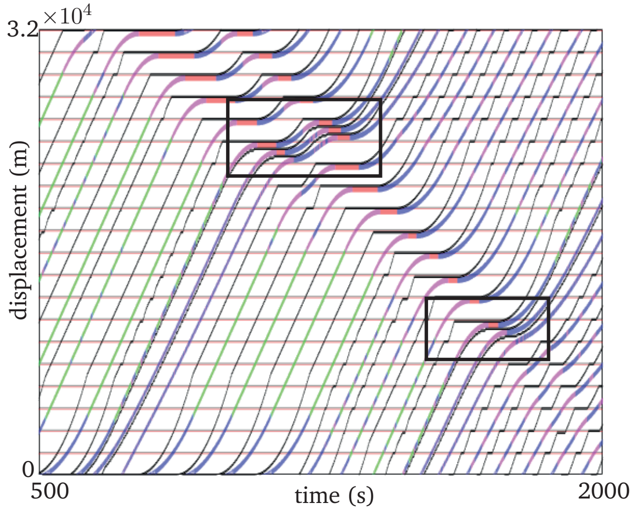

Figure 4: Trajectory plot showing mixed running of CATs and DOGs on a ring with a resulting stop-and-go wave. The legacy block infrastructure is denoted by the overlaid horizontal black lines and red lines which denote the associated safe stopping points. Each train's state is represented by colour: green (at goal speed); magenta (braking); red (halted); blue (accelerating). The black boxes highlight regions with consecutive CATs, where the close following is particularly clear when the trains come to a halt.

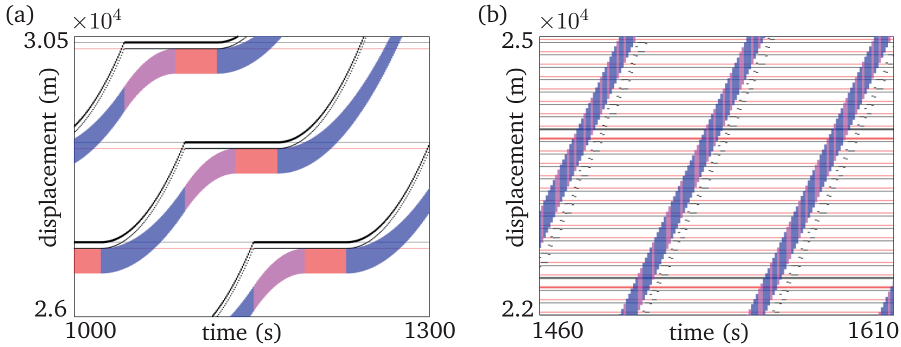

Figure 5: Zoomed-in trajectories. (a) Sub-sequence of legacy trains in a stop-and-go pattern. The additional black lines denote the stopping point of each train and the "watch point" that is a safety margin L_{M} beyond that. (b) Sub-sequence of CATs at an apparently uniform speed. The fine virtual block infrastructure is overlaid (thin horizontal black and red lines). The CATs cannot achieve smooth running at their goal speed, and thus approximate the desired continuous TFM behaviour by a rapid jittering between accelerating (blue) and braking (magenta) states, as their watch points roll over the virtual block infrastructure.

Figure 4 gives a large-scale view of 25 minutes of running over 32 km of track into which 10 trains are injected (5 DOGs and 5 CATs). A stop-and-go wave results. The close-following behaviour of consecutive CATs is particularly apparent as they come to a halt, since in that setting, the net spacing may be as short as the safety margin parameter $L_{\mathrm{M}} := 100\,\mathrm{m}$.

In contrast, Figure 5(a) gives a zoomed view of consecutive DOGs coming to a halt, and shows the fine detail of how safe occupancy is maintained, by initiating a train's braking when its watch point first reaches the rear of an occupied block. At halt, the net spacing of consecutive DOGs is $L_{\mathrm{M}} + L_{\mathrm{B}} - L_{\mathrm{T}} = 1,300\,\mathrm{m}$.

Finally, Figure 5(b) gives a zoomed view of consecutive CATs in apparently constant-speed running. In fact, constant-speed running below the goal speed is not compatible with the four-state simulation, nor can CATs choose their acceleration continuously in this framework. Rather, each CAT approximates the correct continuous-space TFM behaviour by jittering between accelerating and braking states as its watch point rolls over the fine-scale virtual blocks. Potentially, the jittering may be reduced in scale by shortening the virtual blocks. However, to maintain provable safety, blocks must be at least as long as the safety margin L_{M}, and our simulation method requires $L_{\mathrm{M}} > v_{\max}\Delta t$, i.e. the maximum distance that a train can move in one time step – so shortening the blocks requires that the time step Δt is reduced, with the associated computational cost. However, it can be in any case shown that the resulting undesirable oscillations in velocity are rather small, and a modest low-pass filtering of the trajectory recovers a very close approximation to the dynamics of Gipps's CFM.

Acknowledgements

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Can Dedicated Lanes for Automated Vehicles on Urban Roads Improve Traffic Efficiency?

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Abstract

Connected and automated vehicles (CAVs) will behave fundamentally differently than human drivers. In mixed traffic, this could lead to inefficiencies and safety-critical situations since neither human drivers nor CAVs will be able to fully anticipate or predict surrounding traffic dynamics. Thus, some researchers proposed to separate CAVs from conventional vehicles by dedicating exclusive lanes to them. However, the separation of road infrastructure can negatively impact the system's capacity. While the effects of CAV lanes were addressed for freeways, their deployment in urban settings is not yet fully understood. This paper systematically analyzes the effects of CAV-lanes in an urban setting accounting for the corresponding complexities. We employ microscopic traffic simulation to model traffic flow dynamics in a detailed manner and to be able to consider a wide array of supply-related characteristics. These concern intersection geometry, public transport operation, traffic signal control, and traffic management. Our study contributes to the existing literature by revealing the potential of CAV lanes in an urban setting while accounting for the behavioral and topological complexities. The results of this study can support decision-makers in the design of future urban transportation systems and to prepare cities for the upcoming era of automation in traffic.

Keywords: automated vehicles, connected vehicles, managed lanes, capacity

1 Introduction

The development of automated driving functions as well as advances in communication technology will determine the future driving behavior of vehicles. Ongoing research and development activities explore the operation of connected and automated vehicles (CAVs) and their impacts on traffic flow dynamics on freeways and in urban areas, e.g. [Til18]. It is expected that the driving behavior of CAVs will be fundamentally different from that of human drivers. In mixed traffic, neither human drivers nor CAVs will be able to fully anticipate or predict surrounding traffic dynamics which could lead to safety-critical situations. CAVs could potentially avoid such situations by following a conservative driving style which can result in inefficient traffic flow. Also, to reduce possible negative impacts on traffic safety, some researchers proposed to separate CAVs from conventional vehicles by dedicating exclusive lanes to them, e.g. [Zha20]. However, such separation of road infrastructure can again negatively affect the system's capacity.

In recent years, numerous studies addressed the design of dedicated lanes in networks, not only in the context of CAVs. In fact, these studies mostly focused on freeway road facilities, e.g. [Ghi17; Ye18]. However, the structure of urban networks differs quite substantially from freeway settings. A substantial share of capacities is provided by arterials, i.e. multi-lane corridors interrupted by signalized intersections. This consequently affects the occurring traffic dynamics, especially when frequent stopping maneuvers (e.g. caused by mobility-on-demand services) may further reduce traffic flow, e.g. [Stu22]. Interestingly, little attention has been paid to the effects of dedicated lanes in such urban settings. Related studies either focused on the big picture by applying analytical or macroscopic traffic flow models, thereby omitting detailed driving behavior and intersection complexities, e.g. [Mov20; Ami20], or were rather limited to very specific scenarios when applying microscopic models, e.g. [Sha21; Moh19]. To our best knowledge, no study systematically employs detailed microscopic simulation to investigate the potential benefits of CAV lanes in complex urban settings under mixed traffic conditions.

In this paper, we investigate the effects of CAV lanes for urban settings at the local level based on microscopic traffic flow simulation to fill this gap. Thereby, we focus on the essential element of urban networks, a link, and its downstream and upstream intersections. We vary the underlying characteristics referring to geometric intersection design, the number of lanes, road length, traffic signal control settings, public transport operation, and speed limits. The results of the study indicate under which circumstances the deployment of CAV lanes can be beneficial. This is an important input for higher-level methods to design CAV lanes at the network level. Ultimately, the efficient design of CAV lanes in urban networks can be an opportunity to utilize existing road space more efficiently and safely.

2 Methodology

First, we describe microscopic traffic simulation which is the core method of the presented analysis. Then, we depict the base network for which the scenarios are evaluated. Finally, we explain the workflow of the scenario analysis.

2.1 Traffic Simulation Models

Heterogeneity in the driving behavior of human driven-vehicles (HDVs) and CAVs can result in complex traffic flow dynamics, especially in urban areas. Existing analytical and macroscopic modeling approaches consider only aggregated scales and simplified topologies. While they were successfully applied to estimate related capacity gains, they lack the possibility to account for key aspects when analyzing mixed traffic in complex urban networks. Therefore, we use the microscopic traffic simulation SUMO [Lop18] that has been successfully applied for studying the effects of CAVs on traffic flow in the past, e.g. [Li19]. We apply standard models for the behavior of HDVs, and the ones proposed in [Ols20] for modeling CAV behavior, as such were developed based on field tests and thus calibrated with empirical data.

2.2 Base Network

The base network is depicted in Figure 1. It consists of one intersection with the main signal S_m and four approaches. The arrows describe the direction of travel for each link.

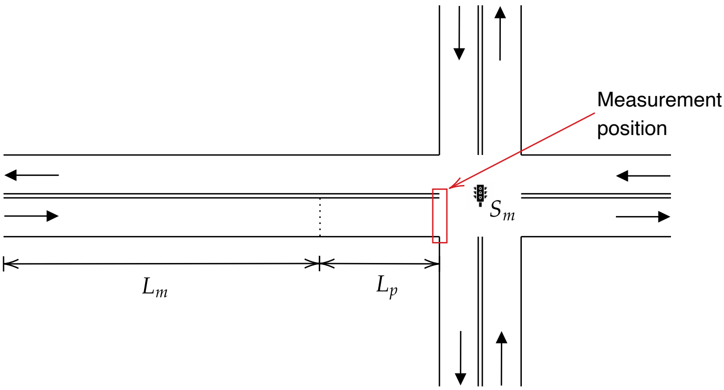

Figure 1: Layout of the base network.

The analysis focuses on link L which is divided into a main segment L_m and a pre-sorting segment L_p. The control logic refers to the main signal S_m. The vehicle throughput is measured at the downstream end of the edge right before the intersection, as highlighted by the red rectangle in the figure.

2.3 Scenario Analysis

The main goal is to systematically analyze the effects of a dedicated CAV lane on traffic efficiency in realistic urban settings. Therefore, we focus on the maximum vehicle throughput as performance indicator. To conduct our analysis, we follow a methodology where we gradually increase the scenario complexity. Figure 2 visualizes the overall workflow.

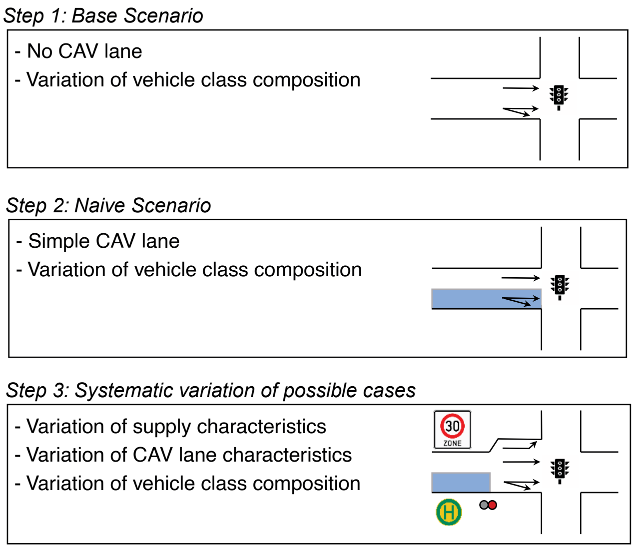

Figure 2: Workflow.

In the first step, we evaluate a simple base scenario to demonstrate the general effects of CAVs on the throughput. Then, we naively dedicate one lane to CAVs and analyze the corresponding effects. On this dedicated lane, only CAVs are allowed to drive, whereas all vehicle classes can use the remaining lane. In the third step, we study a large array of supply-related aspects to identify those realistic urban scenario settings for which the deployment of dedicated CAV lanes maximizes the capacity. This also includes additional traffic management schemes, such as the installation of a pre-signal to allow for a more safe and efficient sorting in L_p, or changing the maximum speed limits.

This gradual increase of intricacy enables us (i) to account for the complexity of urban infrastructure, (ii) to demonstrate the effects of such and their interaction with CAV lanes, and (iii) to show the potential of additional traffic management measures to further improve efficiency. The varied scenario characteristics are shown in Table 1. The characteristics regarding intersection geometry, public transport operation, intersection control, and traffic management are derived from experience and logical thought. The fixed-time control is based on a 90 s cycle time with reasonable green and amber times. We acknowledge that the respective values in Table 1 are not an exhaustive list but assume that the choice covers a meaningful range.

We consider two different CAV classes, namely the "normal" and "all-knowing" model according to [Ols20]. The total penetration rate in the simulations varies between 0 % and 100 % in steps of 25 %. For some penetration rates, we vary the CAV class composition by

Table 1: Analyzed supply and traffic management characteristics.

Category	**Characteristic**	**Values**
Intersection geometry	Number of lanes	2, 3
	Road length	250 m, 500 m, 750 m
	Turning options	Right-turning, right- and left-turning
	Turning lanes	Yes, no
PT Operation	Dedicated bus lane	Yes, no
	Headway	2.5 min, 10 min
Intersection control	Type	Fixed-time, actuated
Traffic management	CAV lane	Left, middle, right
	Pre-signal	Yes, no
	Speed limits	30 km/h, 50 km/h

setting the respective shares to either 0 %, 50 %, or 100 %. This leads to a total of 11 vehicle class compositions including a reference case with 100 % HDVs (see Table 2).

A simulation scenario is defined by specific values of the supply and traffic management characteristics as well as a vehicle class composition. Combining all possible values leads to approx. 12,500 scenarios which are then evaluated with SUMO. Each scenario is simulated for a reasonable period, and with a trapezoidal loading and unloading curve to mimic a rush hour. We ensure that the loading let the system reach its capacity. Last, all simulation runs are conducted for 10 random seeds.

Table 2: Vehicle class compositions.

Index [-]	**HDVs [%]**	**Normal CAVs [%]**	**All-knowing CAVs [%]**
0	100	0	0
1	75	25	0
2	75	12.5	12.5
3	75	0	25
4	50	50	0
5	50	25	25
6	50	0	50
7	25	75	0
8	25	37.5	37.5
9	25	0	75
10	0	0	100