Guest Editorial
Introduction to the Special Issue on Deployment of Connected and Automated Vehicles in Mixed Traffic Environment and the Implications on Traffic Safety and Efficiency

I. Introduction

The gradual deployment of Connected and Automated Vehicles (CAV) in traffic will result in a transition period in which vehicles with various levels of automation and connectivity will have to co-exist with non-connected and non-automated road users for quite some time. Consequently, new types of interactions will emerge (and old types of interactions are likely to become more complicated) between vehicles at different levels of automation and other road users which could have significant implications on traffic safety and efficiency. Understanding the nature of these interactions, how humans might adapt their behavior, how connectivity can be utilized to proactively enhance drivers' driving performance, and how automated vehicles can be programmed to behave in different driving situations to guarantee safety and efficiency remain among the key knowledge gaps that require scientific research. This knowledge is crucial for the development of adequate integration policies of connected and automated vehicles in mixed traffic environment, for updating and improving automated vehicles' algorithms and software, for designing the physical and digital road infrastructure, and for operating and managing traffic on the road network.

This Special Issue contains 22 scientific papers that we have broadly categorized under four major themes: trajectory prediction and control, modelling and simulation, mixed vehicle platoons, and safety and efficiency assessment.

II. Trajectory Prediction and Control

Jiang and Shang [A1] propose a dynamic CAV-dedicated lane allocation method with a joint optimization of signal timing parameters and smooth trajectory to improve the performance of intersections. The simulation results show that the proposed method improves the performance of the intersection compared with that of a fully actuated signal control scheme.

Mousavi et al. [A2] study mixed traffic systems, moving along a single-lane ring-road or open-road. The authors present a robust control strategy that smoothens the traffic flow in the presence of undesired disturbances and parametric uncertainties. They first present a theoretical analysis to prove the stabilizability and detectability of the mixed traffic flow system. Then, they design two $H\infty$ control strategies, with and without considering uncertainties in the system dynamics. By using numerical simulations, the authors demonstrate the effectiveness of the proposed controller.

Wen et al. [A3] developed a decentralized model predictive control strategy for longitudinal velocity control to optimize the vehicle platoon system in terms of car-following behavior. The simulation results show that with the proposed method, CAV platoons maintained a safe distance and quickly completed velocity tracking resulting in improvement in traffic efficiency, fuel economy, driving safety, and transportation capacity.

Jeon et al. [A4] propose a semi-supervised learning framework with auxiliary structures to enable the autonomous vehicle to predict the future reactions of surrounding vehicles. The experimental results show that a plausible reaction can be predicted for the augmented future trajectory of the ego vehicle, which indicates that the network can generalize the interactive behavior of vehicles from a partially labeled dataset.

Li et al. [A5] incorporated reinforcement learning techniques into vehicle merging control to achieve global cooperation. A communication protocol among reinforcement learning agents was integrated with a Soft Actor-Critic algorithm. The results show that the proposed merging strategy generated collision-free merging trajectories with a short travel time while guaranteeing traffic safety in various traffic conditions.

III. Modeling and Simulation

Zhang et al. [A6] discretized the continuous deceleration efficiency of the uphill by introducing variable parameters connected to the vehicle position and gradient and propose further improvement to the hybrid traffic flow cellular automata model suitable for slope bottlenecks based on the principle of the safety distance. The simulation results show that the improved model can simulate the unique traffic flow phenomenon caused by the change in slope conditions. Furthermore, the main factors influencing traffic flow were identified.

Yao et al. [A7] modeled the fundamental diagram of mixed traffic flow with and without dedicated lanes for CAVs. The results show that developing CAVs dedicated lanes under a reasonable CAVs penetration rate does not waste resources and increases traffic congestion while improving traffic capacity.

Huang et al. [A8] investigated the impact caused by mixed traffic on the macroscopic fundamental diagrams under different signal control schemes, demand loading patterns, and

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vehicle penetration rates. The authors used empirical data from Waymo Open Dataset and OpenACC to calibrate the behavioral models in simulation. The results show that the positive impact of autonomous vehicles on macroscopic traffic is still far from ideal since they may be too conservative.

Li et al. [A9] derived a generic Hopf bifurcation structure that can be applied to multiclass traffic models which can capture the complex nonlinear dynamic behavior of heterogeneous traffic flow. The authors applied this method to a connected and autonomous environment, and by using simulation experiments, they verified the theoretical analysis results.

Farah et al. [A10] identified six aspects to consider for modeling automated driving in microscopic traffic simulations. The authors investigate how both empirical and microscopic traffic simulation studies on automated driving have considered the proposed aspects, and identify the state of the practice and the research needs to further improve the modeling of automated driving.

Schrab et al. [A11] present a multi-domain simulation framework, namely, Eclipse MOSAIC, which is able to couple best-in-class traffic, application, and communication simulators as well as to include further models and external native code libraries.

IV. Mixed Vehicle Platoons

Lan et al. [A12] propose a data-driven model predictive control that does not need the exact models of human-driven vehicles or powertrain parameters. The model predictive control design adopts the technique of data-driven reachability to predict the future trajectory of the mixed platoon within a given horizon based on noisy vehicle measurements. The proposed model of predictive control can establish a safe and robustly stable mixed platoon.

Jiang et al. [A13] propose a two-level collaborative control framework of vehicular traffic mixed with connected autonomous vehicles and human-piloted vehicles with advanced driver assistance systems for a signal-free intersection. The proposed method outperforms the state-of-the-art controllers in reducing the total delay and fuel/energy consumption. Furthermore, a sensitivity analysis regarding the penetration rate of CAVs shows that substantial improvements can be achieved even at low to medium penetration rates of CAVs.

Liu et al. [A14] introduce a theoretical framework for head-to-tail string stability of mixed platoons. Head-to-tail string stability allows a lack of string stability due to human drivers, provided it can be suitably compensated by automated vehicles sparsely inserted in the platoon. The proposed framework gives a reduced-order design for head-to-tail string stability only depending on three gains, and it shows that safety improvements can be attained by a reduced-order design only depending on two additional gains. The simulation results show that the string stability/safety trade-offs of the proposed reduced-order design are comparable with those resulting from full-order designs.

Godinho et al. [A15] address in their article the issue of connectivity maintenance in autonomous platoons and stability under complete disconnection. They model the network connection as a Directed Acyclic Graph, and they use a state-machine policy to recover connectivity and regulate the spacing distance under heterogeneous time delays. The results from agent-based and nonlinear simulations show the effectiveness of this approach.

V. Safety and Efficiency Assessment

Ali et al. [A16] adopted an Extreme Value Theory approach to estimate and compare crash risk using traffic conflicts during mandatory lane-changing maneuvers in a traditional and connected environment. In an advanced driving simulator, three randomized driving conditions were tested: baseline (without driving aids), connected environment with perfect communication, and connected environment with communication delay. The results confirm the efficacy of the generalized extreme value models to quantify crash risk using conflict data, and that a connected environment has the potential to reduce crash risk during mandatory lane changing.

Weng et al. [A17] present a novel safety metric that characterizes a subject vehicle's almost safe operable domain and the probability for the subject vehicle to remain inside the safe domain indefinitely, respectively. The authors demonstrate the empirical performance in different operational design domains through cases covering a variety of fidelity levels, driving environments, road users, and subject vehicle driving behaviors.

Zhang et al. [A18] propose a learning framework that combines primitive-based interaction pattern recognition and risk analysis for autonomous vehicles to make complex lane change decisions. The authors identify the dynamic spatiotemporal characteristics and risk formation mechanism of the lane-changing interaction patterns. This framework can help to design and improve the decision-making process during lane changes and enhance the safety of autonomous vehicles.

Garg and Bouroche [A19] evaluate the impact of CAV penetration on both traffic safety and efficiency in realistic scenarios (e.g., imperfect communication, humans' large reaction time, and perception errors), and investigate the trade-off between them. The results show that imperfections in vehicle-to-vehicle communication links and driver's large reaction time have adverse effects on both safety and efficiency, though both still improve significantly as the CAV penetration rate increases. Also, the increase in time headways improves traffic safety significantly despite the negative effects of humans' large reaction times and losses in vehicle-to-vehicle communication; however, this is at the expense of reduced traffic efficiency.

Miqdady et al. [A20] use simulation combined with the Surrogate Safety Assessment Model to evaluate the traffic safety of CAVs with different levels of automation. Different CAV levels were modeled using Gipps' model, followed by a simulation of nine mixed fleets at a motorway segment. The results indicate that the gradual penetration of CAV levels led to a progressive reduction in traffic conflicts, and human-driven vehicles and vehicles with low levels of automation are more frequently involved in conflicts (as follower vehicles) than vehicles with high automation levels.

Hu et al. [A21] characterize the empirical car-following behaviors of the Waymo autonomous vehicle, compare its feature with human-driven vehicles and capture such behavioral differences using the IDM car-following model. The authors conclude that the Waymo Open Dataset trajectories, despite their short length, are suitable for calibrating some of the IDM parameters. Furthermore, current autonomous vehicle behaves in a conservative way to ensure its safety at the cost of traffic efficiency.

Bhattacharyya et al. [A22] investigate driver response behavior to a Human–Machine Interface displaying speed instructions with reference to the Green Light Optimal Speed Advisory strategy. The authors utilize Field Operational Test (FOT) data collected as passive logs of a smartphone app deployed in a French city. Furthermore, the authors use a simulated environment to extend the findings to non-observed cases. The results point out that there may be optimal distance and speed advice for informing the drivers to achieve better response and improved system impacts.

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Appendix: Related Articles

[A1] X. Jiang and Q. Shang, "A dynamic CAV-dedicated lane allocation method with the joint optimization of signal timing parameters and smooth trajectory in a mixed traffic environment," *IEEE Trans. Intell. Transp. Syst.*, early access, May 13, 2022, doi: 10.1109/TITS.2022.3172942.

[A2] S. S. Mousavi, S. Bahrami, and A. Kouvelas, "Synthesis of output-feedback controllers for mixed traffic systems in presence of disturbances and uncertainties," *IEEE Trans. Intell. Transp. Syst.*, early access, Jul. 12, 2022, doi: 10.1109/TITS.2022.3185155.

[A3] J. Wen, S. Wang, C. Wu, X. Xiao, and N. Lyu, "A longitudinal velocity CF-MPC model for connected and automated vehicle platooning," *IEEE Trans. Intell. Transp. Syst.*, early access, Oct. 28, 2022, doi: 10.1109/TITS.2022.3215172.

[A4] H. Jeon, S. Kim, K. Lee, D. Kang, J. Choi, and D. Kum, "Are reactions to ego vehicles predictable without data?: A semi-supervised approach," *IEEE Trans. Intell. Transp. Syst.*, doi: 10.1109/TITS.2022.3221275.

[A5] M. Li, Z. Li, S. Wang, and S. Zheng, "Enhancing cooperation of vehicle merging control in heavy traffic using communication-based soft actor-critic algorithm," *IEEE Trans. Intell. Transp. Syst.*, early access, Nov. 17, 2022, doi: 10.1109/TITS.2022.3221450.

[A6] F. Zhang, Y. Qian, and J. Zeng, "Characterizing heterogeneous traffic flow at a slope bottleneck via cellular automaton model," *IEEE Trans. Intell. Transp. Syst.*, early access, Jun. 17, 2022, doi: 10.1109/TITS.2022.3182352.

[A7] Z. Yao, Y. Wu, Y. Jiang, and B. Ran, "Modeling the fundamental diagram of mixed traffic flow with dedicated lanes for connected automated vehicles," *IEEE Trans. Intell. Transp. Syst.*, early access, Nov. 29, 2022, doi: 10.1109/TITS.2022.3219836.

[A8] Y. Huang, Y. Ye, J. Sun, and Y. Tian, "Characterizing the impact of autonomous vehicles on macroscopic fundamental diagrams," *IEEE Trans. Intell. Transp. Syst.*, early access, Apr. 14, 2023, doi: 10.1109/TITS.2023.3265647.

[A9] T. Li, D. Ngoduy, and X. Zhao, "Hopf bifurcation analysis of mixed traffic and its implications for connected and autonomous vehicles," *IEEE Trans. Intell. Transp. Syst.*, early access, Feb. 16, 2023, doi: 10.1109/TITS.2023.3242826.

[A10] H. Farah et al., "Modeling automated driving in microscopic traffic simulations for traffic performance evaluations: Aspects to consider and state of the practice," *IEEE Trans. Intell. Transp. Syst.*, early access, Aug. 29, 2022, doi: 10.1109/TITS.2022.3200176.

[A11] K. Schrab et al., "Modeling an ITS management solution for mixed highway traffic with eclipse MOSAIC," *IEEE Trans. Intell. Transp. Syst.*, early access, Sep. 23, 2022, doi: 10.1109/TITS.2022.3204174.

[A12] J. Lan, D. Zhao, and D. Tian, "Data-driven robust predictive control for mixed vehicle platoons using noisy measurement," *IEEE Trans. Intell. Transp. Syst.*, early access, Nov. 24, 2021, doi: 10.1109/TITS.2021.3128406.

[A13] S. Jiang, T. Pan, R. Zhong, C. Chen, X. Li, and S. Wang, "Coordination of mixed platoons and eco-driving strategy for a signal-free intersection," *IEEE Trans. Intell. Transp. Syst.*, early access, Oct. 12, 2022, doi: 10.1109/TITS.2022.3211934.

[A14] D. Liu, B. Besselink, S. Baldi, W. Yu, and H. L. Trentelman, "On structural and safety properties of head-to-tail string stability in mixed platoons," *IEEE Trans. Intell. Transp. Syst.*, early access, Feb. 23, 2022, doi: 10.1109/TITS.2022.3151929.

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[A16] Y. Ali, Md. M. Haque, and Z. Zheng, "Assessing a connected environment's safety impact during mandatory lane-changing: A block maxima approach," *IEEE Trans. Intell. Transp. Syst.*, early access, Feb. 16, 2022, doi: 10.1109/TITS.2022.3147668.

[A17] B. Weng, L. Capito, Ü. Özgüner, and K. Redmill, "A finite-sampling, operational domain specific, and provably unbiased connected and automated vehicle safety metric," *IEEE Trans. Intell. Transp. Syst.*, early access, Apr. 13, 2022, doi: 10.1109/TITS.2022.3164358.

[A18] Y. Zhang, Y. Zou, Selpi, Y. Zhang, and L. Wu, "Spatiotemporal interaction pattern recognition and risk evolution analysis during lane changes," *IEEE Trans. Intell. Transp. Syst.*, early access, Jan. 30, 2023, doi: 10.1109/TITS.2022.3233809.

[A19] M. Garg and M. Bouroche, "Can connected autonomous vehicles improve mixed traffic safety without compromising efficiency in realistic scenarios?" *IEEE Trans. Intell. Transp. Syst.*, early access, Jan. 26, 2023, doi: 10.1109/TITS.2023.3238889.

[A20] T. Miqdady, R. De Ona, J. Casas, and J. de Ona, "Studying traffic safety during the transition period between manual driving and autonomous driving: A simulation-based approach," *IEEE Trans. Intell. Transp. Syst.*, early access, Feb. 16, 2023, doi: 10.1109/TITS.2023.3241970.

[A21] X. Hu, Z. Zheng, D. Chen, and J. Sun, "Autonomous vehicle's impact on traffic: Empirical evidence from Waymo Open Dataset and implications from modelling," *IEEE Trans. Intell. Transp. Syst.*, early access, Mar. 23, 2023, doi: 10.1109/TITS.2023.3258145.

[A22] K. Bhattacharyya, P. Laharotte, A. Burianne, and N. E. Faouzi, "Assessing connected vehicle's response to green light optimal speed advisory from field operational test and scaling up," *IEEE Trans. Intell. Transp. Syst.*, early access, Jul. 13, 2022, doi: 10.1109/TITS.2022.3187532.

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