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RESEARCH ARTICLE

Rule-Based On-Off Traffic Control Strategy for CAVs on Motorway Networks: Assessing Cooperation Level and Driving Homogeneity

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ABSTRACT Connected and automated vehicles (CAVs) attract much attention due to their unique behavioral characteristics and the promise to transform road transport systems as we know them today. However, the behavior of such vehicles on the road is not homogeneous since each manufacturer offers different implementations. Cooperation is essential to homogenize the traffic flow of CAVs and prevent delays on congested networks with high demand. This work proposes a rule-based decentralized on-off cooperation strategy at merging locations on freeway networks using CAVs as mobile actuators. The proposed strategy handles bilateral conflicts at on-ramps between vehicles with conflicting trajectories, taking actions at the vehicle level in a lateral or longitudinal direction, to minimize the disturbance for the following vehicles. Furthermore, heterogeneity among such vehicles is assessed through different parameter distributions among CAVs to demonstrate the importance of ensuring homogeneous dynamics in the vehicle operation design. Microscopic simulation is used to demonstrate the robustness of the proposed strategy and the value of homogeneous dynamics. The results show that cooperation of CAVs decreases the average network delay time by up to 46%. Homogeneous driving behavior amplifies the benefit of the cooperative strategy significantly.

INDEX TERMS Connected and automated vehicles, traffic control, driver homogeneity, intelligent transportation systems, traffic management, traffic simulation.

I. INTRODUCTION

Connected and Automated Vehicles (CAVs) are expected to bring significant advancements in the existing road transport systems via new behavioral patterns and capabilities [1], [2], [3]. However, field experiments with partially automated commercial vehicles [4] show the inability of automation alone to resolve traffic congestion. Automated vehicles can not anticipate disruptions downstream, leading to string instability and high energy demand [5], [6], [7]. Cooperation between vehicles seems to be the key to substantial benefits along the above dimensions, as pointed out in preliminary experimental observations [8], [9]. Information exchange enables cooperation, which in turn allows for more accurate traffic monitoring, estimation, and control towards system optimal solutions [10], [11]. The interest in the explicit simulation of CAV's behavior is high and enabled the development of new models from the microscopic to the macroscopic level [12], [13].

City authorities worldwide, e.g., in Switzerland, Sweden, the UK, and the US, investigate new ways of traffic management to anticipate the steady population and mobility growth, curb congestion, and minimize delays [14], [15], [16], [17].

CAVs can further improve existing traffic management strategies in a centralized or decentralized manner aiming to harmonize speeds and homogenize traffic flow

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[18], [19]. Observations show that even highly-automated vehicles behave differently on the road since each manufacturer offers different implementations [4]. Aiming at homogeneity at the vehicle dynamics level is not extensively discussed in the literature, but it can play a critical role in future CAV-populated networks [20].

This work presents a microsimulation study that looks at scenarios with full CAV deployment in high-demand multi-lane motorway networks. A rule-based on-off cooperation strategy for traffic management is proposed. Communication between CAVs and the infrastructure is considered possible. Additionally, different levels of heterogeneity in the vehicle dynamics of CAVs are reproduced through different parameters distribution in the simulation models. Scenarios with different cooperation and homogeneity rates among CAVs quantify anticipated benefits.

II. LITERATURE REVIEW

Traffic congestion in freeway networks leads to a strong degradation of the network infrastructure and reduced throughput. Several control measures, such as ramp-metering (RM) and variable speed limit (VSL), have been proposed in the literature, corresponding to analytical investigations and real-world implementations. The underlying notion in such measures is the redistribution of delays to maximize the network's performance. Therefore, attempting to transfer this notion to the CAVs era is interesting. For a comprehensive overview of control strategies, we refer the reader to the Papageorgiou et al. study [21].

A good overview of optimizing road systems using CAVs is given in [22]. The authors list different approaches to coordinating CAVs in merging areas. They distinguish between centralized and decentralized approaches without crisp conclusions on the best approach. The interest in the possibilities of such solutions is increasing, as shown by the number of published studies.

Letter and Elefteriadou in [23] proposed a proactive longitudinal control algorithm for freeway merging to maximize average travel speed. Their approach is based on vehicle-to-infrastructure (V2I) communication within a range of $150[m]$. During uncongested conditions, the algorithm is able to reduce travel time, increase average travel speed and improve throughput. The capacity of the merge segment is directly related to the safe time gap. Wang et al. in [24] show that early establishing a fixed sequence according to the first-in-first-out principle improves traffic flow. An early adaption of speed and position can improve travel time for low- and high-demand cases. Omidvar et al. [25] proposed a method for mixed traffic that receives arrival information as input and generates optimal trajectories for CAVs while predicting the behavior of conventional vehicles and accounting for deviation from expected behavior. They show that traffic flow starts to improve from a CAVs' penetration rate of around 25%. Jing et al. [26] propose a cooperative game approach to coordinate vehicles and derive optimal freeway merging sequences. Fuel consumption, passenger comfort, and travel time within the merging control zone were used as the pay-off conditions. Ding et al. [27] propose a rule-based method to coordinate two strings of vehicles at highway on-ramps efficiently and safely in the longitudinal direction. They demonstrate the effectiveness and robustness of the proposed method through simulation. Scanrinci et al. [28] propose a novel centralized merging assistant strategy that groups main carriageway vehicles together and collects the intervehicle spaces into gaps that are usable by merging traffic, coordinating the entry of platoons of vehicles released by an on-ramp traffic signal. Akti et al. [29] propose an integrated system that organizes longitudinal and lateral movements with the intention of mitigating shockwaves due to merging maneuvers. A merging strategy based on the game theory is applied for flow management. Simulation results from a single-lane road segment demonstrate the efficiency of this approach. Most existing works in the literature focus on one-lane scenarios with control on the longitudinal direction. At the same time, very few discuss control strategies on multi-lane networks regulating longitudinal and lateral actions.

In [30], the authors approach the optimization of multi-lane freeway traffic with a reinforcement learning technique in mixed traffic. After implementing multiple control strategies such as ramp metering, lane-changing control, or speed control, the algorithm finds an optimal combination of strategies to minimize travel time costs for different penetration rates of CAVs. The study shows that the positive effect of ramp metering is no longer significant if the penetration rate of CAVs is high. In [31], the authors apply a heuristic approach to optimize multi-lane freeway merging for CAVs. They investigate a section of a two-lane freeway with an on-ramp. In this scenario, they compare a non-cooperative driving behavior with a cooperative one. For cooperative behavior, a lane-changing model is in place. All vehicles behave homogeneously, lane changes within the merging area are not allowed, and trucks or other vehicle types are not considered. The results show that the delay time can be reduced by introducing CAVs. In one of the most recent works [32], a novel methodology for integrated lane-changing and ramp metering control exploits the presence of connected vehicles. The authors employ a feedback controller formulated as a Linear Quadratic Integral Regulator to maximize throughput at motorway bottlenecks.

In the literature, there is a high diversity of solutions under different assumptions, i.e., mixed traffic, decentralized/centralized coordination, optimization objectives, freeway network characteristics, etc. At the same time, recent literature studies report that vehicle specifications (powertrain, torque, mass, etc.) play a key role in the dynamics and behaviors observed on the road (acceleration, deceleration, reaction time, etc.) [33], [34]. Nevertheless, how a cooperation strategy is affected by the homogeneity in vehicle dynamics among a class of vehicles, e.g., CAVs, human-driven or autonomously-driven ones, is not extensively discussed. This study aims to fill this gap by a) proposing a cooperation strategy for CAVs, and b) assessing the impact of vehicle dynamics heterogeneity on the cooperation benefits. Simulation results demonstrate the efficiency of the cooperation strategy but most significantly highlight the importance of homogeneous vehicle dynamics towards delay minimization in future road transport networks.

The proposed cooperation strategy is presented in Section III followed by the simulation design (cooperation and homogeneity of CAVs) and definition of the scenarios in Section IV. The results are presented in Section V. Finally, Section VI provides a summary and ideas for further research.

III. COOPERATION STRATEGY

This work proposes a hierarchical cooperation strategy for multi-lane freeways.

The following assumptions are used in the development of the proposed methodology:

- The traffic stream consists of 100% connected fully automated vehicles.
- The assumed communication range is 150 $[m]$.
- Communication between vehicles and the infrastructure is assumed to be instantaneous.

The flow chart is illustrated in Figure 1, and the different components are discussed in the remaining part of this section.

A. CONFLICT DEFINITION

On-ramps on freeways usually create active bottlenecks and attract interest in applying traffic management strategies that keep the mainline service level close to capacity. Looking at a conceptual on-ramp, as shown in Figure 2, several possible cases with conflicts among vehicles can be detected around a merging area. The method in this work assumes communication between CAVs and the infrastructure (V2X) and operates on a first-in-first-out decision principle. We focus on two types of actions that a vehicle can either decelerate or change lanes. We propose a rule-based on-off control strategy after decomposing the problem concluding on six elementary potential conflict cases illustrated in Figure 3.

Each case focuses on the three possible vehicles, i.e., one per lane, closer to the merging area. The idea is that when two vehicles approach the merging area simultaneously, and their projected trajectories intersect, then a conflict arises. This conflict can be resolved if one of the vehicles decelerates or changes its lane to avoid the intersection of its projected trajectory with the trajectory of the second conflicting vehicle.

Each vehicle moves based on a constant headway policy, i.e., regulates its speed according to a desired time gap setting. Therefore, each vehicle i moving on a lane l is assumed to occupy a *personal space area* (psa) longitudinally measured from the position of the front bumper plus the space computed by the vehicle's desired time gap multiplied by its instantaneous speed:

$$psa_{1,l}(t) = v_{1,l}(t)TG_i + L_i \tag{1}$$

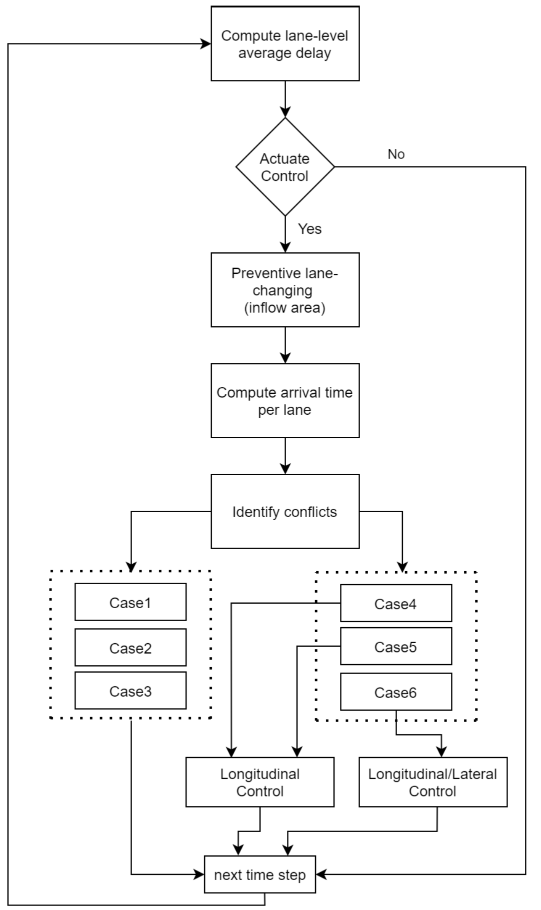


FIGURE 1. Flowchart of the proposed methodology.

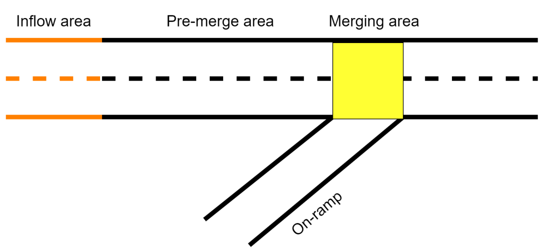


FIGURE 2. Conceptional representation of the on-ramp section.

where TG_i is the desired time gap of the vehicle i, L_i is its length and $v_{1,l}(t)$ is its current speed at time t.

The proposed methodology first focuses on the vehicles per lane that are moving inside the pre-merge area shown in Figure 2 and computes their arrival time to the merge area as follows:

$$at_{1,l}(t) = \frac{k_{1,l}(t)}{v_{1,l}(t)} \tag{2}$$

where $k_{1,l}(t)$ is the distance of vehicle i at time t in lane l from the merge area and $v_{1,l}(t)$ is its current speed.

Please note that number one signifies the position of the vehicle in the lane l as seen from the merging area, i.e., the vehicle closest to the merging area.

If the arrival times of two vehicles differ less than the *personal space area* of any of those vehicles, i.e., as regulated by the vehicle length and its desired time gap, $|at_{1,l_i}(t) - at_{1,l_j}(t)| \leq min\{psa_{1,l_i}(t), psa_{1,l_j}(t)\}$, and if the vehicles' projected trajectories intersect, a conflict is considered.

For the three-lane case, the list of potential conflicts is shown in Figure 3. The simplest case is when one or zero vehicles approach the merging area with close arrival times. In this occasion, no conflict occurs, and therefore, no action is required. The same applies when two vehicles approach the merging area whose trajectories do not intersect. These cases are shown in Figures 3(a) and 3(b).

The next possible case is when two vehicles with intersecting trajectories approach the merging area with close arrival times, i.e., less than their *personal space area*. In this case, the vehicle that drives on the freeway modifies its trajectory through lane changing, so that the new trajectory does not intersect with the trajectory of the on-ramp vehicle. The absence of a vehicle with conflicting *personal space time* on the far left lane signifies that no vehicle is expected to arrive at the merging area soon to raise a conflict. The illustrative representation can be seen in Figure 3(c).

Then, there is the case of a conflict with three vehicles involved. One of the three vehicles must decelerate to delay its arrival time at the merging point to solve this issue. These possibilities are pictured in Figures 3(d) to 3(f)).

In the rest of the section, we decompose the problem into three different parts; the control actuation logic that describes when a control action is instructed; the conflict resolution process that describes how the conflicts in cases 4-6 are resolved; and the description of the proposed framework that describes the overview of the complete strategy.

B. DELAY-BASED CONTROL ACTUATION

The actuation for the proposed strategy is based on lane-level delay monitoring and the assumption that the *personal space area* a vehicle occupies is described by its desired time-gap value. Similarly to the concept of input-output diagrams, the lane-level delay is defined here as the difference between the free-flow travel time and the estimated travel time based on the current speed. Assuming vehicles traveling along a road segment of length K, where the speed limit, i.e. free-flow speed, is V we can compute the free-flow travel time T_{ff} as follows:

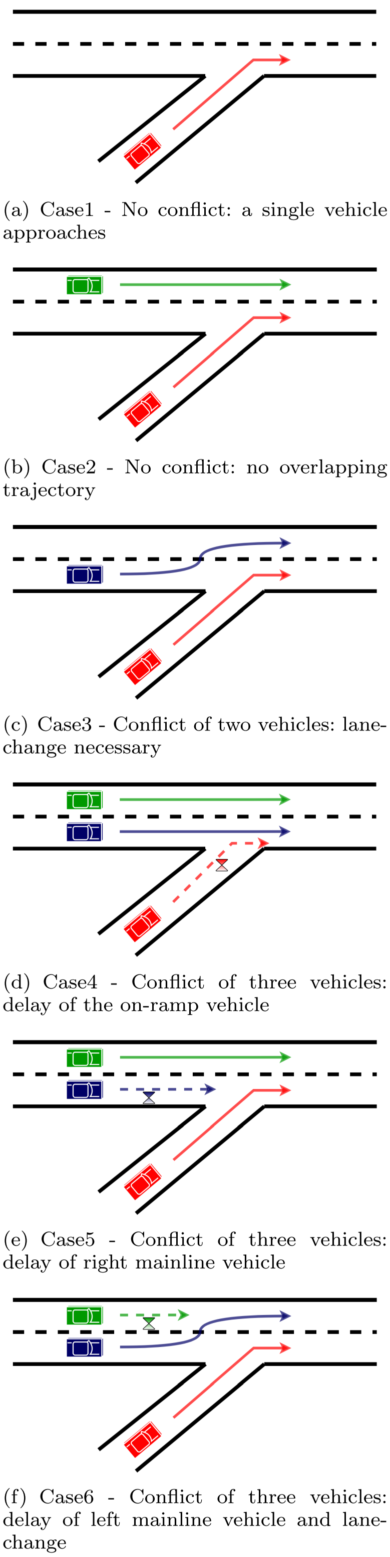
$$T_{ff} = \frac{K}{V} \tag{3}$$

Assuming a vehicle i that travels over the road segment with a constant speed V_i, then we can compute its travel time as follows:

$$T_i = \frac{K}{V_i} \tag{4}$$

Consequently, we can define the delay quantity D, i.e. the deviation of estimated arrival from the free-flow time, for vehicle i as follows:

$$D_i = K\left(\frac{1}{V_i} - \frac{1}{V}\right) \tag{5}$$



(a) Case1 - No conflict: a single vehicle approaches

(b) Case2 - No conflict: no overlapping trajectory

(c) Case3 - Conflict of two vehicles: lane-change necessary

(d) Case4 - Conflict of three vehicles: delay of the on-ramp vehicle

(e) Case5 - Conflict of three vehicles: delay of right mainline vehicle

(f) Case6 - Conflict of three vehicles: delay of left mainline vehicle and lane-change

FIGURE 3. Conceptional case differentiation.

The idea of the proposed control approach is to apply an action on moving actuators, i.e., CAVs. Therefore, we translate the above link-level quantities to time-dependent ones. More specifically, the estimated free-flow travel time for a vehicle i traveling in lane l at time t can be approximated as:

$$t_{ff,l}(t) = \frac{k_{i,l}(t)}{V_l} \tag{6}$$

where $k_{i,l}(t)$ is the distance of the vehicle from the end of the previously described segment (with total length K).

Similarly, the actual travel time of vehicle i, traveling in lane l at time t with speed $v_{i,l}(t)$ is:

$$t_{i,l}(t) = \frac{k_{i,l}(t)}{v_{i,l}(t)} \tag{7}$$

Based on the adopted definition of delay above, we can approximate the delay of vehicle i, traveling in lane l at time t as follows:

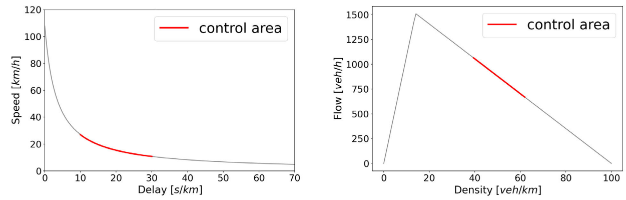
$$d_{i,l}(t) = t_{i,l}(t) - t_{ff,l}(t) = k_{i,l}(t)\left(\frac{1}{v_{i,l}(t)} - \frac{1}{V_l}\right) \tag{8}$$

Finally, the lane-level delay can be computed based on the average delay of all vehicles N_l driving in that lane at the given time t:

$$d_l(t) = \frac{1}{N_l(t)} \sum_{i=1}^{N_l(t)} d_{i,l}(t) \tag{9}$$

Here, we use the lane level delay as an actuator to enable or disable the control at any given time t. The actuation process is iterative over time. We consider two thresholds to enable and disable the control. Before concluding on the actuation thresholds, we assume a triangular fundamental diagram for each lane. The parameter values are a free-flow speed equal to 110[km/h], jam density equal to 100[veh/km], and critical density equal to 15[veh/km]. These parameter values are an approximation based on recent literature studies that use empirical observations from platoons of automated vehicles to reconstruct the triangular fundamental diagram [35], [36].

The proposed strategy is actuated only when significant delays are detected in the pre-merge area (see Fig.2). Obviously, delays are minimal when there is no congestion, and the vehicles drive at the desired speed. As congestion increases, the speed drops, and equation (9) represents the delay quantity in [$s/km/lane$]. The delay time in seconds per kilometer within the pre-merge area is measured constantly for every lane. Under free-flow or driving conditions close to jam density, any management strategy is considered redundant and thus is not actuated. Furthermore, the delay quantity loses meaning for very low speeds (grows exponentially). In this work, we assume that a plausible region for the actuation of the proposed on-off cooperation strategy is for delays between 10[$s/km/lane$] and 40[$s/km/lane$]. In general, these thresholds should be calibrated based on the case study. Figure 4 provides a graphical representation of the lane-level delay and the employed on-off control in this work based on the above values. Figure 4(a) shows how the estimated delay increases as the current speed moves away from the free-flow speed. Figure 4(b) depicts the employed fundamental diagram where the control area of the previous figure is also highlighted.



(a) Delay over average lane-level speed

(b) The congested part of the fundamental density-flow diagram

FIGURE 4. The on-off control logic for an indicative free-flow speed of 110 [km/h] and an estimated vehicles' desired time gap value of 0.9 [s].

C. CONFLICT RESOLUTION

The proposed strategy detects conflicts between pairs or triplets of vehicles and consequently applies a lane changing or a fixed deceleration action to resolve the conflict. In the first case, lane changing avoids crossing the vehicles' paths. In the second case, one vehicle is delayed in order to create enough gap for the other vehicle to pass.

Logically, a deceleration of a vehicle will lead to speed reduction, and additional cumulative delays, for the following vehicles on that lane. Therefore, at this stage, the total disturbance per lane is estimated, assuming that the first vehicle in that lane will decelerate. The definition of the total disturbance per lane is based on the following assumptions:

- A delay estimation for each of the vehicles in a lane can be computed based on Eq. 8.
- Each following vehicle is considered to have a desired time gap. If the current time gap of the vehicle at the given moment is greater than the desired value, then the extra time is considered a buffer time. Buffer time is considered a negative delay quantity.

Consequently, we define the buffer time for the following vehicle i, moving in lane l at time t as follows:

$$b_{i,l}(t) = \max\{0, tg_{i,l}(t) - TG_i\} \tag{10}$$

where $tg_{i,l}(t)$ is the current time gap for vehicle i at time t, based on the distance from its leading vehicle and its current speed and TG_i is the desired (or target) time gap setting.

Finally, the total disturbance per lane can be computed based on individual vehicle delay estimates and buffer times as follows:

$$db_l(t) = d_{1,l}(t) + \sum_{i=2}^{N_l(t)} d_{i,l}(t) - \sum_{i=2}^{N_l(t)} b_{i,l}(t) \tag{11}$$

where $db_l(t)$ is the total disturbance quantity for lane l at time t and $N_l(t)$ the number of vehicle at that lane.

Assuming a perturbation on a lane, the lower the total disturbance utility for that lane is, the lower the negative impact on the vehicles in the lane is expected. Therefore, any control action will be delivered in a more fair way on the network.

D. RULE-BASED ON-OFF CONTROL STRATEGY

The proposed strategy is an iterative process that is implemented for all the vehicles involved in the area of interest and at every simulation step. An algorithmic description is provided in Table 1.

Inside the pre-merge area, all vehicles are monitored. Information about all vehicles within the pre-merge area is gathered at every time instance. The lane-level delays $d_l(t)$ are computed to determine whether the control strategy should be actuated or not. In the positive case, step 2 applies discretionary lane changing for a CAV inside the inflow area as a congestion-preventing measure. The arrival times per lane for the vehicles closer to the merging area are computed to identify a conflict based on the cases illustrated in Figure 3. For cases 4-6, the total disturbance utility per lane is computed. The lane with the lowest total disturbance utility is charged with the corresponding control action, i.e., perturbation due to fixed deceleration or lane changing.

The proposed strategy works at the level of action, i.e., deceleration or lane changing, without optimizing the trajectory of the vehicle during this action, i.e., the deceleration pattern or the lane changing models. Therefore, when a deceleration is decided, the vehicles decelerate with a fixed rate equal to $-2[m/s^2]$ and the discretionary lane changing is decided using the default models and parameters provided by Aimsun [37].

In the simulation, the proposed algorithm works in real-time but real-time implementation can be challenging due to potential delays in communication and state understanding. However, such analysis is considered outside of the present work's scope that is not optimized for that purpose. It should be noted that the proposed strategy in this work can be easily generalized for cases with more lanes either in the mainline, the on-ramp, or both.

IV. SIMULATION DESIGN AND SCENARIOS DESCRIPTION

We assess the proposed cooperation strategy in a freeway network that consists of a two-lane freeway and an on-ramp with one lane. This represents a typical freeway merging area in Switzerland. The network's length is around 1150 $[m]$,composed of a freeway section (approximately 900 $[m]$) and an on-ramp section (around 250 $[m]$). The merging area (around 150 $[m]$) has three lanes, which are reduced to two in the final part. The geometry of the simulated section was chosen to be as realistic as possible. The speed limit on all sections is 120 $[km/h]$. During implementation, care was taken to avoid disturbing influences on the speed traveled, for example, due to tight curve radii. The traffic demand (split 80% cars and 20% trucks) was set realistically (comparable to real-world case studies [20] with congested freeway segments), around 2000 $[veh/h/lane]$ under the theoretical capacity for autonomous vehicles but large enough to create congestion.

TABLE 1. Algorithmic overview of the proposed strategy.

Step1: Compute lane-level delays $d_l(t)$ at time t. If the control actuation criterion is not satisfied GoTo Step5
Step2:If the lane-level delay on the left mainline lane is lower than on the right mainline lane, a vehicle on the right lane inside the inflow area is instructed to change to the left lane if possible. Trucks remain on the right lane.
Step3: Compute the arrival times of the first vehicle per lane, closer to the merging area.
Step4: Identify the type of conflict, i.e. Cases 1-6. For Cases 1-3 GoTo Step5
Step5: Compute the total disturbance utility per lane. Apply the corresponding control action that impacts the lane with the lowest total disturbance utility, i.e. Cases 4-6.
Step6: GoTo Step 1

A. SIMULATION PARAMETERS AND DRIVING HOMOGENEITY

Simulations are performed with Aimsun software. All vehicle classes use the default Adaptive Cruise Control (ACC) car-following model provided by Aimsun Next [38]. The default model from Aimsun was also used for lane changing, based on the Gipps model [39]. It should be mentioned that Aimsun generates the model parameters, such as maximum acceleration, desired time gap, etc., based on uniform distributions around an average parameter values. This will help the reader to better understand Table 2 and Table 3 that describe the parameter set for the simulation scenarios. An overview of the simulation parameters is given in Table 2. The selection of the parameters' values is based on the characteristics of the network and the drivers' common behaviors. More specifically, the cars' maximum desired speed is set equal to the speed limit with a deviation of 10 $[km/h]$. For trucks, this value is similar to the maximum speed permitted on main roads, i.e., 85 $[km/h]$ with the same deviation. The rest of the parameters such as the reaction time, max acceleration, normal deceleration, maximum deceleration, and desired time gap are set to plausible values according to the literature and experimental observations. Finally, Table 2 provides general simulation parametrization used here such as the time interval for the generation of statistics, the number of replications to deal with stochasticity in the simulation, and the simulation time step. The implementation of the cooperative strategy is done via the API interface of Aimsun.

There is evidence in the literature that homogeneity in driving behavior can positively impact the traffic flow [33]. Traffic oscillations and stop-and-go waves are initiated (among others) by disturbances of different driving behaviors. To assess the impact of driving homogeneity in this

TABLE 2. Overview of simulation parameters.

Default Vehicle Parameters					
Parameter	Unit	AV Cars		AV Trucks	
		Mean	Deviation	Mean	Deviation
Max. Desired Speed	[km/h]	110	10	85	10
Reaction Time	[s]	0.8		0.8	
Max. Acceleration	[m/s^2]	3	0.2	1	0.5
Normal Deceleration	[m/s^2]	4	0.25	3.5	1
Max. Deceleration	[m/s^2]	6	0.5	5	0.5
ACC – Desired Time Gap	[s]	1.2	0.4	1.2	0.4
Scenario Parameters					
Length of Statistical Interval	[s]	60			
Number of Replications	[-]	5			
Time Step Length	[s]	0.5			

work, new vehicle classes of homogeneous AVs and homogeneous AV-Trucks were created. These classes have more narrow distributions for the behavioral model parameters. An overview is shown in Table 3. More specifically, each vehicle class, i.e., cars and trucks, is split in two, i.e., the normal one with the parameters as pointed in Table 2 and the homogeneous one. Both maintain the same desired speed but the homogeneous class has lower deviations, for the desired speeds, the maximum acceleration values, the normal and maximum deceleration values, and the desired time gaps. By reducing the deviations around the average parameter values, a more uniform response of the vehicles can be achieved. In addition, extreme values become very rare. In the case of more homogeneous drivers, the maximum desired speed of the vehicles is lowered to come closer to that of trucks and therefore reduce the conflicts between the two vehicle classes. For the rest of the parameters, homogeneity is simulated with reduced standard deviations as shown in the table.

TABLE 3. Comparison of all behavioral parameters that were changed in order to create a vehicle class with more homogeneous driving behavior.

Parameter	Unit	AV Cars		AV Trucks	
		normal	homog.	normal	homog.
Max. Desired Speed Mean	[km/h]	110	100	85	85
Max. Desired Speed Dev.	[km/h]	10	2	10	2
Max. Acceleration Dev.	[m/s^2]	0.2	0.1	0.5	0.25
Normal Deceleration Dev.	[m/s^2]	0.25	0.1	1	0.4
Max. Deceleration Dev.	[m/s^2]	0.5	0.1	0.5	0.1
Desired Time Gap Dev.	[s]	0.4	0.1	0.4	0.1

B. SIMULATION RUNS

A total of 155 replications of the simulation are performed. These are distributed over 31 scenarios, each simulated with five random seeds. The scenarios differ in their composition between the vehicle classes. Here, we should introduce two terms that are used in the rest of the paper to represent the vehicles that comply to the cooperation strategy and the vehicles that have similar dynamics. Hence, we define two types of rates, the *cooperation rate* and the *homogeneity rate*. The cooperation rate corresponds to the fraction of vehicles that follow the proposed strategy. The rest resolve any conflicts on an ad-hoc basis as in unmanaged freeway networks. The homogeneity rate corresponds to the fraction of vehicles having more homogeneous parameter distribution as shown in Table 3. Firstly, the influence of the cooperative strategy is measured by six different cooperation rates of vehicles supporting V2X (and thereby the strategy). In the worst scenario, no vehicle complies with the cooperative strategy (0%). Other scenarios have cooperation rates of 20%, 40%, 60%, 80% and 100%. Secondly, the influence of homogeneity is also measured by six different homogeneity rates (0%, 20%, 40%, 60%, 80%, 100%). Since V2X is a basic requirement for homogeneous driving behavior, the share of vehicles with homogeneous driving parameters always refers to the AVs with V2X, i.e., CAVs. What this means is shown in Figure 5. To evaluate all combinations, 36 scenarios are necessary but since the number of vehicles with homogeneous vehicles stays 0 for all cases where no vehicles follow the cooperative strategy, only 31 scenarios must be considered.

Share of homogeneity among all vehicles	*Share of vehicles following the cooperative strategy*					
Share of homogeneity among vehicles following the cooperative strategy	*0%*	*20%*	*40%*	*60%*	*80%*	*100%*
0%	0%	0%	0%	0%	0%	0%
20%	0%	4%	8%	12%	16%	20%
40%	0%	8%	16%	24%	32%	40%
60%	0%	12%	24%	36%	48%	60%
80%	0%	16%	32%	48%	64%	80%
100%	0%	20%	40%	60%	80%	100%

FIGURE 5. Share of vehicles with homogeneous driving behavior among all vehicles in every scenario. ***Reading example: In the scenario, where 60% of all vehicles are equipped with V2X, and the homogeneity rate among those is also 60%, 0.6 ∗ 0.6 = 36% of all vehicles have a homogeneous driving behavior.***

V. OBTAINED RESULTS AND DISCUSSION

A. COOPERATIVE STRATEGY

Figure 6 compares all scenarios where no vehicles with homogeneous driving behavior are present. Therefore, homogeneity has no impact on these results. It illustrates the development of network delay times in the whole network over the course of the simulation. The values are aggregated over intervals of 10 minutes each. It is visible that the network needs about 30 minutes to load and reach a stable condition. As already mentioned, the share of V2X corresponds to the share of vehicles following the cooperative strategy.

The graph shows that the cooperative strategy can reduce the network's delay time. The larger the proportion of vehicles with V2X, the lower the delay time per kilometer. However, the figure also shows that the delay time is not inversely proportional to the cooperation rate. The time gain is relatively small up to a cooperation rate of 60% V2X vehicles, after which there is a clear drop in delay time. The results show that the cooperative strategy is inefficient when the vehicles with V2X are not the majority of the network's users. The rest of the vehicles negates any benefits arising from cooperation on the road. However, when the cooperation rate increases above 60%, the reduction in the delays decreases exponentially. Over the entire simulation period, the delay time decreases on average from 117 [*s*] without V2X vehicles to 64 [*s*] with 100% V2X vehicles. This corresponds to a reduction of 46%.

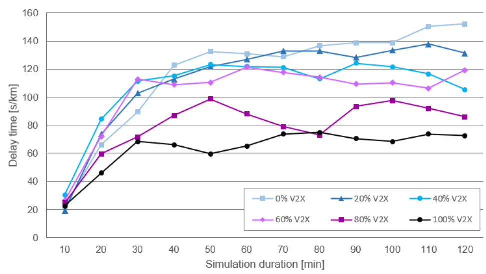


FIGURE 6. Comparison of delay time between with cooperation rates over the whole simulation period. All scenarios are with 0% homogeneous driving behavior.

B. HOMOGENEITY OF DRIVING BEHAVIOR

Figure 7 compares scenarios with different homogeneity rates over the course of the whole simulation. In the compared scenarios, all vehicles follow the cooperative strategy (100% V2X). A warm-up period of around 30 minutes is needed to fill the network. Afterward, the delay time reaches a certain level. Even though the delay time is volatile, a clear trend can be seen. The worst of these scenarios, where 0% of all vehicles have homogeneous behavioral parameters implemented, has an average delay time of 64 [*s*].

On the other hand, the best scenario with 100% homogeneity rate reaches an average delay time of 42.0 [*s*]. This is an improvement of 34%. Hence, homogeneity can help reduce the delay time and the traffic flow more fluent. By analyzing Figure 7 it is remarkable that homogeneity seems to have only a little advantage unless most vehicles drive with homogeneous behavioral parameters. This might have two reasons. Firstly, with a low homogeneity rate, homogeneity parameters have no impact since there is a large number of vehicles with heterogeneous dynamics that influence the overall homogeneity of the network. Secondly, to make the traffic flow smoother, the homogeneous driving parameters slow down vehicles (e.g., due to the lower Maximum Desired Speed). Therefore, with low homogeneity rates, the driving speed on the freeway may decrease without creating substantial benefits from homogeneous driving.

C. SCENARIO COMPARISON

In this section, several key figures for assessing the success of the implemented strategies are shown for all scenarios. In the following tables, average values over the whole simulation period and replications (five per scenario) are presented. In Figure 8 the average delay time in [*s/km*] is shown for all scenarios. The delay time in the base scenario with no vehicles following the cooperative strategy is 117.1 [*s/km*], the worst of all scenarios. With an increased share of vehicles following the cooperative strategy and a higher share of homogeneous behavior among the vehicles the delay time drops drastically. In the best scenario with 100% homogeneously, cooperatively driving vehicles an average delay time of 42 [*s/km*] is reached. This corresponds to a decrease of more than 64%. Comparing the impact of the cooperative strategy and the homogeneity adaptations, it can be stated that it has a bigger impact than homogeneity.

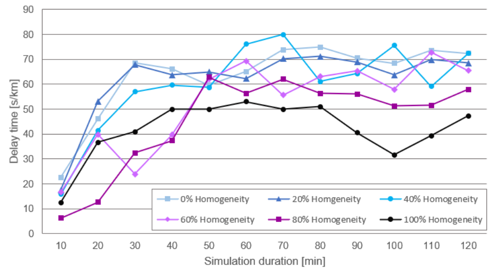


FIGURE 7. Comparison of all scenarios with 100% cooperative driving behavior and different homogeneity rates.

Nevertheless, homogeneity improves the system a lot and has a huge potential. In AVs, homogeneous driving behavior is very simple to achieve since it can be implemented by a software update. However, standard values must be defined by authorities or the car manufacturing industry. The tableau shows some inconsistencies, for example, in the second column where 20% of the vehicles follow the cooperative strategy. This might be due to the already mentioned low number of replications per scenario. Furthermore, the absolute number of cars with homogeneous driving behavior changes in this column only by 4% from one scenario to the next (see Figure 5).

Share of homogeneity among vehicles following the cooperative strategy	Delay Time [s/km]	*Share of vehicles following the cooperative strategy* 0%	20%	40%	60%	80%	100%
	0%	117.1	112.9	107.4	102.4	79.1	63.6
	20%	-	109.8	104.6	95.3	80.7	62.0
	40%	-	102.1	101.9	86.9	79.2	60.2
	60%	-	106.2	99.8	89.4	64.9	52.9
	80%	-	110.7	90.5	80.0	66.7	45.3
	100%	-	106.2	96.6	73.1	64.3	42.0

FIGURE 8. Scenario overview: Comparison of delay time in s/km over all calculated scenarios and the entire network.

Figure 9 compares the flow in all scenarios. This shows a similar picture as before. The flow increases by 12% from the base scenario without a cooperative strategy to the best case with 100% V2X and full homogeneity. With a flow of 3414 vehicles in the best case, practically the entire demand can be served. However, a higher demand must be chosen to determine if a two-lane highway's maximal theoretical capacity can be reached.

Similar results are seen for harmonic speed (Figure 10) and density (Figure 11). The harmonic speed increases from 23.7 [km/h] to 45.4 [km/h]. This is an improvement of more than 91%. The density thereby decreases by around 42% from 50.3 to 29.3 [veh/km].

By looking at the color patterns of the scenario comparison, the same behavior is visible for all key figures (see Figures 8–11). This is an expected behavior since all shown key figures are interdependent.

Share of homogeneity among vehicles following the cooperative strategy	Flow [veh/h]	Share of vehicles following the cooperative strategy: 0%	20%	40%	60%	80%	100%
	0%	3042	3048	3062	3073	3197	3227
	20%	-	3080	3082	3114	3211	3253
	40%	-	3094	3116	3158	3241	3326
	60%	-	3079	3137	3191	3309	3339
	80%	-	3083	3153	3247	3309	3392
	100%	-	3109	3173	3258	3373	3414

FIGURE 9. **Scenario overview: Comparison of flow in [*veh*/*h*] over all calculated scenarios and the entire network.**

Share of homogeneity among vehicles following the cooperative strategy	Harmonic Speed [km/h]	Share of vehicles following the cooperative strategy: 0%	20%	40%	60%	80%	100%
	0%	23.7	24.4	25.3	26.2	31.5	36.5
	20%	-	24.8	25.8	27.6	31.0	37.0
	40%	-	26.2	26.2	29.4	31.3	37.5
	60%	-	25.5	26.6	28.8	35.6	40.4
	80%	-	24.7	28.5	31.0	34.9	43.8
	100%	-	25.4	27.2	32.9	35.6	45.4

FIGURE 10. **Scenario overview: Comparison of the harmonic speed in [*km*/*h*] over all calculated scenarios and the entire network.**

Additionally, Figure 12 shows the number of lane changes in all scenarios. On the one hand, a cooperative strategy can significantly reduce the number of lane changes. The number drops from over 3000 to around 2200 lane changes, corresponding to a decrease of ca. 26%. This is remarkable, considering that the employed strategy triggers additional lane-changing actions for cooperating vehicles. However,

Share of homogeneity among vehicles following the cooperative strategy	Density [veh/km]	Share of vehicles following the cooperative strategy: 0%	20%	40%	60%	80%	100%
	0%	50.3	48.9	47.2	45.8	39.5	34.3
	20%	-	48.5	46.7	44.1	40.4	34.2
	40%	-	46.1	46.3	41.9	40.4	34.5
	60%	-	47.3	46.0	43.3	36.3	32.2
	80%	-	48.9	43.2	40.9	37.1	30.2
	100%	-	47.9	45.5	38.7	36.9	29.3

FIGURE 11. **Scenario overview: Comparison of the density in the network in [*veh*/*km*] over all calculated scenarios.**

Share of homogeneity among vehicles following the cooperative strategy	Number of lane changes [#/km]	Share of vehicles following the cooperative strategy: 0%	20%	40%	60%	80%	100%
	0%	3029	2962	2832	2700	2455	2152
	20%	-	2984	2841	2709	2516	2162
	40%	-	2993	2895	2734	2593	2278
	60%	-	3029	2871	2756	2594	2265
	80%	-	3023	2897	2823	2579	2236
	100%	-	3020	2907	2802	2628	2281

FIGURE 12. **Scenario overview: Comparison of the number of lane changes in all calculated scenarios and over the entire network.**

we assume that since the proposed strategy harmonizes speeds, the vehicles attempt lane changing less often than in the no-control case.

On the other hand, the number of lane changes increases for high homogeneity rates. This is counterintuitive because more drivers with homogeneous behavior are expected to reduce the need for overtaking. A possible explanation could be that increased homogeneity rates lead to large gaps between vehicles, which might trigger more discretionary lane changes for vehicles close to those gaps.

D. DISCUSSION

Comparing the findings with the literature is challenging for several reasons. First, most researchers have focused on single-lane freeways, which have other optimization characteristics. Secondly, different software and various car-following models are used for simulation. In addition, different demand cases, vehicle types, and country-specific differences such as speed limits complicate the comparison.

Nonetheless, the results of [31] are most suited for comparison. They work with a similar network in their simulation and use the same logic for their optimization algorithm. Furthermore, this work assumes uniform driving behavior and traveling speeds implemented for all vehicles. Especially the disturbing influence of trucks is thereby not considered. In contrast to the work of [31], where all vehicle trajectories in the whole merging section are controlled externally, the presented approach in this work only controls specific parts of the vehicle behavior. Therefore, it is impossible to compute exact arrival times at the merging point beforehand, meaning this approach cannot reach optimality. Additionally, the study of [31] uses a non-cooperative control as a base scenario, in which all lane-changing is prevented. This is not the case for the presented work, where the cooperative strategy is compared to conventional AVs. However, the results from [31] are consistent with the here presented values. In a comparable demand case, they reach a reduction of 38% of delay time (compared to 46% found in this study). Also, in terms of flow, a similar finding was achieved with both approaches.

VI. CONCLUSION

We propose a multi-lane heuristic cooperative strategy for connected and automated vehicles (CAVs) in motorway networks. The strategy is implemented through a rule-based on-off control logic. The on-ramp merging is decomposed between six possible conflict cases among the vehicles driving in different lanes (and the on-ramp). Two possible actions are considered, deceleration or lane changing. The anticipated disturbance of an action in terms of estimated lane delays is quantified. The strategy generates the appropriate action in the lane that will create the minimum anticipated disturbance. The simulation clearly shows the benefit of the proposed cooperative scheme. The approach alleviates congestion effectively. To work correctly, a certain cooperation rate of CAVs is necessary.

But in contrast to other works in the literature, the developed strategy also works with vehicles of different states of automatization. Furthermore, it is shown that norms for homogeneous driving behavior for CAVs should be defined. The homogeneous behavior of all vehicles on the road positively affects the traffic flow. With a high cooperation rate of CAVs, the capacity of roads can be slightly increased as smaller distances between CAVs can be assumed. On the other hand, the safety gaps between vehicles remain capacity-determining and set boundaries to further capacity gains.

The proposed strategy comes with some limitations that demand further research to evaluate the full potential of the algorithm. The solution is tested for the cases when all the vehicles move (at least) autonomously with the possibility to be also connected and it is based on the assumption of a constant headway policy for the longitudinal movement of automated vehicles, which can not be the case for very low speeds (the time gap explodes to infinity). Furthermore, communication delays or problems such as broadcast storms are not accounted for. Additional investigations should be performed for different demand cases, precise control for the deceleration and lane-changing actions, and sensitivity analysis for the model parameters that reproduce homogeneous driving. However, results showcase a great potential for coordinated studies that assess traffic control considering explicitly homogeneity in vehicle dynamics.

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