Decentralized Cooperative Intersection Management Based on Connected Autonomous Vehicles for Urban Unsignalized Intersections

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Abstract— **Considering the increasing population and vehicle demand, the development of a safer and more efficient intersection management system is of critical importance. The following paper addresses decentralized intersection management through synergetic cooperation of networked autonomous vehicles to optimize intersection throughput as well as ensure proactive safety of all vehicles. Through Vehicle-to-Vehicle (V2V) communication, autonomous vehicles can obtain real-time information from all road users within the effective communication range, including position, speed, direction of travel, and destination. Based on the information, the priority for crossing the intersection or the order of passage can be determined by coordination between vehicles, so that the conflict zone of the intersection always remains free of traffic. At the same time, low-priority vehicles can also adjust their speed in advance to avoid potential conflicts with other vehicles. A pilot application is used to validate and demonstrate the model-based developed intersection management in a virtual simulation environment. Quantitative analysis of the simulation results proves the performance of the management system, especially in extremely high traffic intensity where the management system can keep traffic flowing in the conflict zone, ensuring efficient operation. The generalizability of the developed management system is also verified by applying it to a complex traffic network consisting of multiple intersections.**

Keywords- Optimal intersection management; cooperative intersection control; connected autonomous vehicles; Vehicle-to-Vehicle (V2V) communication; Model-in-the-Loop-Simulations; model-based systems engineering.

I. INTRODUCTION

As urbanization continues, especially in developing countries, the demand for vehicles to satisfy travel needs is steadily increasing, while the lack and inadequacy of transportation infrastructure exacerbates the serious shortage of transportation resources and the resulting high number of traffic accidents, especially at the intersection and junctions on major roads as frequent accident blackspots in the urban road network.

Although road intersections represent a relatively small part of the total road network, they are responsible for a significant proportion of traffic accidents. According to the Community Database of the European Union (EU database: "CARE") on road accidents, more than 20% of traffic fatalities are attributable to road traffic at intersections [1]. A similar ratio is observed in the United States, where 40% of accidents and 21.5% of traffic fatalities occur at intersections [2] [3]. According to statistics from the Insurers Accident Research, in Germany in 2020, about two-thirds of all cyclist accidents with personal injury recorded by the police in urban areas occurred at intersections, junctions and driveways, with about one in five of these accidents occurring while turning right [4]. The complex traffic network and redundant traffic signals due to numerous junctions often lead to long traffic congestion on major traffic sections during peak traffic hours, which is especially common in large cities with high population density and in small and medium-sized cities with inadequate road infrastructure and is an almost universal problem for the whole society.

To efficiently address the aforementioned road traffic challenges, this paper focuses on the development of decentralized cooperative intersection management through synergetic networking of autonomous vehicles using V2V communication to optimize traffic throughput and also ensure proactive safety at the intersection. The rest of this paper is organized as follows. Section II introduces the related work and the methodology. Section III details the design of the intersection management system. In Section IV, based on representative application scenarios, the developed intersection management is validated and demonstrated in a virtual simulation environment. Section V gives the conclusion.

II. STATE OF THE ART

In this section, the state of knowledge on the topics of intersection management is first presented. Subsequently, the mechatronic development methodology for the systematic structuring of a Cyber-Physical system (CPS) is described.

A. Intersection management

Numerous scientific researches on different aspects have been carried out to optimize the traffic flow at the intersection, whose main objectives are efficiency, safety, ecology and passenger comfort, as shown in Fig. 1.

The research activities focus on the topological characteristics of the traffic system and its traffic signal control, including the design of traffic infrastructure and the geometric design of road networks, the development of more rational traffic control and speed limits, the research of more advanced traffic monitoring and enforcement techniques, and the more accurate evaluation and disposition of traffic resources through more realistic simulation of traffic systems [7] [8]. Although the developed solution approaches in focus on traffic structure can improve the traffic flow to a certain extent, the waiting time at intersections is unfortunately not eliminated regardless of the traffic intensity and thus no longer meets the increasing mobility and social demands [7]. For example, in a signal-controlled intersection, vehicles are instructed the passing order by the cycle change of red and green light, and therefore adjust their speed with the light system. This traffic control approach causes more vehicles to congest at the intersection, and the delay time for vehicles in the conflict zone increases exponentially with traffic volume [9]. That is, vehicles take more time at the intersection, causing inefficient intersection traffic, especially if road users are not evenly distributed within it. Restrictions on mobility can cause driver frustration, irritation, and stress, which encourages more aggressive driving behavior and can further slow the process of restoring a free flow of traffic. [10]

In contrast, cooperative intersection management offers a more proactive solution for scenarios without traffic signals to overcome the aforementioned challenges. cooperative intersection management is developed based on networked autonomous driving and aims at creating and executing a (global) optimal sequence for road users when crossing the intersection. Through the use of communication technology, such as Dedicated Short Range Communication (DSRC) and Celluar Vehicle-to-Everything (C-V2X), as well as their application in autonomous vehicles and also in traffic infrastructure, effective networking with other road users is enabled, leading to early response to potential conflicts between road users in the conflict area and optimization of throughput at intersections due to the increased driving speed [5][6]. According to National Highway Traffic Safety Administration (NHSTA), the effective application of V2V and V2I communication could reduce and/or avoid up to 80% of accidents of any type without impairment [2]. Therefore, cooperative driving is an important driving strategy for future autonomous driving at intersections. In this regard, autonomous driving combines both categories of traffic safety in terms of the traffic environment and vehicles, and the cooperative driving function increases efficiency in this regard [11].

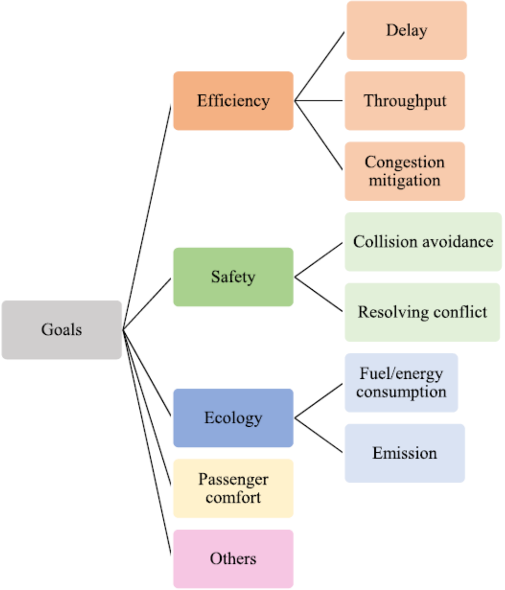

Figure 1. Research goals of intesection management [5][6].

Depending on the degree of automation of road users and its structure, cooperative intersection management is divided into centralized and decentralized strategies.

In centralized approaches, it has a central Intersection Coordination Unit (ICU) that is placed in a certain area around the intersection [12] and globally decides the order or priority of passage at the intersection for all vehicles within the communication range. In [13]-[15], the methods for priority setting are presented, which are developed according to different principles, such as rule-based methods, search-based methods, optimization-based methods, and so on. The strategy mainly relies on Vehicle-to-Infrastructure (V2I) technology to achieve bidirectional communication between vehicles and road infrastructures. With access to extensive information of road users, a global optimum is delivered by ICU [5].

In contrast to centralized intersection management, decentralized intersection management eliminates the need of ICU for dispatching vehicles at the intersection by synergistically networking autonomous vehicles. The networked autonomous vehicles can recognize the current traffic situation and make decisions independently with the support of the exchanged traffic information without the help of an external decision system to fulfil transportation orders safely and efficiently [16]. In decentralized intersection management, vehicles use V2V communication to coordinate right-of-way and adjust their own trajectories. Unlike centralized intersection management, decentralized intersection management usually achieves a suboptimal solution because each vehicle only obtains local information of vehicles in a limited number [17]. In [18], an interactive decision model based on fuzzy logic with integration of conflict identification model is developed based on game theory for vehicles. In [19], a driving strategy based on cooperative game theory is presented for leading time avoidance of the conflicts between vehicles at the intersection. In [20], an algorithm for cooperative driving based on Model Predictive Control is designed for connected autonomous vehicles at unsignalized intersections. However, such approaches do not consider the impact of traffic volume on the reliability of the function.

From the perspective of the functional coverage, most recent researches pay more attention to the cooperative driving strategy of the isolated single intersection, which is called area-wide cooperative intersection management, e.g., [21]-[23]. In fact, the vehicles pass through several intersections in the road network one after another and the vehicle's behaviours at the single intersection are interdependent, which leads to the complicated interactions between vehicles. Moreover, it enables the causality loops in the trajectory planning of the vehicles, in which the calculated trajectories affect each other in different conflict zones, resulting in no reasonable solution and high calculation effort when each vehicle focusses on its optimal trajectory [24]. It should be extended to a network-wide cooperative intersection management system that deals with a road network consisting of multiple intersections. Moreover, many algorithms for isolated intersections, which are developed under certain constraints and for specific application scenarios, cannot be directly adopted for complex road networks consisting of multiple intersections.

The decentralized intersection management system based on networked fully automated vehicles developed in this paper, in contrast to the related research work mentioned above, is mainly used to solve the problem of spatial and temporal causal loops when vehicles pass through multiple intersections in succession. That is, the approach can be applied to both single intersections and road networks formed by multiple intersections, without requiring much work to be invested. The generalizability of the method is not affected by the topological characteristics of the intersection within a certain traffic flow range.

B. Mechatronic structuring

The domain diversity and thus the heterogeneous character of the CPS results in a high system complexity [25]. To handle the complexity of highly integrated systems in a systematic, seamless manner, a clear system and functional structure is first required.

The structuring is carried out by applying the generalized cascade principle, which provides for the use of subordinate functional modules with high dynamics by superimposed functional modules for the local implementation of global target variables [26]. Modularization and hierarchization take central place for structuring. In modularization, subfunctions are derived from the entire system in a top-down process and encapsulated in modules. In hierarchization, these functional modules are arranged hierarchically with defined interfaces. Based on a clear structuring of the entire system, a clear representation of the information flow is achieved.

The definition of the necessary function modules and the hierarchical arrangement of these is carried out using the following six structural elements [27]:

- **Mechatronic Function Module (MFM):** The MFMs are the basic elements of the system and represents the lowest level of the hierarchy. They consist of sensors, actors, information processing and basic system related mechanical structure. This functionally encapsulated modules are the most vital element of the system. It has defined physical and signal interfaces to the superordinate MFG.
- **Mechatronic Function Group (MFG):** The coupling of several MFMs results in a MFG with its own information processing and sensors. They use the subordinate MFMs with their actuators and mechanical structure. MFMs are mainly used for structuring the information processing.
- **Autonomous Mechatronic System (AMS):** Several MFGs, which are coupled by physical and signal interfaces form an AMS in their entirety An AMS is completely independent of its environment and has its own sensors and information processing. It includes the top level of the mechanical structure.
- **Cross-linked Mechatronic System (CMS):** The CMS is a signal-based coupling of several AMS and is the top hierarchical level. It coordinates and optimizes operations by regulating the flow of information and passing on decisions that affect all the AMSs in the network.
- **Autonomous Function Group (AFG):** If several AMS are networked with each other so that they can exchange information. A swarm is formed, which is called AFG. The autonomy of each individual AMS is still given, only the sum of available information has grown. The AFG has additional sensors that provide data for all subordinate AMS. The difference to the original definition of the CMS is, that no decisions are made for subordinated systems, but information is exchanged, and cooperative operation is possible.
- **Cross-linked Function Group (CFG):** Several CMSs can be grouped across domain boundaries as CFG, so that data can be exchanged in structured clusters. A CFG establishes an exchange of information between the CMS in the sense of a complete networking and digitalization.

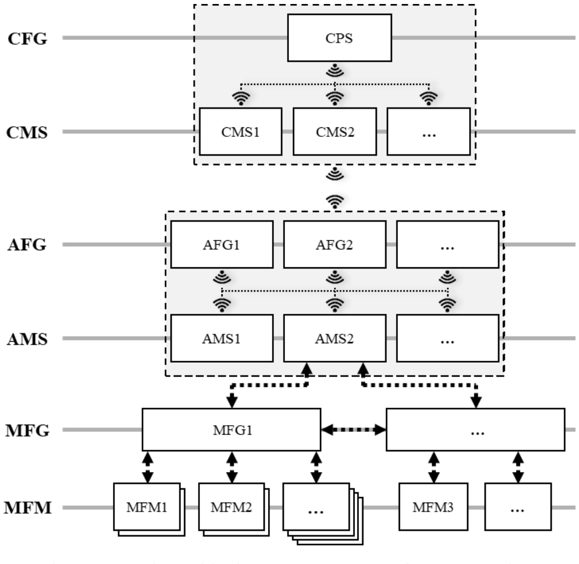

Figure 2. Hierarchical system structure of a CPS on six hierarchical levels [27].

III. DEVELOPMENT OF THE DECENTRALIZED COOPERTIAVE INTERSECTION MANAGEMENT

In this section, the requirements for decentralized cooperative intersection management are collected and defined. Based on this, the system and functional structure as well as the interfaces for integration with other functional modules of an autonomous vehicle in networked traffic systems are designed.

A. Definition of the requirements

Based on the mechatronic development methodology, the requirements for defining the function and structure in the form of requirement specifications and specifications are necessary on the one hand. On the other hand, the requirements are used as a benchmark in the functional validation as well as evaluation of the simulation results [28]. Therefore, based on the analysis of the state of knowledge and the intended scope of application at unsignalized intersections, the following essential requirements for a decentralized cooperative intersection management are defined:

- All road users must proceed through the intersection without collisions and, at the same time, the efficiency in terms of intersection throughput is to be optimized.
- The potential conflicts, especially the dynamic conflicts between vehicles, must be identified early and avoided by appropriate measures.
- For conflict detection, the dynamic traffic information (e.g., direction of travel, current vehicle position and operating conditions) must be continuously updated and transmitted to the concerned road users.
- In case of a conflict between the target criteria e.g., safety and efficiency, it must be ensured that safe driving is always guaranteed.
- The technical constraints regarding the dynamic and kinetic driving behaviours (e.g., available powertrain and braking forces, maximum speed, safety distance) and legal limitations (e.g., maximum speed in urban areas) must be observed during the optimization and a feasible optimum must be defined within their framework.
- The real-time capability and reliability of the intersection management must be guaranteed in any case. I.e., the intersection management must provide a reliable solution within a certain period that allows vehicles to cross the intersection without collisions.
- The universality of the intersection management should not be affected by the topological characteristics of the intersections. Intersection management shall be adaptable to different scenarios and capable of achieving cooperative objectives.
- The intersection management must dynamically adapt to the changing traffic environment (e.g., dynamically varying traffic intensity).
- For smooth communication between heterogeneous traffic participants, the data structure of the information to be exchanged, including data type, format, size, etc., must be uniform.

B. Design of the system structure

Based on the defined requirements, the modular and hierarchically arranged system structure of the highly integrated CPS is derived in accordance with the

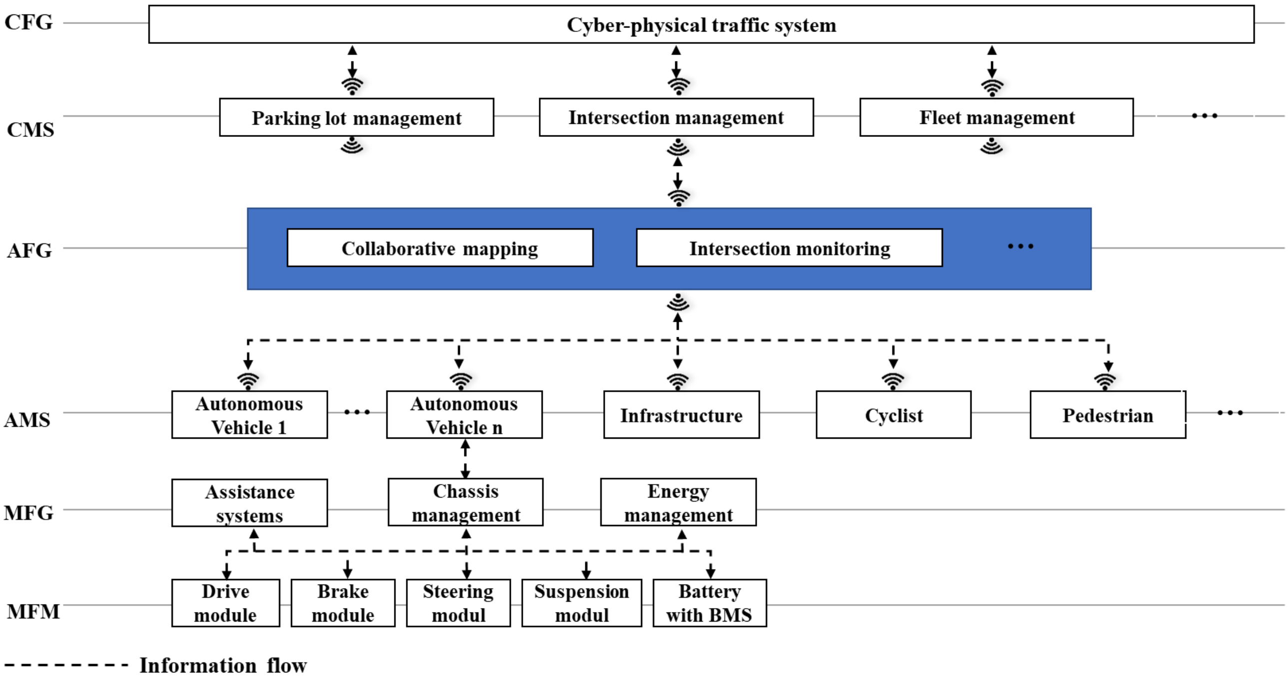

Figure 3. Modular and hierarchical system structure of the CPS.

development methodology for mechatronic structuring in the top-down process, as illustrated in the Fig. 3. Through their highly information integration with each other, a CPS is established at the CFG level.

At the CMS level, it has the management systems to systematically administer the subordinate AMS, which are case-specific developed according to the application areas. The management systems listed work as a central coordinator and strive for a global optimum. Due to the focus of this work, only the intersection management on CMS level and vehicles on AMS level, including the subordinate MFG as well as MFM, are considered here.

Compared to the centralized intersection management at the CMS level, the decentralized intersection management does not play a role as a central coordinator to control AMS, since the vehicles at the AMS level are completely autonomous from their environment in their interconnection. In this case, the decentralized intersection management performs only one task, which is to distribute the information processed and analysed by AFG to the corresponding road users passing through the intersection according to their needs, which enables efficient information provision. In addition, decentralized intersection management enables AMS to communicate with other CMS or even with the highest hierarchy level CFG across system boundaries.

The underlying AFGs are AFG “Collaborative Mapping” and “Intersection Monitoring”. Here, the collected data from the sensors installed at the intersection or the information acquired via V2X communication is analysed, resulting in a panorama of the traffic environment, and obtaining new insights by fusing the data from different sources in different dimensions, and thus road users can make reasonable decisions with the comprehensive information. The AFG "Collaborative Map Generation" provides up-to-date and dynamic map data for all vehicles by highly dynamically integrating information provided via V2X communications, such as the direction of travel, vehicle position and operating states of individual road users, with static, highly accurate reference map to complete them. AFG “Intersection Monitoring” is used to collect information on the status of all road users in impact, to detect potential conflicts at an early stage, and to warn road users of the need for action. The information collected can also be used as a basis for decision-making for subsequent enforcement of traffic regulations and clarification of liability.

At the AMS level, all road users in the considered scenario of decentralized intersection management are networked with each other, while in the context of this work this is limited only to autonomous vehicles. The information processing of the AMS “Autonomous Vehicle” includes the “Status Acquisition” as well as “Communication Module” and disposes the information concerning the whole system. Based on this information, the upper-level commands are translated by the MFG-level functional modules into specific action instructions, which are executed by the lower-level MFM-level functional modules.

The functional groups of an autonomous vehicle at MFG level includes MFG “Assistance Systems”, “Chassis Management” and “Energy Management”. The assistance Systems are used as a combination of the intelligent functions to represent the human drivers in decision making for vehicle guidance. This mainly includes the route guidance to determine an optimal route to a selected destination and the trajectory planning of an optimized driving operation considering the dynamic driving environment based on the selected route [29]. The chassis management refers to the vehicle dynamics control to maintain the desired driving operation (target trajectory), where the target values of the basic driving functions drive, steering, suspension, and braking are determined and issued to the corresponding functional modules [30]. Energy management is used to

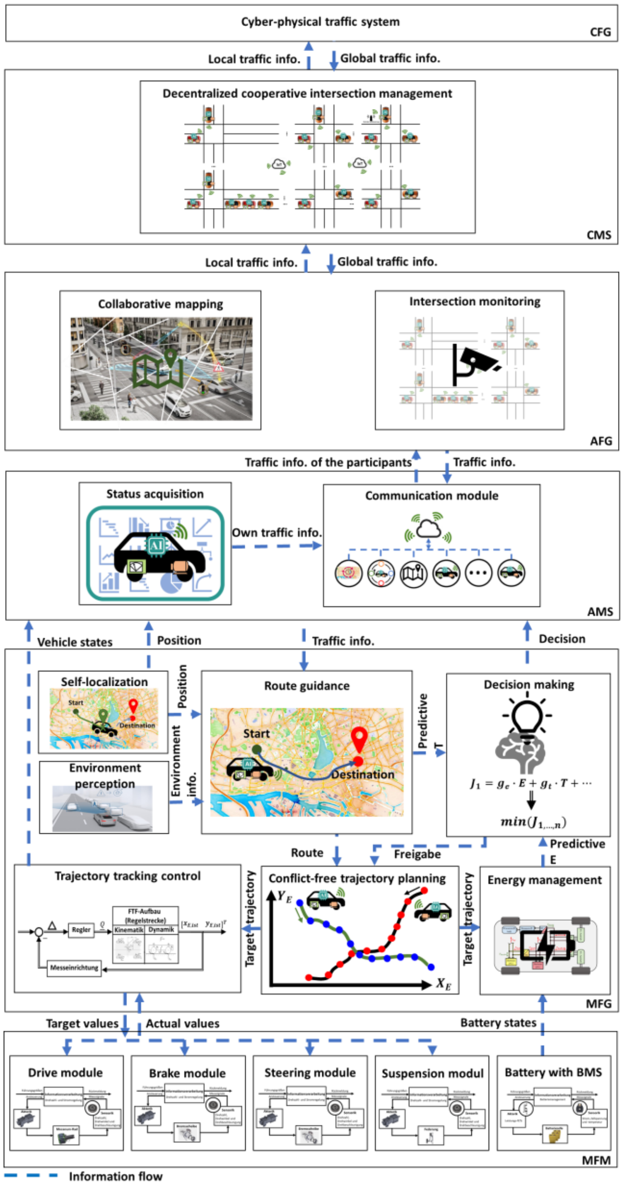

Figure 4. Functional structure of the CPS.

provide the necessary power to operate all mandatory, safety-relevant systems and optionally desirable comfort systems in the vehicle, as well as support for decision-making for vehicle guidance [31].

At the MFM level, in addition to the MFM for implementing the driving behaviour, it has a module for electrical energy supply, which includes a battery module as energy storage and battery management system (BMS) for monitoring the cell states and balancing during charging and discharging.

C. *Design of the functional structure and interfaces*

Form the system structure, the functional structure (cf. Fig. 4) is used to describe the information flow between the functional modules in vertical as well as horizontal directions, which serves as a basis for model description of the studied CPS in virtual test bench.

IV. FUNCTION VALIDATION VIA MIL-SIMULATIONS

In this section, the functionality of the developed intersection management is validated and evaluated with an application scenario under different traffic intensity. Subsequently, its generalizability is verified by applying it to a road network consisting of four intersections.

A. *Simulation scenario*

Fig. 5 represents the application scenario in which the autonomous vehicles are considered as the sole mobile road user and can perform the vehicle guidance independently without the intervention of a human driver. The simulation scenario of the CPS is reproduced with respect to the listed parameters in Table I in virtual test bench and the parameters of the vehicle model are adjusted.

B. *Analysis of the simulation results*

To verify the decentralized intersection management, the CPS is modeled and simulated with different traffic intensity in the virtual test bench. Here, the traffic intensity of motor vehicles in the peak hour is divided into three classes based on the class model of Federal Highway Research Institute (BASt) and simulated, whereby the traffic flow at each entrance in the simulation scenario flows evenly into the intersection:

- Low traffic intensity: $<$ 1000 vehicles/h
- Medium traffic intensity: 1000 vehicles/h -2600 vehicles/h
- High traffic intensity: $>$ 2600 vehicles/h

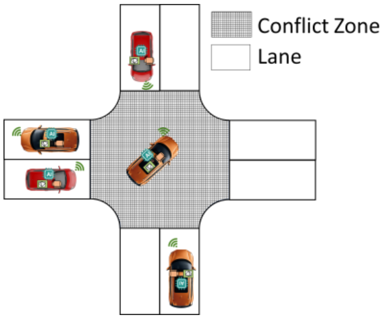

Figure 5. Simulation scenario – single intersection

TABLE I. PARAMETERS FOR DESCRIBING THE SIMULATION SCENARIO

Intersection	
Width of the lane [m]	4
Width of the conflict zone [m]	24
Vehicle model	
Vehicle length [m]	4
Width of the vehicle [m]	1,9
Max. Acceleration $[m/s^2]$	4,5
Max. Brake $[m/s^2]$	10
Max. Velocity [km/h]	50

TABLE II. ANALYSIS OF SIMULATION RESULTS WITH REGULAR TRAFFIC INTENSITY

Traffic intensity [vehicles/h]	720	2000	3600	7200
$\bar{v}_{init}$ [km/h]	43,5	43,4	43,4	43,1
$\bar{v}_{i\_k}$ [km/h]]	46,1	46,4	46,5	40,0
$\bar{v}_k$ [km/h]]	47,7	47,9	47,9	43,1
$\bar{v}_{o\_k}$ [km/h]]	49,2	49,3	49,4	46,2
$\bar{t}_k$ [s]	1,5	1,5	1,5	1,6
$\frac{\bar{v}_{i\_k}-\bar{v}_{init}}{\bar{v}_{init}}$ [%]	6,0	7,0	7,1	-7,8
$\frac{\bar{v}_k-\bar{v}_{init}}{\bar{v}_{init}}$ [%]	9,6	10,3	10,4	-0,6
$\frac{\bar{v}_{o\_k}-\bar{v}_{init}}{\bar{v}_{init}}$ [%]	13,2	13,6	13,6	6,5
$\frac{\bar{v}_{o\_k}-\bar{v}_{i\_k}}{\bar{v}_{i\_k}}$ [%]	6,8	6,2	6,1	15,5

TABLE III. ANALYSIS OF SIMULATION RESULTS WITH IRREGULAR TRAFFIC INTENSITY

East-West traffic intensity [vehicles/h]	576	1600	2880	5760
North-south traffic intensity [vehicles/h]	288	800	1440	2880
$\bar{v}_{init}$ [km/h]]	43,5	43,5	43,5	43,2
$\bar{v}_{i\_k}$ [km/h]]	43,0	42,0	36,5	25,1
$\bar{v}_k$ [km/h]]	46,6	46,0	44,2	36,3
$\bar{v}_{o\_k}$ [km/h]]	50,0	49,9	49,9	48,5
$\bar{t}_k$ [s]	1,6	1,7	1,8	2,3
$\frac{\bar{v}_{i\_k}-\bar{v}_{init}}{\bar{v}_{init}}$ [%]	-1,0	-3,5	-15,9	-41,8
$\frac{\bar{v}_k-\bar{v}_{init}}{\bar{v}_{init}}$ [%]	7,3	5,8	1,6	-16,0
$\frac{\bar{v}_{o\_k}-\bar{v}_{init}}{\bar{v}_{init}}$ [%]	15,1	14,8	14,8	12,2
$\frac{\bar{v}_{o\_k}-\bar{v}_{i\_k}}{\bar{v}_{i\_k}}$ [%]	16,3	19,0	36,6	92,9

During the simulation, the speed profile of each vehicle crossing the intersection is recorded separately, in particular the initial velocity v_{init}, the velocity entering the conflict zone v_{i_k}, the average velocity in the conflict zone $\bar{v}_{o\_k}$ and the velocity leaving the conflict zone v_{o_k}. Fig. 6 shows the speed change of the ten vehicles with vehicle ID from 51 to 60 when crossing the intersection with traffic intensity of 3600 vehicles/h. For intuitive evaluation of the decentralized intersection management, the simulation results with different traffic volumes are analyzed quantitatively and the main variables to represent the performance of the intersection management according to the target criteria are summarized in Table II.

It is obvious that when the traffic flow is less than 3600 vehicles/h, there is not much difference between the corresponding data sets obtained from the different traffic flow simulations, since the traffic flow at the intersection is regular and there is no congestion. However, when the traffic flow is increased to 7200 vehicles/h, it becomes clear that vehicles must slow down or even to zero before entering the conflict zone due to the congestion at the intersection, so the higher priority vehicles that are already in the conflict zone can pass the conflict zone first, and the conflict zone remains open. By comparing the vehicle velocity at traffic intensity of 7200 vehicles/h and 3600 vehicles/h (cf. Fig. 6 and Fig. 7), the difference becomes particularly obvious. Therefore, the average velocity when entering the conflict zone is about

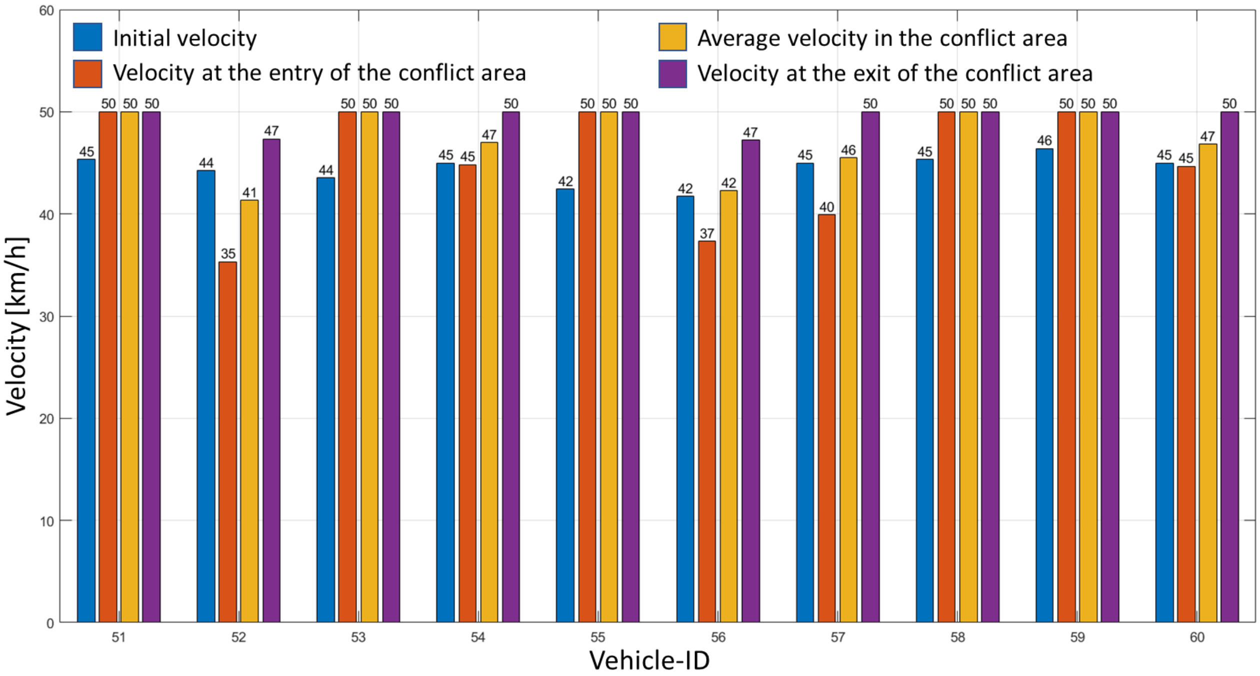

Figure 6. Velocity of vehicles crossing the intersection with a traffic intensity of 3600 vehicles/h.

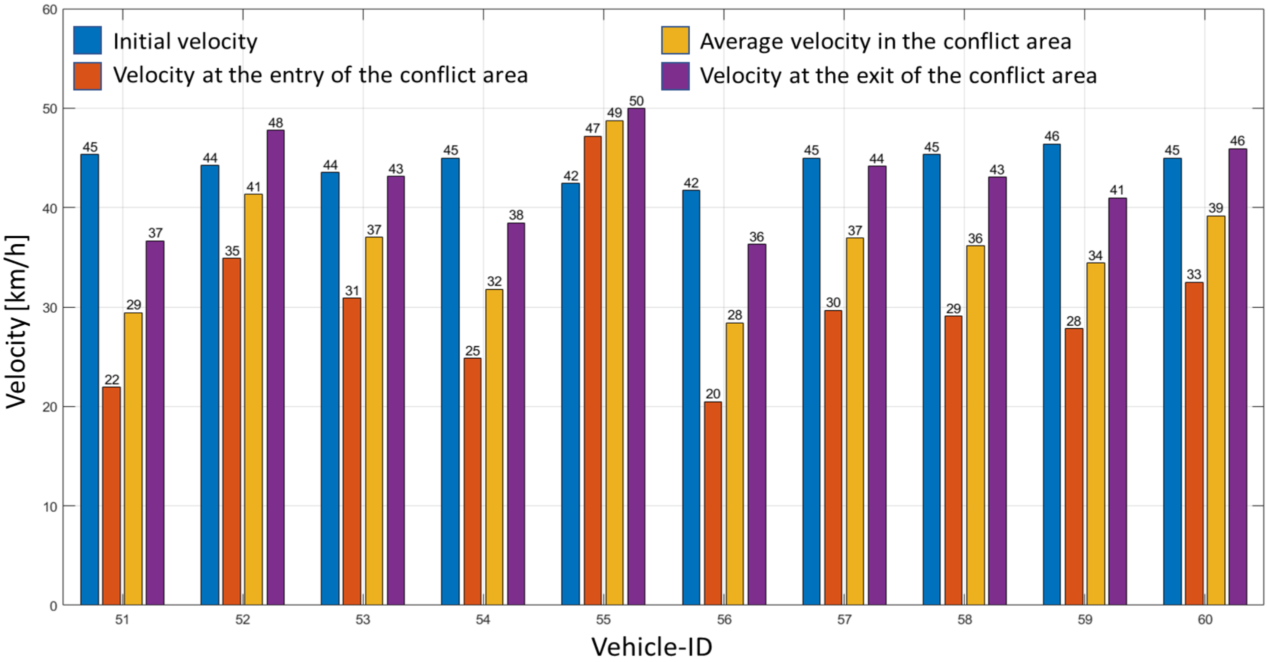

Figure 7. Velocity of vehicles crossing the intersection with a traffic intensity of 7200 vehicles/h.

7.8% lower than the initial average velocity of the vehicles. The average velocity in the conflict zone is increased compared to the average velocity by entering the conflict zone, and vehicles can accelerate through the conflict zone, which is mainly reflected by the fact that the average velocity of vehicles leaving the conflict zone is about 15.5% higher than the average velocity of vehicles entering the conflict zone, and this increase is almost 2.5 times higher than that in the congestion-free circumstance. This shows that decentralized intersection management based on the synergistic cooperation of networked autonomous vehicles can ensure smooth operation of the intersection even under extremely heavy traffic.

Since the traffic intensity at intersections is not regular in all directions, the robustness of the management system should be further investigated when the traffic intensity varies greatly in different directions. Therefore, the intersection management with irregular traffic intensity in different entry directions is researched, and the traffic intensity in east-west direction should be twice as high as that in north-south direction. The essential system parameters are summarized after analysis in Table III. By comparing the cases of regular and irregular traffic intensities in different entry directions, it is found that uneven traffic flow affects the throughput at the intersection. It can also be seen that the average speed at the entrance $\bar{v}_{i\_k}$ is reduced in comparison to the average initial speed $\bar{v}_{init}$ even with low traffic volume, with the drop in $\bar{v}_{i\_k}$ being more pronounced with increasing traffic volume. This is because the vehicles in the lanes with higher traffic intensity have priority by passing through the conflict zone to avoid congestion in the conflict zone, resulting in vehicles in the lanes with lower traffic intensity slowing down when approaching the conflict area reduce or even slow down to zero. However, as soon as the vehicle is in the conflict zone, it accelerates and the average speed $\bar{v}_{o\_k}$ with which the vehicles leave the conflict area at different traffic volumes is close to the maximum permissible velocity of 50 km/h to keep the traffic flow in the conflict zone fluid.

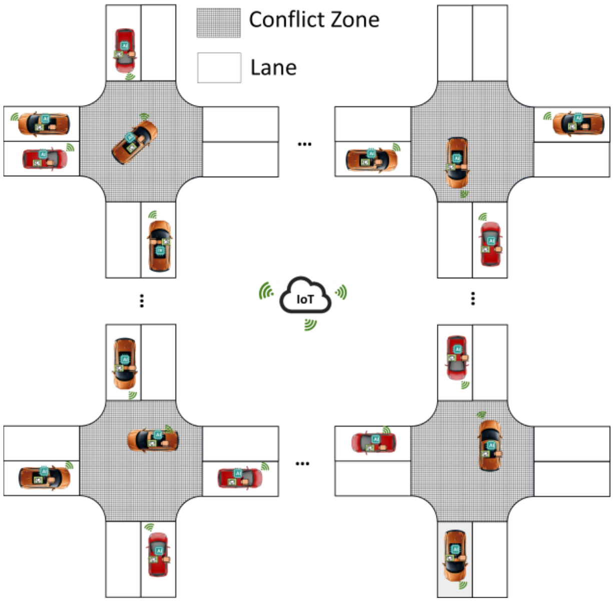

Figure 8. Simulation scenario - road network with four intersections.

To verify the generalization capability of the developed decentralized intersection management, a complex road network consisting of four intersections that are 200 m apart and with different traffic volumes is simulated, as illustrated in Fig. 8. The simulation results proved that the intersection management is also suitable for road networks with multiple intersections.

V. CONCLUSION

In this paper, the decentralized cooperative intersection management system by means of networked autonomous vehicles is designed and developed to optimize traffic throughput and ensure proactive traffic safety. Based on the defined requirements, the system and functional structure of the studied CPS is created, and then modelled in the virtual test bed and simulated with different traffic intensity, where the traffic intensity can be regular or irregular in different entry directions. The functionality of the intersection management is validated and quantitatively evaluated with the support of MiL simulation. By integrating the intersection management into a road network, the generalizability is verified.

In the next steps, the general applicability of the developed intersection management system can be used in intersections with different topological characteristics and verified by simulation. By comparing and evaluating the performance of centralized and decentralized intersection management with different traffic intensity, a new mechanism of intersection management will be developed, which dynamically adapts to the traffic flow by switching centralized and decentralized approaches to achieve the best performance.

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