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AGENT-BASED MODELING AND SIMULATION OF COOPERATIVE DRIVING

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AGENT-BASED MODELING AND SIMULATION OF

COOPERATIVE DRIVING

BY

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A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE

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OF

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ABSTRACT

Cooperative driving is defined as the automated coordination of vehicles based on advanced sensors and telematics. Vehicle-2-X (V2X) technology is emerging as a critical component in the development of autonomous cars. Even though individual sensors and vehicle level systems have become very advanced, their effectiveness must be proven in real traffic conditions. A prelude to on-road deployment is simulation based testing. This overcomes the shortcomings of real world experiments as it is cost-intensive and not feasible for potentially dangerous situation. Implementing adequate traffic simulation requires accurate models of single car behaviors, which lead to representative intervehicle interactions on actual roadways. This thesis presents a review of existing models of microscopic traffic simulations and the current research on coordination strategies for cooperative driving focusing on automated platooning. Coordination paradigms including centralized and decentralized approaches for formation and synchronization of vehicle groups are reported and discussed. Recent work on in the area addresses specific scenarios of cooperative driving. The thesis at hand proposes a decentralized coordination model of platooning. In detail, this is achieved by modifying existing car-following models that are reviewed beforehand. The proposed *Cooperative Platoon Model (CPM)* is an extension of the Intelligent Driver Model (IDM) and Gipps' Following Model that achieves coordination through coupled communication. A further contribution to this thesis is the development of a microscopic traffic simulation environment that serves as a platform for implementing the CPM. First simulation results show solid performance of the CPM in stability and the gap spacing strategy. The simulation environment is programmed in Python 2.7.

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LIST OF ABBREVIATIONS

ABM	Agent-based Modeling
ADAS	Advanced Driver Assistance Systems
CAH	Constant Acceleration Heuristic
CFM	Car Following Model
CMS	Collision Mitigation System
CRP	Common Relevant Picture
DAS	Driver Assistance Systems
DCB	Discrete Choice-based
FV	Following Vehicle
GAM	Gap Acceptance Model
ITS	Intelligent Transport System
IV	Intervehicular
IVC	Intervehicular Communication
LV	Lead Vehicle
MAS	Multi Agents Systems
MOBIL	Minimizing Overall Braking induced by Lane Change
ITS	Intelligent Transportation Systems
LCM	Lane Change Model
OBU	On-Board Unit
OO	Object Orientation
P…	Potential
RB	Rule-based
RSU	Roadside Units

LIST OF SYMBOLS

a) LIST OF VARIABLES

A, a	m/s^2	Maximal acceleration
α	$-$	Constant Threshold
acl	m/s^2	Acceleration
B	m/s^2	Maximal deceleration
b	m/s^2	Comfortable deceleration
dcl	m/s^2	Deceleration
ds	m/s	Desired speed
dt	s	Discrete iteration time
λ	$-$	Weighted coefficient
m	$-$	Group size
m_0	$-$	Desired group size
S, s	m	Desired gap at standstill
t	s	Time
T	s	Time gap (for IDM)
T	s	Reaction Time (for Gipps)
V	m/s	Velocity (for Gipps)
V^0, v_0	m/s	Desired velocity
X, x	m	Position
$\dot{x}$	m/s	Speed
$\ddot{x}$	m/s^2	Acceleration

b) LIST OF SETS AND INDICES

c	Vehicles
CAH	Constant Acceleration Heuristic
CPM	Cooperative Platoon Model
D	Distances
G	Group of Vehicles
IDM	Intelligent Driver Model
i	Subject Vehicle
$i-1$	Preceding Vehicle
$i+1$	Following Vehicle
l	Specific lane
IVC	Transmitted via IVC
s	Objective Value
P	Platoon
S	Slower Platoon
T	Time Horizon
V	Relative Speed
X	Platoon leader
Y	Non platoon vehicle

1. INTRODUCTION

1.1. Problem Statement and Motivation

Cooperative driving is the synchronization of vehicles on roadways, enabled by emerging Vehicle-2-X (V2X) communication technology. Although promising, its potential for improving traffic performance still needs to be exploited. To achieve a traffic state with accident-free automated driving, researchers have been investigating methods to provide drivers/vehicles updated and relevant knowledge about the driving conditions. Enhancing the vehicular environment perception to its maximum is one option to gain the insight of the environment. However, combining low-level data such as motion parameters to high-contextual information such as intentions and future actions of other road users into useful knowledge is a difficult problem. Since some of these signals are, and may always be unpredictable because of human involvement, sensors and algorithms face the challenging task of predicting the trajectories of neighboring vehicles. Traffic safety requires this task to be executed with a very high degree of robustness. A practical solution is to broadcast these cues immediately upon their execution, reducing some uncertainty about the future states of traffic. Coordination strategies can further eliminate the uncertainty of human actions by taking over vehicle control. Thus, complementing the on-board sensors on a vehicle with communicated information enables cooperation and coordination of vehicles, thus coming one step closer towards an accident-free traffic state.

Coordinated driving can help enhance achievement levels for three traffic performance goals: fuel efficiency, traffic throughput and traffic safety. Apart from this, easing the stress and strains for the driver by relieving him from tasks of vehicle

stabilization and guidance is a driver-assistance goal. It can be argued that heterogeneous traffic (i.e. a mix of different vehicles, drivers and roadway conditions) results in variance in desired speed, spacing and decision-making that may lead to unfavorable lane changing decisions, acceleration or deceleration (Huebner 2012). As the number road users increases, utilizing the existing infrastructure efficiently has become a primary concern for traffic management systems. Coordination of vehicle groups presents one practical solution to alleviating the variance occurring in traffic operations. In an automated formation driving, internal controllers and actuators on vehicles can be partially or entirely in charge of the driving operation. Human vehicle guidance is characterized by imperfect operation resulting in oscillation of longitudinal and lateral speed rather than maintaining a constant value. Further, limited capacities in perception lead to delayed reaction of the human driver which is also the cause for the suboptimal driving performance. Utilizing coordinated formations can largely diminish the driving task from the driver and homogenize the traffic flow. In particular, this could result in maintaining a constant and smaller intervehicle spacing, higher mean velocity, fewer lane changes, acceleration and deceleration maneuvers. The elimination of variance in throttling and braking can contribute to the fuel efficient driving. Likewise, a platoon of coordinated vehicles cruising at a speed with the lowest fuel consumption can multiply these effects. The PATH project noted that fuel consumption was reduced by 7% when using group formation (Michaelian and Browand 2000).

1.2. Objective and Methods

This paper reviews the existing research efforts for cooperative driving techniques with the focus on modeling and simulating formations on highways. In recent years, reports on this topic have been constantly growing. While there are different notations to describe the coordination methods on freeways, they are all related to self-organizing vehicle groups. Throughout the literature, different terms are used to describe those formations since they distinguish in the configuration, properties, rule sets and objectives of the collective vehicles. Prominent usages are platooning or collaborative driving systems (Hallé and Chaib-draa 2005; Halle, Laumonier, and Chaib-Draa 2004; B. A. Kesting, Treiber, and Helbing 2000; Yu, Kamel, and Gong 2013), formations or cooperative groups (Frese, Beyerer, and Zimmer 2007), clusters (Huebner 2012) or group-oriented driving (J. Görmer and Jörg 2013; Jana Görmer and Mumme n.d.). All these have in common the characteristic that they obey a certain internal rule set and thus achieve coordination by maintaining a defined intervehicle spacing. The objective of this thesis is on the one hand to provide a conceptual design of an integral platooning strategy by modifying exisitng car following models to achieve an coordinated platooning. On the other hand, the propsed model shall be implemented in a simulation environment that is developed in prior using an open-source programming language.

Chapter 2 deals with the classification of self-organizing vehicles. An overview of related work and the two major coordination paradigms is given. Operative coordination problems and respective algorthims are presented. In chapter 3, models for microscopic (individual) driver behavior are discussed. A realistic modeling of the car following behavior and the lane change decision making is a prerequisite for simulations of traffic

flows. The growing relevance of agent-based modeling (ABM) in the context of traffic simulation is also a topic in this chapter. Presenting a concept for platooning is the objective in chapter 4. Here, the layers of platoon control are introduced. The global layer provides a rule-set for vehicles to form a platoon. If the condition is met, the control is passed successively to the next underlying layer. The development of an original traffic simulation environment is then provided in chapter 5. The fundamental simulation design is explain and models of car-following are implemented to present the findings of this thesis. This work closes with a summary and an appraisal.

2. RELATED WORK

2.1. Background of Cooperative Driving

The capability of a driver to simultaneously perceive the vehicular environment, to navigate through a highly dynamic traffic and to react with appropriate maneuvers in order to avoid critical situations is an astounding feature of humans. Reducing driver workload and increasing the traffic efficiency are primary reasons why many researchers seek to reproduce those skills on machines under the prominent term of autonomous driving. *DARPA (Defense Advanced Research Projects Agency) Urban Challenges 2007* is one instance presenting satisfactory applications of routing autonomous vehicles under real traffic conditions. The background of this competition is the demonstration of current proceedings and performances of autonomously driven vehicles. One vital contributions for the safe navigation of those unmanned vehicles are the use of state-of-the-arts sensors such as stereo camera, 2-D and 3-D lidar sensors. Merging, processing and assessing the acquired data into one dataset enables a broad capturing of the vehicular surroundings and the respective dynamics.

Autonomously driven vehicles are primarily designed to navigate through traffic with the subject of collision avoidance. Therefore, the guidance strategy in presence of other road users is highly defensive and not operating optimally in order to increase the traffic throughput. For instance, the intervehicle spacing strategy on highways is not fully developed to improve mobility as the requirement for absolute collision avoidance is the main focus in the competition. Without coordination among the vehicles, an efficient and yet stable automatic control is difficult to attain. Recent projects on

cooperative driving show cooperative driving is best achieved by coordination through inter-vehicular communication (Di Felice, Bedogni, and Bononi 2013). Against this background, the realization of automated driving is partially dependent on the developing stage of vehicular communication and the strategies for coordinated and synchronized guidance of the traffic.

Autonomous driving consists of a broad set of advanced driver systems that may be divided by their function (safety, workload reduction, emission reduction etc.) and by the road environment (urban, highway, intercity). Thereby, cooperative platooning is considered as an integral requirement for automated high systems (AHS). FIGURE 1 depicts the multitude of advanced driver assistance systems and their development into higher automated systems.
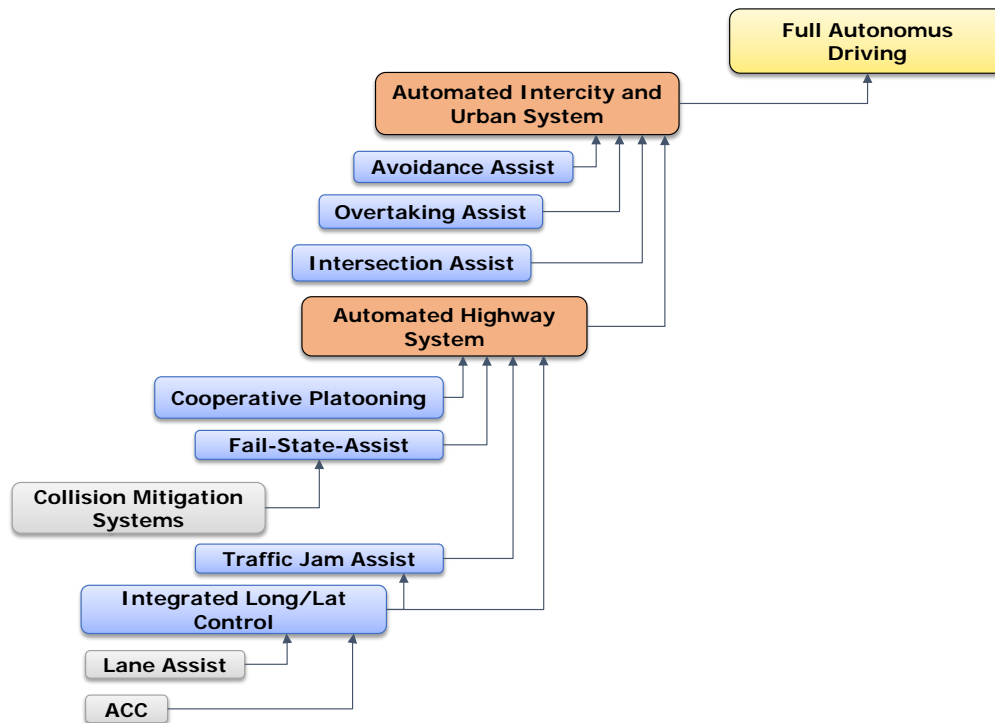
FIGURE 1 Development from ADAS to Automated Systems

Detailed specifications of those systems are:

- Adaptive Cruise Control (ACC) allows an automated longitudinal control of straight traffic with the driver monitoring the system.

- Lane Assist ensures the stability of lateral control and lane keeping within the present driving lane; monitoring through hands-on.

- Collision Mitigation Systems (CMS) evaluate the criticality of approaching a preceding vehicle and decelerates accordingly to avoid or mitigate an inevitable collision.

- Integrated longitudinal and lateral control is the fusion of both ACC and Lane control under the supervision of the driver. Equipped with an intelligence for lane changing, it yields first characteristics for automated driving.

- Traffic Jam Assist is an autonomous driving function to navigate through low-speed traffic with standstill as fail-safe-state.

- Cooperative Platooning involves platooning of vehicles and global coordination with non-platoon vehicles including cooperative maneuvers and safety functionalities.

- Fail-State-Assist is fallback mode for sudden driving incapableness to guide the vehicle to the hard shoulder.

- Automated Highway System enables complete autonomous driving within the specific road segment on highways.

- Overtaking Assist helps the driver to avoid unsafe overtaking maneuvers.

- Avoidance Assist is an alternative strategy to CMS and initiates avoidance maneuvers under the premise of knowing the surrounding.

- Intersection Assist coordinates the flow of traffic by warning and avoiding potential collision at intersections

- Automated Urban and Intercity System combines the abilities of AHS with preventive collision avoidance systems with flexible reaction to unforeseen events

- Full Autonomous Driving means unrestricted readiness of automated driving that is proven to be equally or more safe than a human operator.

This thesis focuses on the platooning on highways as one contribution to the ultimate goal of autonomous driving. As mentioned before, automated platooning is a measure to tackle suboptimal conditions on highways with portions of mainly longitudinal control. Shortage of road capacities around the world poses one example. Improving traffic throughput is therefore an integral motivation for forming vehicle groups. Traffic congestion is a negative phenomenon in terms of the traffic flow. Knowing the underlying causes of traffic jams is, therefore, vital to deduce a countermeasure.

Traffic Congestion. According to the Federal Highway Administration (FHWA) ("Congestion" n.d.), a common cause is given when the weight of traffic exceeds the road capacity. This can be due to repeating circumstances. The capacity can drop when there are obstacles on the lanes, e.g. road work, parking on lanes, narrowing lanes, accident or lane closure. Other external influences may be weather conditions. Systematic bias can be the unsynchronized or malfunctioning infrastructure, (e.g. long green-light periods, pedestrians not permitting vehicles to turn etc). Another reason might be the ineffective behavior of road users, e.g. rubbernecking. Hereby, the drivers are distracted by events outside of their car leading to congestion which has been widely discussed as a "phantom" traffic jam and an explainable system behavior. According to (Kerner and Konhäuser 1993), the braking of a vehicle leads to amplification of its following drivers' braking, resulting in a traffic jam after a critical density has formed. Adaption to such known system behavior to eliminate negative effects in the traffic is one integral motivation of platooning.

Workload. Objectives of today's research efforts on vehicular safety focus on the development of advanced driver assistance systems (ADAS) and the crosslinking of current system applications with restraint systems (Bra2). In light of this trend, the range of functions as well as the equipment rate of such systems in serial cars are expected to grow constantly. The variety of information and warning systems in present sedans and luxury cars may already be overcharging the driver. These excessive information – also called information overload – carries risks particularly in complex driving tasks where the driver has to focus his attention on simultaneous subtasks. Under this circumstance, an additional acoustic signal reminding of the service check may overstrain the driver

during a lane change in a dense traffic. Negative effects like this are no further issues when the in-vehicle computer takes over the control. Warning systems are mostly informing the driver when an imperfect vehicle navigation leads to critical situations. Algorithms can help eliminating dangerous driving scenarios systematically by cooperative maneuvers and reduce the necessity of warnings such as predicted lane crossing, approaching vehicles from rear in blind spot or critical approaching on a preceding vehicle.

2.2. Vehicular Communication

Due to a constantly increasing number of road users and imperfect resource sharing of roads, the rate of accidents and congestions is rising. Experts believe new advances in communication technology between vehicles (Vehicle to Vehcile, short: V2V) and with the infrastructure (Vehicle to infrastructure, short: V2I) can form a cooperative system where the users exchange information and cooperate, thus triggering the next leap in traffic safety, comfort and fuel economy. Establishing a powerful and reliable communication network is therefore the primary concern for higher-level vehicle coordination. Essential incentives to support the IVC (intervehicular communication) are arguably the following: (1) IVC has a broader horizon in contrast to any other available vehicle sensors and provides full 360-degree capturing of the environment that is far more reliable than local sensors. Because of the radio propagation, vehicles can deliver information from objects obstructed from view and are not affected by weather conditions. So warnings about different hidden hazards are reported in a timely manner. The overall telematics horizon is thus enlarged as portrayed in FIGURE 2.
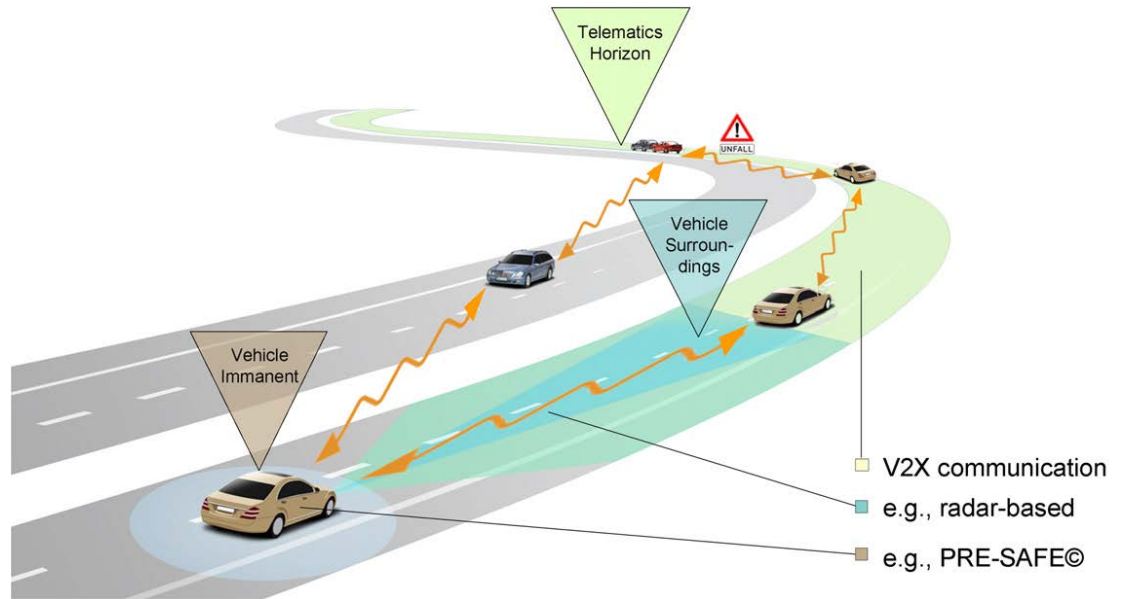
FIGURE 2 The telematics horizon (Weiß 2011)

(2) Communication can aggregate various types of information in one package. This is a central difference to conventional sensors that are designed to process one specific physical quantity. (3) IVC allows coordinated organization of vehicles to enhance the traffic from a macroscopic point of view by sharing information relevant to specific situations (Weiß 2011). The benefits in detail comprise – but are not limited to – following applications such as

- Information and warning systems (on road incidents or traffic alerts)

- Enhancing classic applications such as ACC to Cooperative Adaptive Cruise Control (CACC)

- Merging assistance of vehicles on the highway (Cooperative Merging)

- Assisted following of a leading vehicle (Cooperative Platooning)

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- Assisted avoidance and mitigation of collisions (Cooperative Collision Avoidance)

However, promoters of cooperative driving are confronted with new challenges. One problem is the necessity of estimating the reliability of information of external resources. An even greater problem is the penetration rate of equipped vehicles with V2X communication hardware as this narrows the type of functions. The ultimate challenge is therefore the design of the migration strategy. This applies both for technical as well as political issues since an extensive integration in the infrastructure as well as in cars is required to fully exploit the potential of cooperative driving.

One possible scenario is the introduction of V2X application in three consecutive phases. In the first phase, advanced driver information beyond the current telematics horizon contributes to the foresighted driving (see FIGURE 2). The second phase addresses traffic efficiency and safety. Present ADAS are adapted to the dynamic environment with regard to neighboring vehicles and their next maneuver intentions. Synchronization of the vehicle guidance is also a crucial topic in this phase that can help to improve dramatically the traffic efficiency, fuel economy and safety. The last phase marks the ultimate goal of cooperative driving. In an ideal state, vehicles and road site units (RSU) are connected via V2X hardware to tackle coordinated maneuvering, e.g. intersection assistance and merging assistance. The full development of different cooperative functions will set the necessary foundation for autonomously driven vehicles.

Automated platoons as the thesis' topic can be allocated to the second phase. The process of platooning deals primarily with the stationary driving state where the speed, acceleration and intervehicle spacing is at an equilibrium. While some autonomous platooning systems may cover further complex scenarios, special cases as merging and splitting at highway exits, low speed guidance, toll gate navigation or instantaneous obstacle avoidance are not subject to this work.

2.3. Coordinated Platoons

Present Applications of ADAS are not designed to increase mobility. Vehicles with ACC Systems can alleviate the traffic perturbation and navigation systems with dynamic routing can bypass congestions in a timely manner. Yet, the use of road capacities is barley increased (Witte 1996). Beginning with the PROMETHEUS projects, a novel approach is studied to platoon vehicles on a designated lane while regulating small intervehicle gaps (Zhang 1991). This concept gained international attention at the DEMO1997 in San Diego and the term "platoon" was generally acknowledged by researchers in the field of Intelligent Transport System (ITS) (Ozguner et al. 1997). More recent collaborative projects called KONVOI in Germany study the applications with heavy-duty trucks (Bergenhem et al. 2012). All projects have in common the intervehicular communication integrated in On-Board Units (OBU) that is a prerequisite for a highly stabilized longitudinal guidance.

Prominent projects within the last centuries study varying platooning concepts as these are determined by the different goals and motivation. Among those projects are SARTRE, PATH, Energy ITS, Grand Cooperative Driving Challenge (GCDC) and SCANIA that are based on one or more of the following variations.

Scope of control. While SCANIA and GCDC offer longitudinal automation, Energy ITS, PATH and SARTRE propose an integrated control of both longitudinal and lateral.

Vehicle types. The platoon may consist of vehicle types distinguished between their weight, determining the physical capabilities such as the acceleration and braking characteristics. While SCANIA, PATH and Energy ITS consider a homogeneous platoon with identical vehicle types, SARTRE and GCDC assume platoons with mixed types like trucks and passenger cars.

Traffic integration. The concept of V2X-based platooning is enabled through special local conditions of the traffic infrastructure such as designated lanes, ordinary or special markings. In that case, the traffic conditions are integrated in the process of coordination. In some applications, however, vehicle formation is feasible without modification of the existing infrastructure.

Considering the above mentioned requirements of current platooning projects, the following paragraphs provide detailed insight of those applications.

As a European Commission co/funded FP7 project, SARTRE has the mission to provide integrated solutions allowing platooning formations on public motorways without the modification of the given roads. The configuration of the road train is such that the lead vehicle is a manually driven heavy duty truck. Following vehicles consist of mixed types of vehicles (trucks or passenger cars) and the process of following is incumbent upon the controller both for lateral and longitudinal motions. The decision

of a joining or leaving the platoon is subject to the driver. Expected contributions of the road train are improvement in fuel efficiency, safety and driver comfort.

Under the premise to apply an automated platooning in unmodified public motorways, the V2V communication is the most suitable choice. Vehicles share their local information that would be otherwise not available by means of conventional sensors. Within the platoon, operations such as sensing and controlling are distributed and also shared. While the lead vehicle is controlled by human, automated control of the followers are dictated partly by the leader and partly by the dynamic state and captured information of the immediate surroundings of the local vehicle. Each follower has the intrinsic goal to maintain a defined intervehicle gap (longitudinal control) while the target trajectory (lateral control) is an external specification by the choice of the platoon leader. In exceptional situations as emergency or during inconclusive transmitted data, the autonomous controller may intervene the vehicle guidance. In terms of intervehicle spacing, the goal is to minimize the headway distance with subject to the safety gap. In other words, the longitudinal objective is to maintain a set gap to the downstream vehicle and to retain the option for evasive maneuvers in case of emergency.

Coordinated maneuvers of the platoons are achieved by the multidirectional communication. This implies the ability to share local information with any members of the road train. Sensoring motion of the preceding vehicle through local sensors is prone to lag and enforces errors. Bearing this in mind, the shared information is not only more precise than range sensors as radars of following vehicles, but also gives the upstream followers "foresight" that is not available due to the restricted vision by

adjacent platoon members. If for example the lead vehicle increases acceleration, the response of the rear followers will be delayed with local sensors, as the reaction needs propagate through each platoon member. As a consequence, the likelihood of lateral and longitudinal oscillation and instability of the road train rises.

Similar to SARTRE, the original goal of PATH is also the increase of the motorway capacity without expanding infrastructure as a countermeasure for the growing mobility demand. Platooning appeared as an optimal strategy as one of their studies proves that the lane capacity may enlarge up to three times when driven in a platoon of ten (James B. Michael n.d.). Automated platoons in this project follow the idea to eliminate the uncertainty of human driving behavior. Therefore, the control of every vehicle is subject to the platooning controller on the OBU. The platooning models of the PATH project ensured that the inter-platoon spacing guarantees a collision avoidance in case a preceding platoon is involved in a crash situation, so no follow-up emergency situation with another road train will happen. At the demonstration of the National Automated Highway System Consortium Demo 1997, the platoons successfully kept an intervehicle gap of $4m$ and performed various maneuvers such as lane changes, merging and splitting to and from platoons with the aid of automatic control. The core unit for the sensing, processing and actuating signals as well as the unit of IVC was integrated in a single core Pentium computer, meaning the data volume, preparation and processing in this case were manageable. Vehicle occupants reported a smooth driving experience while feeling also the safe mechanical vehicle guidance. The deviation of the headway distance is reported to be 20cm RMS error which implies that those are the magnitude of tolerable stability variances. Coping with energy saving measures are more recent

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targets of the PATH project. Subject to the platoons are mostly trucks as they have the best potential for energy saving due to the reduction of air drag. Major benefits of truck platooning is again the efficient use of road capacity where the truck throughput can be doubled per hour and per street segment. The proof of concept was successful with intervehicle spacing of 4m at a platoon of three trucks.

Tackling platooning in urban and motorway settings is the objective of GCDC in 2011, motivated by recent advanced in the communication systems. Promoting the deployment and application of V2X based cooperative systems is the major driver of this project. Providing more road capacity is again one of the strategic goals. The center of attention is the fusion of local sensor signals with externally received data packages to derive high-contextual information of the surrounding state. Technical equipment consists of the standard vehicular wireless access IEEE 802.11p and real time kinematic GPS to enhance the data reliability of exchanged information. The scope of control comprised the longitudinal motion in an urban and motorway setting. Equal controller setups allowed any vehicle to take over the role of the lead vehicle and also switch the roles from leader to follower and vice versa.

A selection of current projects have been discussed and reported. They all have in common the enlargement of detection horizon with the aid of IVC combined with vehicle local sensors. The majority of projects rely on non-commercial local sensors and communication hardware. Energy ITS for example uses lidar sensors that are superior to commercial radar systems, but are not cost efficient for serial production. GCDC relies on sophisticated positioning through real time kinematic GPS that is barley permanently available on public motorways. SARTRE, PATH and Energy ITS offer

longitudinal and lateral control, whereas only SARTRE offers multilane lateral control in terms of neighboring vehicles to merge into or split from the formation. The rest propose and integrated stability control for lane keeping besides the car following. Note that lane keeping is a safety and workload reduction measure but neither contributes to the efficient utilization of road capacities nor to the reduction of fuel consumption. Generally, the platoon should consist of homogeneous vehicle properties and avoid mismatches of e.g. weight, as this may lead to critical crashes in emergency situations. Mixed characteristics in acceleration is prone to destabilized intervehicle spacing when the lead vehicle throttles or brakes. Against this background, minimal gaps within the platoon is apart from the traffic efficiency aspect a measure to prevent incompatible vehicles to join the platoon. Noticeable is the focus of the stability of the platoon. Most projects pursue proof of concept and avoid complex platooning scenarios as the merge and split and interaction of multiple platoons. Therefore, there is a lack of global coordination strategies and directives when multiple platoons or single vehicles with platoons encounter a conflict of their individual goals which might occur when a driving unit blocks the upstream vehicle.

2.4. Classification of Vehicle Formation

2.4.1. *Formation based on Trajectory Tracking*

It is crucial to distinguish between classical *trajectory tracking* around UGVs from *cooperative leader-follower approaches*, since the former has also the leader-follower setup. The former focuses on the use of mobile robots to scout unknown terrains. Work on coordination on public roads falls under the latter approaches. Path following mobile robots are also used for stabilization control, while cooperative leader-follower setups

tackle the domain of vehicle guidance and routing strategies. Another indicator is the communication. Classic trajectory tracking relies almost exclusively on onboard sensors while the cooperative leader-follower negotiates via V2X. In the context of platooning, we define that *cooperative driving* requires that the coordination is achieved through intervehicle communication. In this paper, classic UGV leader-follower approaches are associated strictly with trajectory tracking methods and leader-follower approaches imply cooperative driving on highways. Note that both trajectory tracking and leader-follower methods can either have centralized or decentralized structures.

2.4.2. *Coordination Strategies*

To achieve a self-organized vehicle formation in traffic, the developer needs to specify whether a *centralized coordination* or a *decentralized coordination* approach will be followed. This will influence the allocation of roles and ultimately the autonomy given to of each platoon member.

Centralized coordination is a classic hierarchical configuration of the control and communication flow, whereas there is one leading vehicle with deterministic or modelled driving behavior or a centralized RSU that conducts the planning and instruction of coordination techniques. Two variants are distinguished in the literature: the leader-follower concept and the "virtual" leader.

The leader-follower concept for platooning is an extension of CFM approaches, and can be regarded as a cascading CFM model. The virtual leader approach is examined in (Rothery 1992) and (Kometani and Sasaki 1959). This paradigm emerged from the critique stating the leader-follower concept is not flexible as the state condition of the

leader is regarded as exogenous input for the followers, and no control feedback from the follower is taken into account. In the proposed method, the follower keep a predefined orientation and position relative to one designated leader. Known state variables of the leader are positioning and heading. In contrast to the "classic" leader-follower approach, this method generates a virtual leader that is calculated by the reference trajectory of the real leader with an offset. By this means, the original trajectory of the leader is estimated to increase robustness of the controller. The motivation is driven by an environment with limited information and is directed on the operative driving task.

Decentralized coordination. Distributing the task to individual elements of the system was proposed as a variant to early leader-follower concepts. The decentralized coordination resolves the negative impact of the centralized architecture's unilateral autonomy of the leader. In the decentralized approach, two main questions need to be resolved: (i) the extent of local control of vehicle agents; and (ii) the coordination of each agents' controller (Hallé and Chaib-draa 2005). The first problem requires a model representation for the longitudinal and lateral control behavior. Car following models and lane changing can provide appropriate guidance for this problem. To answer the second question, it should be noted that decentralized models are not dependent on a human-driven leader, but can make decisions without external guidance. Moreover, the agents can communicate with each other. Exchanging the individual states can be used as feedback control for decision and control algorithms to reach a collective coordination. The data-rich environment as a result of advanced telematics allows for

more flexibility as regards further applications on formation techniques and ensures higher robustness in data reliability as opposed to traditional sensors.

Discussion. In (Hallé and Chaib-draa 2005),the two contrasting coordination paradigms are investigated by evaluating the coordination process merging and splitting of a single vehicle into and out of a given platoon.

Centralized coordination means a hierarchical relationship in communication and chain of command. The role of the leader broadcasting instructions and guidelines. All relevant information or maneuver requests of single platoon members are directly communicated to the platoon leader. Communication with non-platoon entities is negotiated exclusively through the leader.

Decentralized coordination implies that platoon members share the same knowledge base and internal rule set for self-induced maneuvers. The driver's knowledge is generated when joining the platoon and updated whenever a merging or splitting maneuver is performed. The leader role is still existent, but merely as a representative for inter-platoon communication and does not dictate the activity of the agents. Information exchanged between subjects includes dynamical states such as position, velocity, acceleration as well as formation related data such as in-platoon positioning based on an indexing method. For merging and splitting, the mediated communication protocol through the leader is skipped, and drivers negotiate these maneuvers independently.

Platoon-specific information is called *common knowledge* and is updated whenever a merge or split happens. This knowledge includes the ID and the in-platoon position,

dynamic state. In line with this, Halle proposes the *virtual Blackboard* method to organize the communication and coordination. Each vehicle keeps a blackboard to broadcast its internal data and to receive messages about external information. This method is also used to negotiate and solve conflicts by associating costs. For instance, when two platoons intend to perform a group operation, but only one of them can actually execute it due to collision risk, the costs of interest are evaluated to prioritize the operation that yields the most global benefit.

In summary, the key characteristics of the cooperative driving systems can be depicted with five domains as shown in FIGURE 3.
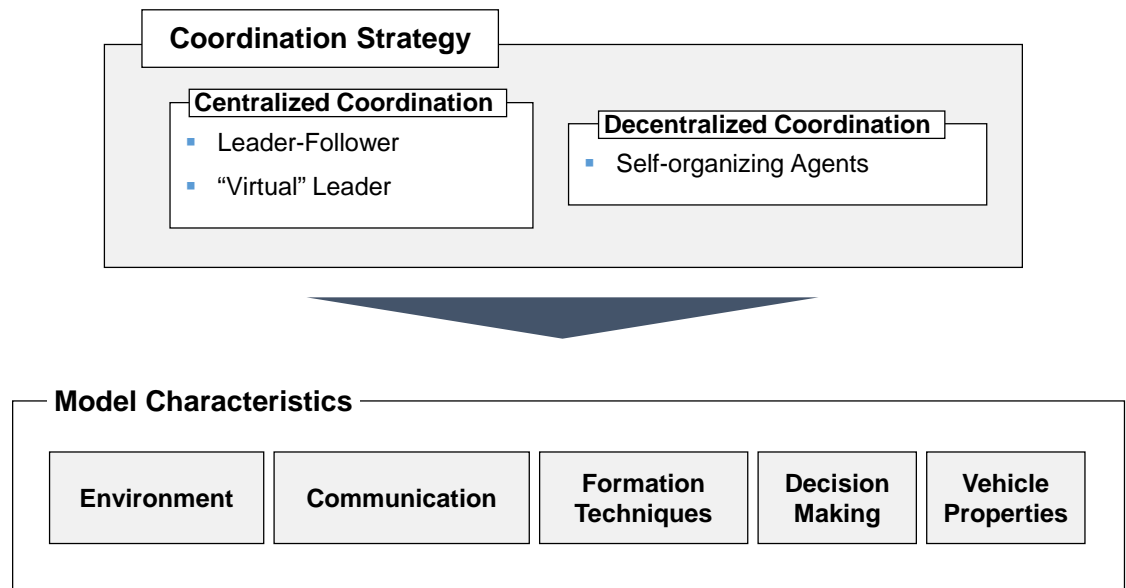
FIGURE 3 Framework of Collaborative Driving Systems

The limits and boundaries of modeling a cooperative platoon as a whole are defined by the scope of these five key model characteristics.

Environment modeling comprises the road topology as well as the infrastructure as a whole. Typically, formation techniques are used on freeways, resulting in rare uses of RSUs. With regard to the road topology, relevant criteria are the number of lanes considered, the inclusion of exits and whether the space is discrete or continuous.

Communication modeling is subject to the agent architecture and describes to what degree the communication topology is modeled realistically. This includes the reproduction of data loss or latency.

Decision making is the underlying set of methods for agents to interact accordingly to the own state and the environment state in a pre/defined and target-oriented manner.

Formation techniques describe the capability of agent-individual methods to maintain certain spacing to other vehicle agents. Associated states of the platoon makes the formation technique at hand individual. Required information for formation techniques through the drivers own perception, communication or both is crucial for the chosen descriptive method.

Vehicle properties are the dynamic variables of interest. Depending of the work, the key variables are different. Relevant values range from classical motion quantities e.g. position, velocity, acceleration to high dynamic quantities like yaw angle, slide slip angle, jerk to relative values e.g. time gap, spacing, relative velocity and acceleration.

2.4.3. Coordination Algorithms

In the previous section, the two main approaches for coordination have been discussed. Current works on highway platooning rely on the use of dedicated short range

communication (DSRC), which is the communication protocol of vehicular ad-hoc networks (VANET). Many strategic questions still need to be resolved. Some of these are:

1. What are the global and local objectives and are the conforming or divergent?

2. What is the order of communication and the communication topology?

3. Who is in charge of the final decision making for the collective as well as the individual?

A review of the literature identifies methods utilizing the following approaches as responses to these questions: leader-follower, graph-based approaches, distributed agents and other approaches. A selection of these approaches and their implementations are presented below:

Leader-Follower. As stated in 2.4.2, leader-follower approaches may be trajectory tracking robots of cooperative vehicle agents. In the former, the leading vehicle follows a predefined track or is controlled by human drivers. Using optical, ultrasonic or radar sensors to locate the relative position, the followers have the knowledge of the target trajectory they need to follow. In this centralized approach, only one trajectory tracking algorithm is implemented for each platoon member. The concept is simple to understand and implement. On the downside, there is no feedback from the followers and the formation coordination is lacking robustness. Once a vehicle loses track of its preceding vehicle, the formation destabilizes (Consolini et al. 2007, 2008; LIU and TAN 2007; Tanner, Pappas, and Kumar 2004). Applications are predominantly aimed for

reconnaissance in an unknown terrain where the requirements and assumptions are different than motorway automation scenarios. Applications for the longitudinal traffic are presented in (Frese, Beyerer, and Zimmer 2007).

In (Halle, Laumonier, and Chaib-Draa 2004), three driving scenarios for platoons are presented. First is the stabilization of platoons, meaning the vehicles maintain intervehicle spacing in a manner that the state is quasi-stationary. This condition arises when a formation does not perform a state transition (e.g. acceleration, deceleration or merging / splitting). Merging refers to a maneuver that involves a single, non-platoon member merging into an existing platoon. Methods for performing this might be a single vehicle approaching from the rear of the formation and becoming the last link of the collective. This is the simplest method, since it merely requires one member vehicle's and the merger vehicle's communication. In a variant, a single vehicle merges into a platoon moving in parallel with the platoon opening a space for the candidate vehicle to merge. To execute this approach, Halle uses centralized methods where the leader, the candidate for merging and the vehicle that will follow the merger after this task are involved. Respectively, the leader, splitter and the successor vehicle of the splitter before the task are involved in the configuration of splitting. The detailed maneuver is as follows.

(1) Merger/Splitter communicates its intention to the platoon leader

(2) The leader broadcasts the specification of the necessary maneuver e.g. intervehicle spacing, lane change or collective speed to the platoon members

(3) Gap creator (upstream vehicle) decelerates for supplying space for the merger and the merger executes lane change

Khan (Khan and Boloni 2005) proposes a centralized approach where the leader determines the dynamic desired state of the platoon based on the global knowledge of the network. Such knowledge is gained by overlapping individual information of single vehicles to aggregate the distributed information by using telematics. Delivering the information to a centralized leader may be computationally expensive as distant messengers need to route this information via intermediate vehicles ("multi-hop") to the leader.

Graph-based Approach. A novel approach for modeling the highway as well as the group formation is presented in (Huebner 2012). The modeling tools of petri networks are utilized to discretize the road network. According to the decomposition principle, the hierarchical description of the traffic resolution can be the network level (highest), road network level (medium) or the formation network level (lowest). In the lowest resolution, road segments are assigned multiple nodes for each lane, respectively while the token marks the presence of a vehicle at the segment. The transitions map the possibilities for interaction, for changing position longitudinally or laterally.

The global objectives is to reach homogeneity in traffic behavior, meaning a cluster of vehicles with similar properties needs to be formed. The similarity between vehicles is calculated by the quantified difference of the properties (attribute distance) that does not exceed a certain threshold. Vehicles share the same classes when all of the properties do not violate the similarity constraint.

These properties are *maximal acceleration*, *maximal velocity* and *length of vehicle*. To construct a group, vehicles conduct an accessibility analysis of vehicles in the vicinity. The local agents pursue a *maximal density* within a cluster subject to *minimal interactions* of cluster members. Thereby, a cluster can be distributed on all lanes laterally or longitudinally. Utilizing the Dijkstra-algortihm, each vehicle determines the shortest path to their desired state in a formation.

In his work about formation of cooperative groups, Frese (Frese, Beyerer, and Zimmer 2007) designs a decentralized strategy for exploiting potentials of safety. In order to get the maximal knowledge about the environment, a *common relevant picture* (CRP) is proposed in which all available data through vehicle internal sensors and environment detecting sensors of all road users is aggregated. Thereby, any set of vehicles that is in the communication range contributes to the CRP regardless of the driving direction or physical separation, meaning vehicles on bridges can also share information with cars in the underpass. Constant monitoring of the environment via the CRP allows early hazard detection and the onboard units autonomously intervene when the sole human control would lead to an accident. There are two levels of cooperation: information exchange and cooperative behavior. Vehicles that are not physically separated are able to perform cooperative behavior, meaning cooperative vehicles are a subset of information-exchanging vehicles.

The graph-based discretization of the road area forms a partition of the road network. The vertices represent parts of the road that are connected by directed edges. The weight function assigns each edge the minimal time a vehicle requires to drive between two vertices. The shortest path between two cars needs to be found in order to

distinguish between information sharers and cooperative eligible vehicles. The range of cooperation is given by a threshold radius with a vehicle as a focal point.

After obtaining a distance measure, the objective function can be established to find the optimal group assignment. Let $G=\{c1,\ldots,cm\}$ be a cooperative group with c as vehicles. Then we define the objective function s(G) to be a weighted sum of several terms,

$$s(G) := \lambda_D s_D(G) + \lambda_V s_V(G) + \lambda_S s_S(G) + \lambda_T s_T(G) \tag{2.1}$$

with the relative weighted parameters to be $\lambda_i > 0$. The first term s_D denotes the distance d between vehicles c_i and c_j within a group. It is defined as

$$s_D(G) := \begin{cases} 0, & if\ m \leq 1 \\ \frac{1}{m(m-1)}\sum_{i=1}^{m}\sum_{j=i+1}^{m} d(c_i, c_j), & if\ m > 1 \end{cases} \tag{2.2}$$

Here, the denominator separates the influence induced by the number of groups. The second term s_V denotes the relative speed among the platoon members, which is directly linked to the expansion or compression rate of the group. Expansion is present when the relative velocity becomes negative and therefore indicates the need of formations. It is controlled by the function

$$s_V(G) := \begin{cases} 0, & if\ m \leq 1 \\ \frac{1}{m(m-1)}\sum_{i=1}^{m}\sum_{j=i+1}^{m} \frac{\partial}{\partial t} d(c_i, c_j), & if\ m > 1 \end{cases} \tag{2.3}$$

The actual group size should be approached by the deviation function of actual group size against the desired group size m_0. Hereby, forming one-vehicle groups is avoided.

$$s_S(G) \; = \; (m - m_0)^2 \tag{2.4}$$

The last term $s_T(G)$ assesses the period of time a vehicle is part of the group. This will prevent from "hopping" between two platoons frequently due to small fluctuations in other terms. t_i is the period of time since vehicle c_i joining the group G, whereas t_T is a constant threshold.

$$sT(G) = \frac{1}{m} \sum_{i=1}^{m} \begin{cases} t_i & if \; 0 < t_i < t_T \\ t_T & if \; t_i = 0 \; or \; t_i \geq t_T \end{cases} \tag{2.5}$$

Distributed Agents. The distributed agent approach is an agent-based leader-follower tactic to implement self-organizing platoons. The platoon formation may be achieved by group forming, conflict solving, global coordination and local decision-making (Hung 2011).

Agent technology is most suitable to reproduce natural occurring swarm behavior such as sardines swarms. Those swarms are formed to protect the sardines against predators. Each sardine has similar physical properties as size, swimming speed or appearance. The movement of sardines also dependents on the neighborhood. If one sardine detects a predator, it will rapidly change its direction to avoid the danger. This reaction affects largely the neighboring sardines that will follow the shift in direction according to urgency which cascades until the swarm as a collective has changed its heading. From this behavior, a set of premises can be resolved to make design decisions of the platoon. Like each sardine can detect a hazard, every member of a platoon is capable to inform the group about his own desires or global conflicts. In the driving

context, there is no need to broadcast globally the information. Communication packages are rather conveyed to the immediate neighbors.

Agents exhibit behaviors leading to reactive and proactive actions. The instance of the sardines is clearly an instance of the former characteristic, as the sardines do not possess any set of measures to preventatively avoid hazardous situations, but rather react when necessary. However, connected vehicles can communicate with each other. The animals merely take action, but vehicles may interact by exchanging relevant information to solve a conflict. Further, telematics assisted vehicles can pinpoint crucial information to the leader and thus initiate a global coordination, which yield a self-organizing character rather than a chain reaction. Addressing group conflicts presumes the existence of platoons following divergent objectives. The formal distinction is the homogeneity and heterogeneity of agents. Heterogeneous agents imply diverging traits within the agent population. In the context of automated vehicle guidance, this circumstance is ideal to aggregate agents into platoons with collective features. As for local decision-making, this is relevant when the agents are provided with individual goals. This is useful to give the agents more autonomy to represent individual desires and targets of a single driver. Implementing local decision-making power is associated with a rule set to prioritize between global objectives and individual targets. Preferably, the pursuit of local goal is allowed whenever they do not conflict with global goals.

The previous section described the approach with regards to *centralized* and *decentralized* approaches, *reactive* and *proactive* behavior, *non-existent* and *existent* communication, *homogeneous* and *heterogeneous* traits as well as *global* and *local* goal pursuit.

In (J. Görmer and Jörg 2013), Goermer assumes heterogeneous traits with contrasting values in *desired speed, maximal acceleration* and *maximal deceleration.* The choice of these parameters is justified against the background that the platoon needs similar motion profiles in order to perform consistent group operations. For instance, contrasting acceleration capacities would result in emerging gaps between under frequent speed changes.

The driving scenarios considered are platoon forming, conflict resolution, global coordination and local decision making. In the discussion that follows, forming and global coordination scenarios shall be briefly explained.

Forming. In order to establish a formation with similar vehicles, an algorithm for evaluating the dissimilarity is required. Assume the platoon *PX* consists of a set of vehicle of two types: a platoon leader and followers. The *X* in *PX* denotes the platoon leader. His role is to represent the platoon for potential candidates to be integrated in *PX*. The method for accepting or declining a candidate vehicle Yi with $i \in I = \{1,\dots,n\}$ of a set of non-platoon vehicles to join the platoon *PX* is controlled by the dissimilarity function $f(X,Y)$. Thereby, *Y is* accepted to *PX* if following condition holds

$$f(X,Y) < \alpha \qquad\qquad (2.6)$$

α is a constant threshold for the dissimilarity condition. The subject of comparison are the parameters maximal acceleration, maximal deceleration and desired velocity. If the dissimilarity between the platoon leader and candidate f(X,Y) is smaller than α, the candidate will extend the existing platoon.

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Note that this method requires a representation for X that can be either a mean value of every member vehicle. Due to computational cost, it is more practical to designate the leader as the representative for the dissimilarity function.

A known method to assess the dissimilarity of two objects is to illustrate those objects in a three-dimensional space and to calculate the distance of the key parameters. Assuming a Vehicle V has the properties $V(ds, acl, dcl)$ desired speed, maximal acceleration and maximal deceleration respectively, the distance function can be expressed as:

$$f(X,Y) = \alpha_1 \frac{|ds_x - ds_y|}{s_{ds}} + \alpha_2 \frac{|acl_x - acl_y|}{s_{acl}} + \alpha_3 \frac{|dcl_x - dcl_y|}{s_{dcl}} \qquad (2.7)$$

where s_{ds}, s_{acl}, s_{dcl} are tolerance parameters to ease the fulfillment of the dissimilarity function. The values are normalized at the same time. A tolerance gap is introduced due to the assumption that identical values of motion parameters are unlikely to occur. $\alpha_1, \alpha_2, \alpha_3$ denote weight coefficients to parameterize the significance of respective motion properties. The sum of all weight coefficients should hold the constraint of (2.3)

$$\alpha_1 + \alpha_2 + \alpha_3 = \alpha \qquad (2.8)$$

Global coordination is a measure to allocate lanes to platoons according to the priority when a conflict occurs and vehicles block a faster approaching platoon from

behind. The priority is directly proportional to the desired speed of a platoon leader. The priority is evaluated and allocated with subject to the Dominance function:

$$Dom_l(P,S) = card_l(P) - \sum_{P^a \in S} card_l(P^a) \qquad (2.9)$$

Here, l donates the specific lane, P is the subject platoon and S the set of slower platoons Pa with respect to P. The platoon leader selects lane l when $(P,) \geq Domk(P,S) \geq 0$ with $l \neq k$. This equation ensures that the platoon with highest priority (= highest desired speed) needs to perform the smallest number of lane changes among its members as possible. In line with the priority, this algorithm is repeated until the queue of conflicts are resolved. After the platoons are being assigned to a lane, the global coordination algorithm triggers the lane change for vehicles that are on (a) different lane and (b) require changing the lane since they will be blocked by a preceding vehicle or will be obstructing an upstream vehicle. The lane change algorithm is based on Gipps.

In (Khan and Boloni 2005), the choice for a non-platoon vehicle to join a formation is ceded to the individual agents and their local algorithm to assess the neighborhood. The problem of the platoon speed is addressed when assuming that followers merely adopt the speed of its lead. As a result, the platoon speed is dictated by the slowest link in the group that destabilizes the formation. Decision-making for joining or leaving is incumbent upon the agents and is controlled through utility and cost functions.

Vehicle-2-X. A vital advantage of the V2V communication is its feasibility. This technology does not require any infrastructural road-site units, but depends on vehicles

with respective communicating system units. Once it is installed on a vehicle, those cars can exploit the potential of cooperative driving whereas the V2I technology is merely in the scope of designated road-site units.

2.4.4. Summary

In this section, the evolution of automated platooning has been reviewed. The motivation for cooperative driving has been addressed. The essential advantage of automated platooning on the highway is the simultaneous improvement of traffic throughput, fuel efficiency and workload reduction of drivers. Depending on the objective, however, the suitable strategies and algorithms can vary. While some researchers see the objective fulfilled by the mere formation of vehicle groups (Khan and Boloni 2005), other researcher propose strategies of negotiation and coordination of inter-platoon conflicts (Huebner 2012; Hung 2011). The distinction of the two coordination paradigms is pointed out and selected coordination algorithms are presented. TABLE 1 is a selected overview about the multitude in the field of vehicle formation.

TABLE 1 Overview of motivation, approaches and strategies for self-organizing vehicles

No.	Year	Subject of Research	Keyword	Motivation	Scope of Simulation	Communication
1	2013	Optimization of cooperative platoon formation	Platoon, optimization problem, GPS	Lane capacity on unmodified public roads	Analytical	V2V multi-hop
2	2007	Robust formation adaptive control using second order kinematic model	Formation control, mobile robots	Robust control only using relative motion	Analytical bicycle model, hardware experiment	-
3	2009	Decentralized formation control of unicycle robot	Formation Control, Virtual Structre	Countermeasure for leader-follower disadvantages	Analytical unicycle model, hardware experiment	-
4	2012	**Project** SARTRE Optimal parametrs for platoon maneuvers, e.g. optimal gap for merging	Road Train, Platoons	Assist driver, traffic safety on unmodified public roads	Submicroscopic. Driver model, vehicle model and environment model	V2V for group coordination, l2V ("backoffice") fur support and business application
5	2005	Algorithm for highway formation strategies.	Convoi driving, ad-hoc coalition	Technically inexpensive solution for formation	Microscopic Traffic	V2V using self-developed hardware devices ("motes").
6	2012	Automated Platooning on Highway	Platooning, cooperative ACC (CACC)	Exporlative Analysis, Parametize penetration rate of CACC on traffic	Controller modeling, microscopic traffic	V2V
7	2010	Platooning autonomous vehicles with V2V	Platooning, IDM DSRC	Lane capacity Eleminate stop-and-go	Microscopic Traffic	V2V

TABLE 2 Overview of motivation, approaches and strategies for self-organizing vehicles (continued)

No.	Control and Coordination	Platooning Concept	Key parameters	Objectives	Packages Program Language	Reference
1	Linear programming problem	Decentralized Leader Follower	Travelled distance in a formation, destination	Allocate single vehicle at highway entry a platoon so the collective travelled distance maximizes	VISSIM DLL	(Systems n.d.)
2	Feedback linearization and sliding mode compensator for control	Leader-Follower Trajectory Tracking	Relative speed and relative bearing	Robustness against internal pertubations and external uncertainty	-	(Shi-cai and Da-long n.d.)
3	Decentralized control unit and mutual coupling	Virtual Leader Trajectory Tracking	Absolute translational and rotational motion	Robust tracking, autonomous decision for following	Python	(van den Broek, van de Wouw, and Nijmeijer 2009)
4	Automated lateral and longitudinal control. Centralized control.	Centralized Leader-Follower coordination	Platooning distance, velocity	Minimize required maneuver duration, maximiaze platoon density, avoid oscillation platoon vehicles	PLEOPS. MATLAB/Simulink for vehicle model	(Bergenhem and Robinson n.d.)
5	Human drivers assisted by CCD	Distributed	Current, maximal and desired speed	Minimize the utility-function.	TinyOS nesC	(Khan and Boloni 2005)
6	Car following Model CACC with V2V	Centralized by RSU	Desired and relative speed, acceleration, headway, gap error	Success/failure ratio of joining maneuver. Number of joining options	SUMO OMNeT++	(Segata et al. 2012)
7	Modified IDM Slidin Mode Approach	Centralized Leader-Follower	Intervehicle gap error, desired acceleration	Minimize desired gap error Maximize density	SUMO TraCI	(Fernandes and Nunes 2010)

UAVs are suited for free space reconnaissance where the environment is an unknown factor. As the road topology of a highway is well known and the lanes can be simplified as discrete lateral positions, robust path following algorithms become obsolete for highway platooning. However, certain characteristics may contribute to desirable model states. The virtual structure in (van den Broek, van de Wouw, and Nijmeijer 2009) assumes imaginary lead vehicles to control the robots. In the same manner, virtual leading vehicles may be employed to overcome the *gap problem*. When a potential platoon member signalizes its request to merge between two platoon members, virtual vehicles may be deployed for a coordinated gap setup. The process for a coordinated lane change is proposed in FIGURE 4
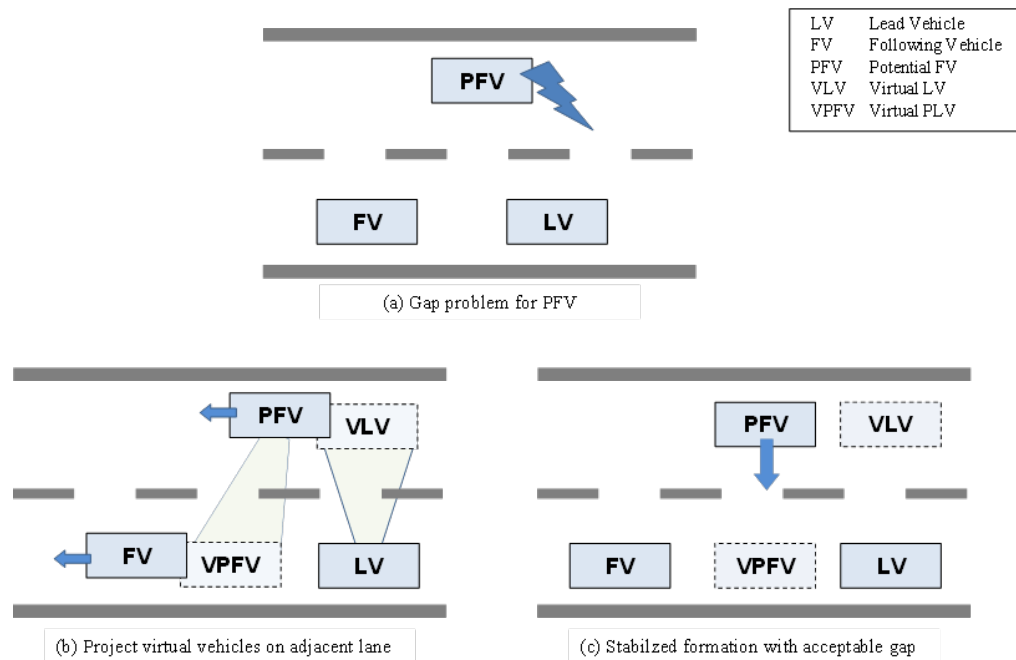

FIGURE 4 Strategy for coordinated lane change. Gap problem for a potential following vehicle (a) deceleration due to virtual vehicles (b) and resolving gap problem (c)

In (a), PFV (consisting of LV and FV) cannot perform a lane change due to a gap problem. He requests the coordinated lane change which projects virtual vehicles. The projection is an exact copy of the dynamic state of LV and PFV on the adjacent lane. The virtual preceding vehicle imposes deceleration on the upstream vehicles as implied in CFMs. After stabilizing the intervehicle spacing, the gap problem is resolved and PFV can initiate a merging into the platoon.

Considering the growing intelligence of board computers and the emerging technology of Vehicle-2-X, those systems will be confronting new challenges in managing themselves. Since each individual motorist follows his own preferences and destinations, it is unlikely that the traffic of future is controlled by one central top domain. The arrangement of traffic will be rather determined by decentralized units that strive for matching shared goals and global consensus. By this means, no motorist will be patronized in his decision and automated intervention is merely carried out providing that it is consistent with the individuals' intent. Against this background, it is a reasonable conclusion to consider agent technology for experimentation, evaluation and validation of vehicular networking.

Apart from individual cases, most longitudinal cooperative driving strategies resort to decentralized coordination approaches when facing large-scale control problems, and distribute the tasks to single vehicles to exploit available computational resources of the platoon. Furthermore, each vehicle can make own decisions (as long as it does not violate the global goal) in line with its local preferences (*9*). Further, the experience has shown that decentralized architecture has advantages in reusability, synchronization and scalability. The drawback of decentralized coordination is the exhaustive search for

coordination plans to be decided on. When the rule set results in a high complexity in negotiation patterns, the decision-making might be inefficient (*34*). Therefore, safety-relevant applications yield better performance with centralized coordination, as the subordinate members obey the instruction without negotiation.

The works reported present a progression with respect to specific tasks of cooperative platooning on highways. However, many contributions neglect the preferences and autonomy of actual drivers, as their decision-making is assumed to be completely overtaken by autonomous controllers in cooperative driving. Considering how the traffic and the cooperative driver assistance systems will evolve over time, assuming full capabilities of autonomous controllers is not immediately practical. Coping with heterogeneous vehicles with and without V2X communication and cooperative platoon controllers is a vital aspect that is mostly ignored, except in (Segata et al. 2012). The interaction between human drivers and autonomous vehicles should be the main focus for upcoming related work and critical problems should be addressed first. A fully developed autonomous platoon must be robust against systematic and human behavior to pose a satisfactory validation of concept.

3. DESCRIPTIVE METHODS FOR TRAFFIC SIMULATION

3.1. Background of Traffic Simulation

The development of safety and comfort systems around the vehicle has grown constantly over the past decades. The vehicle as well as the infrastructure are equipped with intelligent systems to collect toll, unburden the driver or increase the safety while driving. However, the introduction or modification of those in-vehicle systems or roadside units (RSU) requires careful evaluation and inspection.(Yu, Kamel, and Gong 2013) Computer traffic simulations form a practical approach to tackle those problems. First, it is versatile in creating scenarios which makes it a powerful tool. The time required for calculations to conduct simulations can be accelerated compared to an actual field test, thus the outcome is quickly available. Besides this time- and cost effectiveness, it is possible to recreate scenarios that are difficult to reproduce in the real world. Traffic safety is a broad topic tackled by many scientists which requires an interdisciplinary research approach to understand the complex sociotechnical systems in the traffic. The influence of human decision-making implies a large set of uncertain events that cannot be fully described by one-dimensional chain of events. In the real world, the traffic participants are constantly influenced by the vehicle, infrastructure, environment and the human driving behavior. The drivers are making constant negotiations as in regulating short-term traffic, as in overtaking or offering space to merging in lanes.

Core units of microscopic simulation is the representation of the car following and lane change behavior. Let us assume a single lane situation with a following and a preceding vehicle. The follower has the aim to regulate a spacing to avoid collision at

any given state. Further, the intention for lane changing and the evaluation of its feasibility need to be modelled. A mathematically correct description of those behaviors is an integral part of microscopic traffic simulation. In the literature, there is a consensus about the superordinate term Car Following Model (CFM).

As the models concerns with the control decisions while following a vehicle ahead, the follower is also called subject car and the preceding vehicle is called object car.

3.2. Traffic Simulation Tools

The research on ITS deals with the efficiency of different traffic scenarios. Therefore, traffic-related datasets of various traffic scenarios are required for comparative purposes. Due to the tremendous cost of data collection without endangering road users, the number of feasible traffic configurations with real traffic objects is limited. Simulation tools offer the opportunity to design and simulate ranging from microscopic to macroscopic traffic models on computers. Primary purpose of traffic simulation systems is the imitation of traffic objects' behavior (e.g. vehicles, signal lights) by appropriate mathematical models (e.g. CFM). Nowadays, traffic simulation systems play not only a vital role in transportation research, but also in the field of traffic management. In the center of a traffic simulation system are the car following and the lane change model. However, every simulation tool has its own limitation regarding flexibility, used models, modularity or in the entities, processes and scale. Therefore, the following sections show the different packages and their aptitude for traffic simulation.

3.2.1. AIMSUN

AIMSUN is a commercial microscopic, microscopic traffic simulation software of Transport Simulation Systems ("Aimsum" n.d.).The microscopic level simulation serves to generate and analyze small traffic scenarios. AIMSUN uses the CFM and LCM of Gipps for simulating the drivers' behavior. The macroscopic level simulation is dedicated to large-scale traffic scenarios. The CFM and LCM are modified to the more extensive scenarios in order to reduce the computing power. Hence, short time dynamic has little impact for this scale of simulation and is therefore negligible. Traffic scenarios can be automatically generated from a GIS-file. AIMSUN also offers a graphical user interface for modeling and tweaking individual traffic scenarios. The graphical output is either a two-or three-dimensional animation. At the end of a simulation run, the report of traffic data can be saved in a database. External applications may access traffic objects through the provided programming interfaces. Supported programming languages for the object interfaces are Python or C. AIMSUN is compatible with Windows and can communicate with applications of Linux and MAC OS.

3.2.2. VISSIM

VISSIM is the global leader on the market of microscopic traffic simulation system (Assenmacher 2007). The system was developed in 1970 by the University of Karlsruhe in Germany. PTV then distributed the system as commercial software in. VISSIM decided on the physio-psycho CFM of Wiedemann (Wiedemann 1974) to simulate the driver behavior of road users. This program also provides a powerful graphical user interface for rapid design of various traffic scenarios and for simple control of the simulation. During the simulation, the behavior of the simulated traffic objects is

represented through two- or three-dimensional animations. Pedestrian interactions are also part of the software for safety related scenarios. Similar to AIMSUN, VISSIM offers the feature for data collection and export in an external file and provides the opportunity for model customization via different programming interfaces, e.g. Visual Basic, Visual C++,Visual J ++ or Python. Compatibility restrictions apply with applications of Linux.

3.2.3. PARAMICS

Developed by QuadstoneParamics, PARAMICS is a full scalable, multimodal traffic and pedestrian simulation software for operation assessment. The underlying CFM is based on the psycho-physio following model by Fritzsche (Fritzsche and Ag 1994). PARAMICS provides various tools for ordinary users and developers to design and simulation of traffic scenarios with two- and three-dimensional graphical animation. One special feature of PRAMICS is the so-called "network simulation" function. Each computer is considered to be a processor node and is responsible for a simulation. Multiple computers are linked whereas one takes the role of the process manager allowing simultaneous runs of simulation scenarios. Results from different runs are gathered, formatted and summarized by the central processor manager. The idea is to compare the simulations results of different nodes. This function is helpful when a particularly large-scale scenario is the subject of interest. A special reporting tool helps processing and displaying dynamically the simulated data. For developers, PARAMICS provides the ability to control transport objects through a programming interface with Visual C++.

3.2.4. SUMO

SUMO is an open source microscopic traffic simulation package for handling large road networks (Dias, Abreu, and Silva n.d.). Developed by the Institute of Transportation Systems at the German Aerospace Center, SUMO accounts for space continuous and time discrete vehicle motion of different types and provides further interesting extensions like simulating real-time GPS traces. SUMO provides a graphical tool visualizing the simulated road topology and traffic. Scenarios are handled with XML files and real road networks can be imported with free available models of real traffic roads from open street maps. Due to its high portability and the options for V2X communication, SUMO has been emerging as one of the frequently used traffic simulator for IVC.

3.3. Microscopic Traffic Simulation

3.3.1. Car Following Models.

Car following models have been widely discussed. Due to its rather simple nature, researchers were successful in developing mathematical formulations of this subtask. Understanding the car following behavior leads to understanding the traffic flow on highways, as this subtask occurs frequently in this road type.

Typical critical maneuvers during the longitudinal drive are the spacing to a preceding car, which is determined by the relative speed, the reaction time and the maximum deceleration specific to the vehicle. The reaction time is strictly speaking a composition of perception, decision making and execution time. A small portion, but relevant in critical situation is also the time from applying the brake pedal until the

brakes to take effect. The sole focus on speed and spacing as model parameters is the result of the early findings and is applicable to a traffic stream with steady speed with each car maintaining the same spacing (Rothery 1992).

Car following models of single lane traffic are successfully implemented, because the following cars have the tendency to "copy" the driving strategy of a preceding vehicle. That being said, the behavior of the following cars becomes predictable. Understanding the mechanism of the subtasks allows the description of car following behavior. If lane changing is neglected, the car following can be divided into following three subtasks (Rothery 1992).

Perception. The relative speed between preceding traffic, the environment and the subject vehicle serve as visual perception and the dynamic motion. Motion parameters of interest are subject vehicle velocity and acceleration, preceding vehicle velocity acceleration, spacing, relative speed, rate of approaching, and higher derivatives of those motion as "jerk". For safety relevant situations, functions has the time gap and time-to-collision.

Decision Making. The driver acquires information obtained by his perception over time and deduces the dynamic state of his vehicle and surrounding objects. The process of interpretation is based on the knowledge of the vehicle's class of property. Along with the obtained information and the repertoire of driving experience, the driver develops a driving strategy. When the actions based on the strategy becomes automatism, it is regarded as driving skills.

Control. The experienced driver has a set of control commands to guide and maneuver the vehicle while maintaining stability. This process relays on the constant feedback from his subject responses and the state in environment.

The involvement of human behavior is the reason why the facets of the driving task so opaque. Expressing the operator of a vehicle as a unique transfer function has its limits as the different conditions provoke divergent responses (Ellson 1949; Tustin 1947). Current approaches of car following models are – however – not the explicit formulation of human behavior. A proven approach is the response-stimulus relationship that grossly sums up the physiological and psychological processes within the driver. Other approaches have also proven to be a satisfactory expression of the car following. Selected models are presented below.

Chandler's Model. A simple model was presented by Chandler in the 1950's

$$a_n(t) = c\Delta_v(t - T) \qquad\qquad (3.1)$$

$a_n(t)$ denotes the acceleration of a following vehicle at the time t. $\Delta_v(t - T)$ is the relative speed between following and preceding car. T is the iteration step time and c is a sensitivity coefficient. It determines the reaction intensity to changes of the object vehicle. Provided there is no speed change, the follower adapts the speed of his predecessor. This CFM can be described verbally as a function of response = stimulus * sensitivity and is the origin of many subsequent models. This model's key parameter is the relative velocity.

Gazis, Herman and Potts' Model. It is an extension of Chandler's model based on the assumption, that the subject's behavior is not only dependent on the relative speed, but also the spacing at the time. By incorporating the intervehicle spacing, the model can be described as

$$a_n(t) = c * \frac{\Delta_v(t - T)}{\Delta_x(t - T)} \tag{3.2}$$

With higher distance to the predecessor, the effect of velocity change is reduced and vice versa.

Wiedemann's Psycho-Physio Model. In contrary to the linear models before, the psycho-physical CFM of Wiedemann is variable according to the current driving mode.(Wiedemann 1974) The four driving consist of free driving, approaching, following and braking. The core of the model is the calculation of the acceleration as a function of relative speed and headway distance. Those two variables span a coordinate and depending on the operational state of the subject car, one of the four modes takes effect.

Gipps' Model. Unlike the aforementioned models, Gipps follows another approach by determining the maximal velocity $V_{sbj}(t + T)$ that the subject car can theoretically achieve at the time step of$(t + T)$. It is calculated under consideration of two constraints. The first one is a capacity constraint, where it is assumed that the subject vehicle attains its desired velocity by the maximal acceleration. The equation includes merely terms of subject's velocity, acceleration and a delay constant.

Given that there is a preceding vehicle, the second equation incorporates relative motion parameters to limit the maximal velocity of the subject vehicle at the next time step. The value of $V_{sbj}(t + T)$ is in case of a maximal deceleration of V_{obj} in a way, that the position of $X_{sbj}(t + kT)$ is lower than the halt position of $X_{obj}(t + kT)$. The key properties of this equation are the maximal deceleration as well as acceleration rate, speed and position of respective vehicles, the length and a desired spacing at deceleration until standstill.

Treiber's Intelligent Driver Model. The Intelligent Driver Model (IDM) is a continuous equation calculating the acceleration. It is a function of gap s, ego-velocity v and relative velocity Δv. Given the master equation, this algorithm implies different driving modes simultaneously.

$$a_{IDM}(t) = \frac{dv}{dt} = a \left[1 - \left(\frac{v}{v_0} \right)^{\delta} - \left(\frac{s^*(v, \Delta v)}{s} \right)^2 \right],$$ (3.3)

$$s^*(v, \Delta v) = s_0 + vT + \frac{v\Delta v}{2\sqrt{ab}}$$ (3.4)

According to what driving mode is present, the respective terms are cancelled out. This expression comprises the free driving strategy $\dot{v}_{free}(v) = a \left[1 - \left(\frac{v}{v_0} \right)^{\delta} \right]$ as well as a comfortable approaching strategy $\dot{v}_{brake}(s, v, \Delta v) = -a \left(\frac{s^*}{s} \right)^2$ which is significant when the actual spacing values decreases the desired safety spacing $s^*(v, \Delta v)$ (Treiber, Hennecke, and Helbing 2000).

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Free driving is dominated by the desired speedv_0, the maximum acceleration a and the sensitivity exponent δ that controls the acceleration in an approach mode. s_0 is the minimum spacing value that is relevant for low speed profiles and dictates the effective minimum gap s^*. Further, the velocity dependent spacing is combined of the subject speed v, the desired time gap T and a dynamic component that is triggered in non-stationary traffic conditions where $\Delta v \neq 0$. The latter component decides about the magnitude of the deceleration, which is no less than b in normal situations and becomes significantly lower than b in critical situations.

3.3.2. *Lane Change Models*

Lane change models are besides the CFM the second crucial descriptive method for reproducing real traffic phenomena. Generally, the lane change procedure can be decomposed in two phases: (i) motivation phase and (ii) execution phase. In phase (i), the motivation for lane change is evaluated. Provided that the decision-making for a lane change is given, phase (ii) is initiated. The main problem of lane changes occurs when it is rejected due to insufficient gap in the adjacent lane, which is called *gap problem.* In the execution phase, the feasibility of a lane change is examined in line with a preset safety criteria. Only if both phases have positive outcomes, a lane change is actually conducted. According to (Ros, Martinez, and Ruiz 2014), the two most popular domains are rule-based (RB) models and discrete choice-based (DCB) models.

Rule-based lane change. As the term is stating, there is a rule set that lists the reasons for lane change. An integral algorithm examines the feasibility of a lane change by considering the gap acceptance criteria. Those are based on typical motion values as

the intervehicle spacing or velocity profile. Gipps' (Gipps 1986) Gap Acceptance Model (GAM) states that driver n will change to lane i if following conditions are met:

- On the lane i exists enough space for lane change

- Driver n needs to ensure that his prospective following vehicle (upstream vehicle) s can follow him without violating safety criteria

- Driver n needs to ensure that he can follow the prospective preceding vehicle (downstream vehicle) p without violating safety criteria

The safety criteria refers to whether the decelerations to the respective preceding vehicle is feasible considering the gap between n and p and s and p at the moment of transition. The calculation for the velocity is carried out by the CFM of Gipps. While other GAM are presented in (Hidas 2005; Liu, Van Vliet, and Watling 2006), the Gipps' model is still widespread among traffic simulation.

Discrete choice-based Models. These algorithms predominantly rely on probabilistic functions for estimating specific attributes while the decision-making process. Such attributes can encompass neighborhood variables that include neighboring vehicles and their state and driver attributes such as driving style or strategy. In the second phase the feasibility of a lane change maneuver is evaluated. The core procedure is the same as the RB lane change strategies.

Among of the DCB models, MOBIL has gained broad acceptance among researchers. (A. Kesting, Treiber, and Helbing 2007) It stands for *minimizing overall braking induced by lane change* and determines the utility and the risk associated with

lane changes in terms of longitudinal traffic scenarios. The utility is derived by an incentive criterion. Hereby, the utility of changing lane is examined in accordance to the subject driver's desires. Furthermore, constraints of the safety restrictions have to be accomplished for the approval of a lane change. Specific to this GAM is the thoughtful behavior of the driver, who does not expect the prospective upstream vehicle to exceed an uncomfortable braking threshold. Moreover, the incentive criterion weighs between the subject's advantage of a lane change – measured by the increased acceleration – against the disadvantage imposed to upstream drivers – measured by their deceleration rate. A politeness factor p can control the decision-making egoistically or altruistically. Another unique property of MOBIL is the asymmetrical overtaking strategy that is interesting for specific traffic rules as the "keep-right" directive.

3.3.3. Discussion

In this section, a few approaches of linear and non-linear car following models are presented. The stimulus-response models encompass the models of Chandler (Chandler, Herman, and Montroll 1958), of GM (Chakroborty and Kikuchi 1999) and of Gazis, Hermann, Rothery et al. (Rothery 1992), where the driver's reaction is assumed to be linear to the stimulus he perceives. Those models are usually simple due to linearity and vary with the incorporated parameters that can be relative speed, headway distance and relative acceleration, additionally to the common parameters response time T and sensitivity coefficient λ. The IDM of Treiber is a special case of those algorithms, as it implies several driving modes in one equation. This model considers the decrease in acceleration rate as more and more a vehicle approaches its predecessor. Interesting is the fact that this is partially achieved through a "comfortable" brake that is desirable for

human drivers. There exist more domains of CFM as the safe distance models of Kometake and Sasaki (Koetani and Sasaki 1959) or Gipp's Model(Gipps 1981) where the drivers have the safe spacing as a desired reference state. Wiedemann's model belong to the field of psychophysical models, where thresholds represent different perception modes of the driver provoking defined reactions. The Nagel and Schereckenberg's cell-based model encompasses space-discrete framework, where the space is sliced into an equidistant set of cells and the vehicles are able to occupy those cells.

As for the modeling of vehicle formations, the CFM models require to reproduce realistic traffic phenomena, e.g. the "phantom" traffic jams and also are limited in complexity. The IDM and Nagel Schereckenberg's model have proven to replicate traffic flow as observed in reality. In light of dynamic systems, the space-continuous IDM benefit from the capability to determine the state of traffic at any time. While psychophysical models as Wiedemann's are also considered and implemented for research of naturalistic behavior – such as in the simulation framework VISSIM QUELLE – the disadvantages are the many threshold parameters that require proper calibration. In contrary, the IDM manage with rather few parameters to reproduce different driving behavior. This model was previously applied for imitating adaptive cruise control (ACC) system behavior (B. A. Kesting, Treiber, and Helbing 2000). Considering that vehicles to date are equipped with ACC and the first generations of automated platoons will enhance existing system behaviors of driver assistance systems, it is reasonable to resort to CFM that inheres system behavior. While IDM provides flexibility and realistic behavior, caution should be exercised on account of its collision-

free property. When applying the IDM algorithm, rear-crash are not existent since the deceleration get as high as necessary to avoid collision which is not a realistic representation of the physical braking process. Also, a foreign vehicle merging into the same lane as the subject vehicle with a small gap can cause overreaction in deceleration which is not a satisfying replication of the human behavior, as it is assumed that an abrupt braking of the preceding vehicle is unlikely. Those aspects need to be taken into consideration when developing a simulation framework based on IDM. In (B. A. Kesting, Treiber, and Helbing 2000), adequate manipulation of the IDM algorithm is proposed to eliminate the undesired system bias to approach a more naturalistic driving behavior.

In recent related works, the trend of IDM as underlying CFM is recognizable. The growing popularity is owed to its simplistic, yet realistic model. The number of design parameters is straightforward and it better replicates the human behavior of taking the time gap as a basis for spacing unlike the Gipps model whose gap choice is based on maintaining a collision free constraint. Although models of Wiedemann incorporate more complex human behavior, the IDM presents a practical solution for both usability and accuracy. Its subsidiary developed lane change model MOBIL fulfills the advantages. It has an altruistic parameter that balances between a subject driver's utility of lane change against the imposition of a hard brake of the upstream traffic. The IDM is also used to imitate systematic behavior, e.g. the ACC. The restriction of IDM is the collision-free property. Not only is this property improper for investigating safety relevant scenarios, but also causes unrealistic behavior when other neighboring vehicles change lane in front of the subject car. When the initial spacing of the new preceding

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vehicle is small, the braking response of the subject driver is affected disproportionately. Modifications are inevitable for respective use cases. A solution is proposed in (B. A. Kesting, Treiber, and Helbing 2000), (Liebner et al. 2013).

3.4. Agent-based Modeling in Traffic Simulation

3.4.1. *Agent Technology*

The agent technology is growing rapidly in many fields of research and applications such as manufacturing, real-time control systems or ITS. The agent technology yields a high performance when used on large-scale problems with dynamic uncertainties. Similar to the divide and conquer algorithms in the computer science, the decomposition of problem domains and distributing it on agents is the underlying paradigm of this modeling approach. According to Adler, there are three properties suitable for ABM:

- The problem domain is distributed geographically

- The problem domain and its subsystems are in a dynamic environment

- The subsystems need to interact

Considering those requirements, there is a consensus among researchers that the domain of traffic systems is appropriate for agent-based applications. That is because the vision of automated driving shows consistent coherence with the paradigm of agent technology. The fastest path to set up an autonomous driving environment is the availability of every subsystems' information that is subject to the traffic. This includes motion and status quantities of other road users and the utilization of roads and highways.

The sharing and exchanging is enabled by the Vehicle-2-X technology that will be an integral part of future automobiles. It is worth mentioning that the pure exchange of existing data is not the sole reason for the upcoming generation of collaborative driving. The immense data found inside and outside of vehicles enables to predict the intentions of drivers. Many researchers are currently working on mathematical models that allow predicting likely actions and the intent of each driver, based on the behavior of driving the car. Sharing those knowledge about each traffic participant elevates the possibilities in intelligent coordination of the traffic that was not possible before.

3.4.2. Theoretical Basis of Agent Technology

Definitions of agents are slightly diverging and not unified in the literature. Prominent researchers in this field are Wooldridge and Jennings (Michael Wooldridge n.d.) who also introduced the term of agents in computer science. According to ("ker95.pdf" n.d.), an "agent is a computer system that is situated in some environment, and that is capable of autonomous action in this environment in order to meet its delegated objectives". This is a frequently used citation and basically states the existence of an agent in an environment that is in constant action and feedback interaction with entities. FIGURE 5 describes the abstract composition of an agent. It shows that an agent can perceive with sensing modules the state of the environment and make decisions according to its programmed artificial intelligence. Here, the agents' desires and goals are integrated that largely determines the decision-making. With their actions, agents can influence the state of the shared environment dynamically.
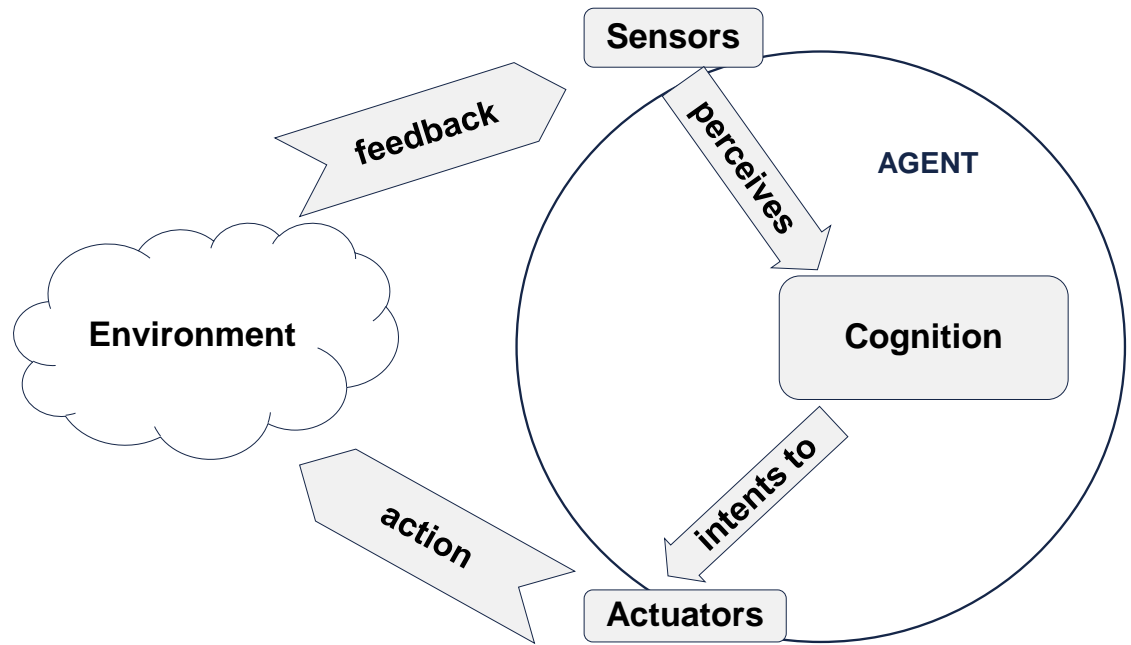
FIGURE 5 Abstract depiction of agents' interaction in the environment

Especially the cognition unit determines the uniqueness of agent behavior for the problem at hand. The perceived "intelligence" of an artificial programming object is influenced by the logical way it processes external information considering its internal rules and goals. The next paragraphs are dedicated to present some prominent approaches to describe the nature of agents.

Programming Perspective. From the programming perspective, agents are frequently regarded as autonomous entities and not seldom as a progressive variant of objects. To understand the agent technology, it is necessary to understand the object orientation (OO) paradigm. According to Odell (Odell and Consultant 2002), the OO decomposes the program into local variables and local methods that are described in classes. Objects are created based on the underlying class and the specific methods and local variables become inherent to the assigned object. Thereby, the manipulation of the

control structures gains transparency and versatility. However, the invocation of methods is processed by an external control thread. Objects require external statements and are passive structures. In contrast to objects, agents inhere self-adjusting properties, allowing them to take initiative. Not only do they have their own control structure including methods and local variables, but also self-organize their invocation. The autonomy is generated by the sum total of rules and goals that results in the rule base of the model. Besides the autonomy, the interactivity is a further integral part of agents. Communicating agents might request, send or urge other agents to communicate or invoke different actions. This act of entering into negotiations is unique to agent behavior, meaning an agent can either accept, decline or hold requests. At an ideal point, centralized control structures or top down functions become obsolete as the agents are capable of self-controlling (Parunak 1997).

	Modular programming	Object-oriented programming	Agent-based programming
How does a unit behave? (Code)	Local	Local	Local
How is the process of the unit? (State)	External	Local	Local
Unit invocation	External (call function)	External (message)	Local (rule base)

Table 3 Programming Approaches (Parunak 1997)

Reactive Agents. Rather naive approaches of developing agents are presented by Chapman (Babek Habibi n.d.) and Brooks (Brooks 1991). Classes of reactive agents are able to make decisions with little information at hand which is dominated by a simple

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internal rule set. Agents' actions are triggered depending on the current state of the environment based on if-then logic. It is argued that such reactions are natural in reality as humans act unconsciously and instantaneously in situations that require immediate response. Those agents are straightforward and do not require complex cognition modelling. On the downside, their instant reactions are not necessarily optimal. Additionally, those decisions may be conflicting with other goals of them or may be redundant when the environment state has changed. What this concept lacks is also a communication layer to realize cooperative behavior throughout the population of agents.

Deliberative Architecture. In contrast to reactive agents, deliberative agents possess explicit symbolic models of the real world. Decisions about the actions of an agent are based on logical reasoning, pattern matching and symbolic manipulation. The decision making process is referred to as "inference" (Michael Wooldridge n.d.).

One instance of deliberative agents is the BDI agent with the three mental attitudes *beliefs, desires* and *intentions* (Michael E. Bratman 1999). Decomposing the cognition of an agent into these three metal attitudes allows a more complex reasoning and decision-making. Thereby, beliefs represents the perception of a selected state of the environment and the anticipated state in the future. Desires are a set of desired states of the environment. Those can be complementary or conflicting. Intentions are the internally preferred goals that an agent pursues. For achieving its desires, an intention consists of a sequence of expedient actions to change the environment to its desired state.

3.4.3. Applications in Traffic Simulation

Traffic and Transportation Systems comprise many independently acting intelligent entities which are in constant interaction to achieve individual or global transportation goals. These include drivers, intelligent OBUs or RSUs. The distributed nature of the traffic infrastructure opens suitable ways for Multi-agent Systems (MAS) for modelling and simulation of ITS as they provide an intuitive method to describe autonomous entities of the road network. Here, each intelligent element in the traffic is modeled as an agent. They can have identical, similar or diverging goals, properties and range of actions. Furthermore, they can negotiate to prioritize actions and may have intrinsic motivation to act without external trigger. The use of MAS has been widely recognized for investigation of modelling various transportation problems including urban traffic management and control and route guidance on a macroscopic level and cooperative driving and safety applications on microscopic level. Additionally, transportation domains as railroad traffic control or airport operations are further subjects for ABM (Chen, Cheng, and Member 2010).

In the scope of public motorways, research has tackled to model the individual behavior of drivers represented by agents. The following paragraphs are dedicated for different approaches of representing traffic interaction with multi-agents.

On the **operational level**, the driver stabilizes and controls the vehicle through the immediate surroundings. The focus is the modeling and simulation of individual driver behavior. Moreover, the driver and vehicle are modelled independently to imitate real control behavior. Desired velocity, different acceleration- and deceleration behavior are

variables of interest determining the car following as well as the lane change behavior. Not seldom are the vehicle dynamics accurately modeled in a chain of control structure containing driver model, steering model, powertrain model and vehicle model.

The **tactical** level comprises guidance of vehicle through the dynamic environment of the traffic flow. In the scope of freeway driving, this involves the choice of driving lane depending on the individual foresighted driving behavior. That is, the early trajectory planning and feedback control to arrange in the traffic. The lane choice and the according acceleration or deceleration can facilitate the merging traffic. Such traffic situations are relevant when drivers aim to make turns which is the case at the entry and exit lanes on freeway or lanes with adjacent intersections on urban roads.

Simulations on **strategic level** deal with problem statements of traffic management and routing. Objective goals are reduction of road capacity and increase of traffic efficiency by reducing or avoiding congestions. The focus is in particular directed to the collective behavior in the traffic as a system and collective rerouting through navigation systems or roadside units is a favorable means to encounter those suboptimal phenomena.

4. CONCEPT OF AN INTEGRAL PLATOON MODEL

4.1. Framework of Platooning Strategy

The last chapter dealt with the descriptive methods of traffic simulations. Integral parts are the car following behavior and lane change models. There are different kind of approaches concerning the modeling of human driver capabilities and should be selected according to the relevant use case. This chapter deals with the development of a model for cooperative platoons. Presented is the framework for an integral platooning model that can be decomposed in the operative, tactical and strategic level of modeling. The chapter shows the successive composition of the entire model by picking up the boundaries of the key characteristics as shown in FIGURE 3. From a programming perspective, ABM is a reasonable approach as the vehicles can be considered as decentralized decision-makers that have settings in a shared resource (environment) and can sense the dynamically changing state of the road. They can influence the state (occupied position in road) and affect it by (re-)action by inherent methods (following, lane changing). Having the agents (vehicles) communicate individual properties and dynamic states elevates the coordination capacity and makes the movement of the global system more efficient. Projecting it to the real world, communicating agents are soon to become a feasible technology through the equipment of Vehicles with V2X communication hardware and the advanced technology of VANET. Furthermore, the data-rich environment on the traffic will communicate drivers' intention such as desired speed or destination not only to local vehicles, but to a network of surrounding vehicles and traffic objects. These prospective technical intelligence will propel safety and coordination in ITS. One vital assistance system will be the automated platooning

function. Before tackling the model architecture, essential questions of the model boundaries need to be resolved. For this purpose, the framework for cooperative driving systems is once again utilized FIGURE 3.

Environment modeling. In the scope of this work, the road setting is assumed to be a public highway. At first, the roadway arrangement needs to be clarified. In a real life setting, curves may be relevant for the platoon stabilization when the curvature bend is significantly high. In that case, an automated lateral control becomes mandatory as the trajectory during the curvature determines the travelled path. A lead vehicle driving on the outside of curve may be closed in by a follower who cuts the corner on account of the difference in travelled distance. The lanes are therefore assumed straight at any time, so that curvatures are neglected.

Furthermore, the types of traffic objects should be defined a-priori. Automated platooning is a function that is supposed to be available location-independent, meaning its functionality is not controlled or managed by any RSUs. Although SARTRE has proposed a platooning concept via V2I where the RSUs are called "back offices" assisting to couple non-platoon vehicles with platoons, those back offices still remain as supporting devices. The pivotal data communication is handled by the V2V protocol. Other traffic entities as signal lights are not subject to the work. Thus, vehicles are the only class of traffic objects considered.

Highway exits as well as narrowing or enlarging lanes are boundary cases between two static lane numbers in the simulation environment. This work assumes a constant total of lanes and dynamical changes are omitted. Lastly, the simulation framework needs to

be addressed. Since the car-following or lane changes are highly dynamic maneuvers, appropriate resolutions of time and space are required. The developed program is space continuous and time-discrete. The delta of time is adjustable, so sudden changes of the vehicle state can be approximated without having the necessity to calculate continuously.

Communication modeling. Possible properties of modeling communication is the utilized protocol, the data size transmitted, latency, emulated signal distortion, data-loss by default, propagation physics and class of communication. In reality, the V2X communication will not only share vehicle-internal data, but also data about remotely sensed environmental data or infotainment-related data. A prioritization is in that case expected. While there is a significant amount of research about modeling the propagation of communication signals, it is not the focus of this work. Here, different classes of transmitted data are neglected and information are assumed to be exchanges under any circumstance.

Decision making. This unit can be described as the cognition module of an autonomous agent. It has a reactive structure, meaning that the agent triggers a preset action on certain stimuli. In that case, the following driver does not evaluate his option but rather decides target-oriented. In a deliberative structure, agents are more proactive by nature and act upon intrinsic motivation, meaning an external stimulus is not necessary. This might be the negotiation process when a single driver strives to join a platoon. The decision making processes are different in the layer architecture of platooning, This will be explained in greater detail in later sections.

Formation techniques. The fundamental formation technique is the appropriate spacing which marks the steady state of a platoon. In more sophisticated platooning, the joining operation is feasible not only by closing in from the rears, but also merging laterally from a neighboring lane. Higher level formation techniques allow also sub-platoons to join or leave a larger platoon. At the same time, those operations are not feasible with conventional vehicle local perception as those do not provide sufficient robustness. The aid of IVC is a mandatory prerequisite for cooperative maneuvers. In this work, the focus is to develop a strategy for synchronization of the longitudinal control. Approaches of a merging strategy into platoons is not further considered in this thesis.

Vehicle properties. Vehicles are simulated as microscopic models, meaning rigid bodies are assumed. Interaction of driver and components of vehicles like power transmissions and drive trains are considered as a unified system, thus driver intentions are directly translated into the desired motion. Imperfect throttle control or latency between driver input and powertrain response are not modelled.

The population of vehicle types are considered heterogeneous. In real traffic, vehicle have different weights and engine performances influencing the overall capacity of acceleration and deceleration. In addition, due to the individuality of each driver, they will consequently have differing desired velocities. Also, the driving experience influences what the driver conceives as a "safe" headway distance.

Under these premises, the framework of the platoon strategy are explained in the following section. Some of the model characteristics are distinguished depending on which control layer is applied.

The aim of the work is to present a framework for a cooperative platooning system that considers the heterogeneous physical properties of vehicles and the mixed equipment ratio of V2V communication devices. The design of the framework is strictly hierarchical and consists of three layers (see FIGURE 6): vehicle local layer, platoon layer, global layer. The bottom layer utilizes more reactive behavior of agents while the top layer comprises of more deliberative agent behavior.
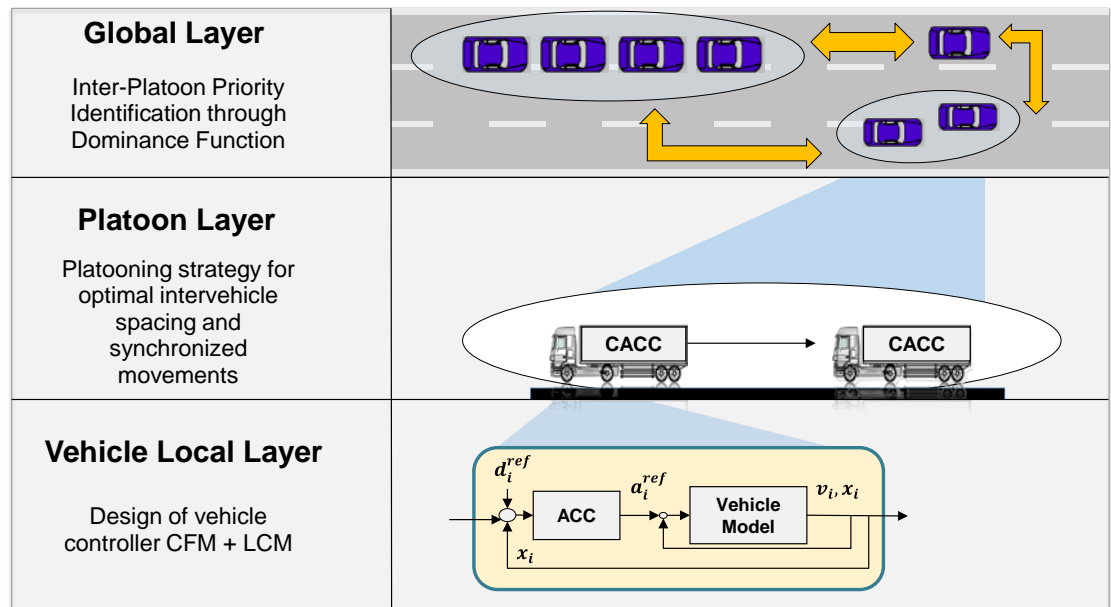

FIGURE 6 Layer Architecture of Cooperative Platoons

4.2. Vehicle Local Layer

In the most bottom layer, the controller of the vehicle is implemented. As mentioned before, the driver and vehicle are subsumed to one integral unit where the sensing processing and actuation are carried out.

As discussed in 3.3. the driver behavior is determined by the implied model characteristics. The types of model can be either approached to naturalistic human behavior, in which case the time for reaction, decision-making and neuro-motoric action needs to be implemented. Moreover, a human driver seeks to apply throttle and braking smoothly to experience a comfortable drive. Machine-driven models on the other hand can replace the driver module in the decision making process. ACC and CC are types of controllers that calculate the appropriate acceleration to any time to ensure the targets of the driver. In this work, the target is to sound out an appropriate model to attain synchronized driving. As the platooning function shall overtake the control from the human, it is necessary to include machine-driven behavior that reproduces the motion profile of this longitudinal ADAS.

From the algorithm perspective, the CFM are utilized for the calculation of dynamic states of the vehicle i, that is the position $x_i(t)$, the speed $\dot{x}_i(t)$ and the acceleration $\ddot{x}_i(t)$ at each moment $t \in T$ with T as the simulation time horizon. Most CFMs – including IDM - are explicitly determining the acceleration whereas the speed and position is subject to numerical integration in a time discrete simulation framework. The block diagram can be generally expressed as FIGURE 7.
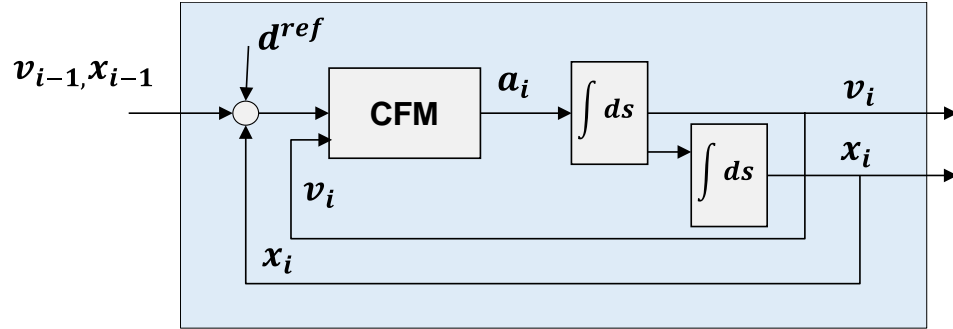
FIGURE 7 Block Diagram of a general algorithm for calculating vehicle dynamics

The general algorithm for vehicle dynamics is a non-linear feedback loop where the driver-vehicle unit is expressed as the CFM in the block diagram. It is fed on the one hand with the external stimuli from the lead vehicle and on the other hand with the control quantities from the loop. The CFM block is the gain function determining the throttle or acceleration and two integrations calculate the respective velocity and position to the iteration. Control quantities are the gap between the subject and object vehicle as well as each velocity to calculate the instantaneous acceleration.

The numerical integration of velocity and position are shown below:

$$\dot{x}(t + dt) = \max(\dot{x}(t) + \ddot{x}(t)dt, 0) \tag{4.1}$$

$$x(t + dt) = x(t) + \dot{x}(t)dt + \frac{1}{2}\ddot{x}(t)dt^2 \tag{4.2}$$

The max function for the equation of speed ensures that the vehicle is prevented from driving backwards.

4.2.1. Longitudinal Controller – Gipps' Model

For the human-driven behavior, it is appropriate to find a model consisting of model parameters that corresponds to human characteristics, including reaction time. Gipps' non-linear CFM seems to yield a solid performance for human driving characteristics as it is used in several simulation packages (e.g. AIMSUN, SUMO). Additionally, the physiological aspect of reaction time is expressed explicitly.

Parameter for Gipps CFM	
A_i	Maximal acceleration of vehicle i
B_i	Maximal deceleration of vehicle i
S_{n-1}	Desirable gap between i and $i-1$ at standstill
$V_i(t)$	Instantaneous velocity of vehicle i at time t
V_i^0	Desired velocity of vehicle i
T	Reaction time of the driver to take action
$X_i(t)$	Position of vehicle i at time t
X_i	Estimated position when applied full brake

It is notable to mention that the controllers' input variables are the speed of the own car and the preceding car and the gap between two cars. All other parameters are considered static throughout the simulation. The identification of the instantaneous acceleration is largely determined by the velocity and the maximal deceleration performance of the car ahead. In contrast to the many other CFM, the model of Gipps does not determine the acceleration A_i but rather explicitly the maximal velocity at time $t + T$ that the vehicle V_i can attain. $V_i(t + T)$ is subject to two constraints. The first capacity constraint that dictates the maximal attainable speed in the next iteration is based on the non-linear gain of the maximal acceleration capability of the vehicle A_i. By this means, the function $V_i^{max}(t)$ is calculated as:

$$V_i^{max}(t+T) = V_i(t) + 2.5A_iT(1 - \frac{V_i(t)}{V_i^0})\sqrt{0.025 + \frac{V_i(t)}{V_i^0}} \tag{4.3}$$

Where V^0 denotes the desired speed. The constants 0.025 and 2.5 are model parameters to imitate the reaction time and to approximate naturalistic. The second constraint is the downstream vehicle $V_{i-1}(t)$ where vehicle i is directly influenced by his preceding vehicle to avoid collisions. In this case $V_i(t+T)$ is chosen so that V_i can stop at a safety distance S_{n-1} given that the downstream vehicle applies full brake. The position of the downstream vehicle is in that instance computed as follows:

$$X_{i-1} = X_{i-1}(t) - \frac{V_{i-1}^2(t)}{2B_{i-1}^*} \tag{4.4}$$

Here, the star at B_{i-1}^* denotes the estimated braking capability as the following vehicle has no knowledge about the vehicle specification of other road users. Coupled with the halt position of X_i and given that this value must fulfill $X_i \leq X_{i-1} - S_{i-1}$, then the following speed $V_i^{pre}(t+T)$ subject to a preceding car is given by

$$\begin{aligned}&V_i^{pre}(t+T)\\ &= B_iT * \sqrt{B_i^2T^2 - B_i[2[X_{i-1}(t) - X_i(t) - S_{i-1}] - V_i(t)T - \frac{V_{i-1}^2}{B_{i-1}^*}}\end{aligned} \tag{4.5}$$

Both velocity equations 4.x and 4.x combined, the safety following speed for the vehicle is computed by the equation 4.x

$$V_i(t+T) = \min(V_i^{pre}, V_i^{max}) \tag{4.6}$$

4.2.2. *Longitudinal Control – IDM*

In light of machine-like behavior, the IDM poses a practical solution. Although its original intention is to approach human driving behavior, the algorithm provides ideal approaching and braking that is hard to attain for humans. Therefore, it is well suited for ACC like longitudinal control. The equation (2.3) and (2.4) are already mentioned in Section 3.3.The summary of the model parameters are shown below

Parameters of the IDM	
a	Maximal acceleration
b	desired deceleration
T	Desired time gap
s	Headway distance
s_0	Jam distance
v_0	Desired velocity
δ	Free acceleration exponent
c	Coolness factor

The determining control feedback inputs are the own velocity, gap and the relative velocity respective to the downstream traffic. What is unique about this approach is that it has a collision free property, meaning the deceleration gets high as necessary to avoid a collision. Those high values have no practical meaning as they are beyond the physical capability of a vehicle. However, as the normal highway is characterized by steady-state flow of the traffic, emergency situations are treated as exceptions and can be ignored for certain studies. Yet, negative effects are observed when a neighboring vehicle cut the lane in front of the subject car. In this instance, a new preceding vehicle appears with gaps significantly lower than the desired spacing and little velocity difference Δv. As a result, the subject car initiates unrealistically high braking whereas the human driver ordinarily relies on the fact that vehicles will not apply emergency brakes without apparent reasons and classifies the situation as mildly critical (D. A. Kesting 2008).

To suppress a brake overreaction, the model needs appropriate modification so that the driver is able to distinguish between a moderate and severe critical situation. Kesting (B. A. Kesting, Treiber, and Helbing 2000) proposes a constant acceleration heuristic (CAH) to give the driver this additional decision unit. The premises of CAH are as follows:

- The acceleration of the lead vehicle will not change abruptly for a few seconds

- Time gap and minimum spacing are neglected during this period

- Drivers reaction time is assumed to be zero (no delay)

In order to maintain a crash-free condition, one needs to judge whether the relative speed to each other is at an equilibrium when the minimum gap s is reached. With respect to the values of headway, speed, velocity and acceleration of the preceding vehicle v_l and a_l, the computed acceleration a_{CAH} is defined as:

$$a_{CAH}(s, v, v_l, a_l) = \begin{cases} \dfrac{v^2 \tilde{a}_l}{v_l^2 - 2s\tilde{a}_l} & if \ v_l \Delta v \leq -2s\tilde{a}_l \\ \tilde{a}_l - \dfrac{(v - v_l)^2 \Theta(v - v_l)}{2s} & otherwise \end{cases} \quad (4.7)$$

$\tilde{a}_l$ is the effective acceleration $\tilde{a}_l = \min(a_l, a)$ to prevent the following car to drive above its physical limits provided that the lead vehicle has higher acceleration performance. Negative approaching rates are considered not to be critical so the Heaviside function eliminates the last term of the second case.

The distinction when to activate the a_{CAH} and the a_{IDM} is given by an expected lane change into the same lane ahead. Vehicles performing a lane change will automatically communicate their intentions and this will be the switch for the acceleration strategy.

4.2.3. Lane Change Model - Mobil

Based on the assessment of criticality of the local traffic simulation, the MOBIL LCM computes the decision for changing the lane. Essential for the assessment are the positions of the neighboring vehicle as depicted in FIGURE 8.
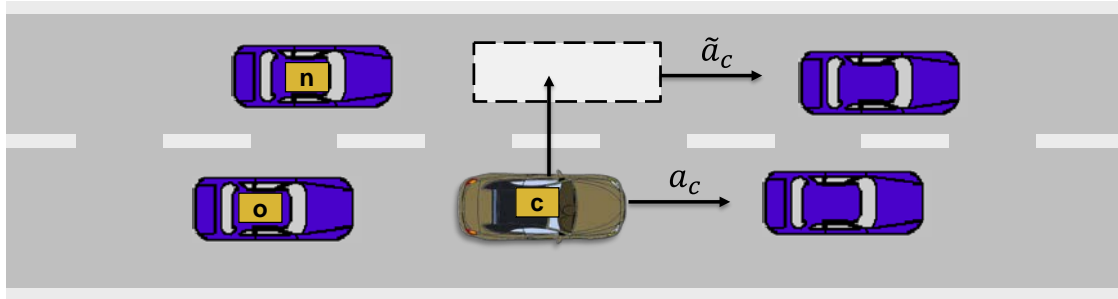

FIGURE 8 Considered lane changing maneuver by vehicle c

For an instance of lane change, vehicles on the current and target lanes are considered inputs to the LCM. Vehicle c is the subject vehicle considering a lane change to the target lane. The upstream vehicles both in current and target lanes are denoted o and n respectively. Inputs to the model are further accelerations of all relevant vehicles before the lane change and after the lane change. Before the lane change, the denotations are a_c, a_n and a_o whereas the updated acceleration after the lane change are $\tilde{a}_c, \tilde{a}_n$ and $\tilde{a}_o$.

Two criteria are given to actually perform an instantaneous lane change, namely (i) the safety criterion is fulfilled and (ii) the incentive for a lane change is above the

threshold. The safety criterion refers to the imposed deceleration $\tilde{a}_n$ of the upstream vehicle n after the subject vehicle c has performed a lane change to the target lane.

$$\tilde{a}_n > -b_{save} \tag{4.8}$$

The acceleration of n is then influenced by the difference of velocity between n and c, as the algorithm of IDM is largely determined by relative speed between the lead and following vehicle. In particular, larger gaps are required when the velocity of n is significantly higher than the potential lead vehicle c. In the same manner, if the relative velocity is small the model is more likely to accept a lane changing decision. In contrast to other gap acceptance models, MOBIL rather evaluates the dependency of the acceleration among the relevant participants leading to concise model formulation and more humanistic behavior. Respect for the upstream vehicle ensures that the potential new follower n does not have to apply full brake. Therefore, the condition of $b_{safe} < b_{max}$ should hold any time, which is roughly $9\ \frac{m}{s^2}$ on dry roads. In other words, the lane change will induce a braking reaction of the follower in the target that is never higher than b_{safe}.

Given the safety criterion, performing a lane change will not endanger the subject vehicle or surrounding vehicles. The need of a lane change is, however, not apparent. The incentive criterion ensures that an improvement of the situation will take effect. The key figure for improvement is the desired acceleration that can be approached or fully achieved by leaving the current lane. An interesting option for the MOBIL algorithm is that the improvement involves surrounding vehicles as well. The degree of respect of neighbors is determined by the politeness factor p. Assumed is a traffic with no directive

to hold on right lane, so that there is no difference in effect when changing to the left or right lane. The incentive criterion is expressed as follows:

$$\tilde{a}_c - a_c + p(\tilde{a}_n - a_n + \tilde{a}_o - a_o) > \Delta a_{thr} \qquad (4.9)$$

The first term represents the utility of the subject driver with the new acceleration $\tilde{a}_c$. Subtracting the current acceleration a_c may either result in a gain or loss of acceleration. Likewise, the local acceleration of the following cars both in the current lane and target lane vary before and after lane change. The extent to which the driver has respect to the utility of the two immediate upstream vehicles is controlled by the weight of the politeness factor. On the right hand side, a switch threshold is introduced to prevent "lane-hopping", meaning a frequent change of lanes due to marginal improvements. In summary, when the subject vehicle's acceleration gain is significantly higher than the weighted acceleration increase and loss of other vehicles, a lane change is favorable and is initiated. Note that the switch threshold Δa_{thr} affects the global behavior of lane-changes while the politeness factor is a specific property of the individual driver.

What makes the model interesting is the changing behaviors which are observable in similar forms in the real traffic. Adjusting the model parameter p result from altruistic to egoistic driving strategy. $p = 0$ neglects entirely the benefits of surrounding vehicles while p>1 equates or give priority to the advantages of adjacent vehicles compared with the local utility.

4.2.4. Discussion

The presented CFM and LCM are subject to implementation in the work at hand. The motivation for the choice of two models of car following behavior is due to the approximate nature of all CFM. The general underlying assumption of prominent linear CFM is that the driver follows a deterministic action when encountering a specific stimulus. Each model will naturally have diverging deterministic model parameters to imitate different driving modes. Gipps Model includes the fact that imperfect estimation capabilities of the driver are accepted. Empirically collected data are used to derive the latency in reaction. While empirical data is not biased with artefacts, it has limited justification for developing a global CFM since the behavior of drivers vary according to the specific driving environment and situation. On this account, another model is considered. Free-driving, approaching a lead car and braking strategies are subject to the IDM. What both models have in common is the headway distance and the own velocity as feedback inputs. The IDM uses moreover the relative speed to the traffic ahead. This is an important aspect because the acceleration strategy is not only a function of its own speed but also of the velocity difference. Shortcoming of the IDM is the collision free property that avoids crashes even in the worst case. Later in this chapter, both advantages of the models are combined to realize cooperative maneuvers.

The lane changing model MOBIL does well in imitating the decision-making process. Unlike gap acceptance models that merely assess the acceptable gap between two neighboring vehicles, MOBIL evaluates the gain or loss of acceleration of all involved vehicles in the lane change. The accepted gap varies depending on the speed therefore needs adjustment and extensions of the basic model. MOBIL incorporates

both safety and incentive criteria in two equations, making it powerful relative to its conciseness. This model is appropriate to model variability of the driver which is inherent to agent structures.

Note that the MOBIL is a decision-making model and not a lateral controller. In an analysis of longitudinal highway simulation, the lateral control is simplified as the intra-lane control, that is, the variance of the lane center is not affecting the stability of a platoon. In most cases, it is acceptable to consider lane changes as discrete events.

4.3. Platoon Layer

In the previous section, the longitudinal controllers to realize platoon formations have been explained. In this section, the control strategies of conceptual platoons are presented. As discussed in 2.3, platoons may occur in multitude of configurations. A platoon consisting of merely human drivers emerge naturally on highways, but they are highly instable because of the heterogeneous spacing strategies and latency in reaction to changing velocity of the downstream traffic. Coordinated driving is feasible with current remote sensors. The degree of synchronization grows with advanced telematics modules. Two possible control strategies of platoons are depicted in FIGURE 9.
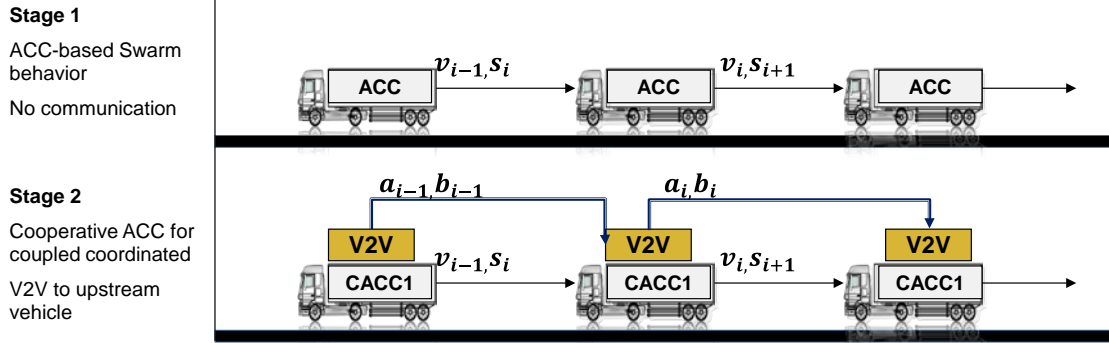
v_{i-1}, s_i ACC v_i, s_{i+1} ACC

ACC

a_{i-1}, b_{i-1} a_i, b_i

V2V   V2V   V2V

CACC1 v_{i-1}, s_i CACC1 v_i, s_{i+1} CACC1

FIGURE 9 Stages of Control Strategies for Platooning.

ACC-based Swarm Behavior. This degree of coordination is possible with ACC
equipped vehicles. It is a naïve swarm behavior that take the necessary information from
the remote local sensors and is processed by the OBUs. From the modeling perspective,
this behavior is already implied in various CFM. The control input quantities are the
headway distance of the preceding vehicle relative to the following car s_i and the
velocity of upstream vehicle v_{i-1} and the own velocity v_i. The IDM uses these very
quantities to derive the instantaneous acceleration in the iteration. The availability of
those information is ensured by the local sensors. As the model formulation of the IDM
is deterministic, the reaction of the model to dynamic changes ahead are processed
immediately. By this means, the IDM fulfills the machine-like control of an ACC-based
system. Limits of this swarm platooning is that there is no means to transmit the desired
spacing of individual participants within the platoon. As a consequence, the
intervehicular gap will show inconsistency. Cautious drivers are likely to set the desired
gap as high as possible due safety concerns when in reality, a shorter gap still fulfills
the minimal safety criteria. Another effect is that the preset spacing of ACC controllers
are robust against sudden emergency brakes. The information of the braking capability

for the control relevant object (=lead vehicle) is not available. Although modern radar sensors coupled with camera detection are able to classify the vehicle types such as heavy duty trucks or passenger cars, the weight of a vehicle cannot be reliably estimated by visual information. However, the inertia due to the weight plays a vital role for the actual braking performance. In light of this fact, the spacing strategy should be vehicle-dependent rather than to assume the same spacing for any downstream traffic. Due to pessimistic attitude of drivers towards short spacing settings on the one hand and the constant spacing strategy preset by the ACC on the other hand, the overall efficiency and safety may not be ensured. These negative effects are tackled with the aid of IVC in following stages.

Coupled Coordination. In this stage, the coordination is achieved through vehicular communication that will be a mandatory prerequisite for any participating platoon members. Additionally to the data conveyed in the first stage, two immediate successive vehicles are coupled for a unidirectional message transmit. Here, the preceding vehicle transmit its vehicle local properties to its follower. By obtaining the maximal feasible acceleration and deceleration capabilities, the following vehicle can adapt its spacing, braking or throttling intentions accordingly. In terms of modeling, the required information are the respective parameters a_{i-1} and b_{i-1}. Although these parameters are handled as subject properties into the model of IDM, those of the lead vehicle are not taken into consideration. On the contrary, the Gipps following model does consider the braking performance of the control relevant object. Gipps determines the halt position X_{i-1} of the vehicle ahead with the equation (4.4). In this term, the braking performance of vehicle $i-1$ is estimated through the human driver. In the

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coupled coordination, B_{i-1}^* becomes deterministic and the equation can be modified as shown in (4.10)

$$X^{IVC}{}_{i-1} = X_{i-1}(t) - \frac{V_{i-1}^2(t)}{2B_{i-1}^{IVC}} \tag{4.10}$$

Where B_{i-1}^{IVC} is the transmitted quantity for the brake performance of the control relevant object. Therefore, the halt position $X^{IVC}{}_{i-1}$ is also not an uncertainty anymore, leading to the modified car-following equation (4.11)

$$V_i^{IVC}(t+T)$$

$$= B_i T * \sqrt{B_i^2 T^2 - B_i[2[X^{IVC}{}_{i-1}(t) - X_i(t) - S_{i-1}] - V_i(t)T - \frac{V_{i-1}^2}{B_{i-1}^{IVC}}} \tag{4.11}$$

Note that $V_i^{IVC}(t+T)$ is a control strategy in the presence of a leading vehicle to assure the minimal acceptable distance to avoid a collision when the lead vehicle initiates the emergency brake. The renewed Gipps' model becomes adaptive with regard to the preceding vehicle's braking capability. By this means, the model is robust against variability of properties in the traffic and ensures a collision-free spacing that is in contrast to the IDM's collision-free property physically feasible (Note that IDM imposes unrealistically high deceleration as necessary to avoid collision).

In order to incorporate the new control strategies, the combination of both models is proposed to present the *Cooperative Platoon Model (CPM).* Equation (4.12) represents the CPM that ensures a minimal safety gap and rapid responses to changes in preceding motion profiles. Note that the CAH is applied when a neighboring emerges

on the current lane with a small headway distance. The critical situation is given when the emerged lead vehicle is below the target time gap $T_{current} < T$.

$$a_{CPM} = \begin{cases} a_{CAH(s,v,v_l,a_l)} & if \ T_{current} < T \\ \min\{a_{IDM}(v_i, s_i, v_{i-1}), V_i^{IVC}(t+T)\} & otherwise \end{cases} \quad (4.12)$$

The proposed CPM model's performance will be implemented and first validation of the performance will be given.

4.4. Global Layer

The global layer coordinates the emergence of group formations and the coordination between platoons. The vital condition for engaging into a platoon is the shared goal. Vehicles with similar velocity profiles are prone to form a platoon. In doing so, the coordination strives for individual vehicles or platoons not to block higher-speed platoons.

In light of these observations, it is desirable to form a platoon with vehicles that share similar acceleration profiles and desired speed that allows a more synchronized motion profile. A practical criterion to form platoons is dissimilarity algorithm as proposed by the group oriented driving techniques of Goermer. (J. Görmer and Jörg 2013) The observed properties for similarity are maximal acceleration, maximal deceleration and desired speed. These vehicle internal parameters can be requested when a vehicle approaches another car within the communication range. Running the dissimilarity function as described in 2.4.3 evaluates the qualification for both vehicles to form a platoon. If the criteria is met, the control is passed to the platoon layer and then further to the vehicle local layer. Provided that the forming criteria are not met,

vehicles proceed to follow their own desired speed. This procedure is subsumed in a behavioral rule set that any vehicle in the traffic obeys. The rule set is depicted in FIGURE 10.
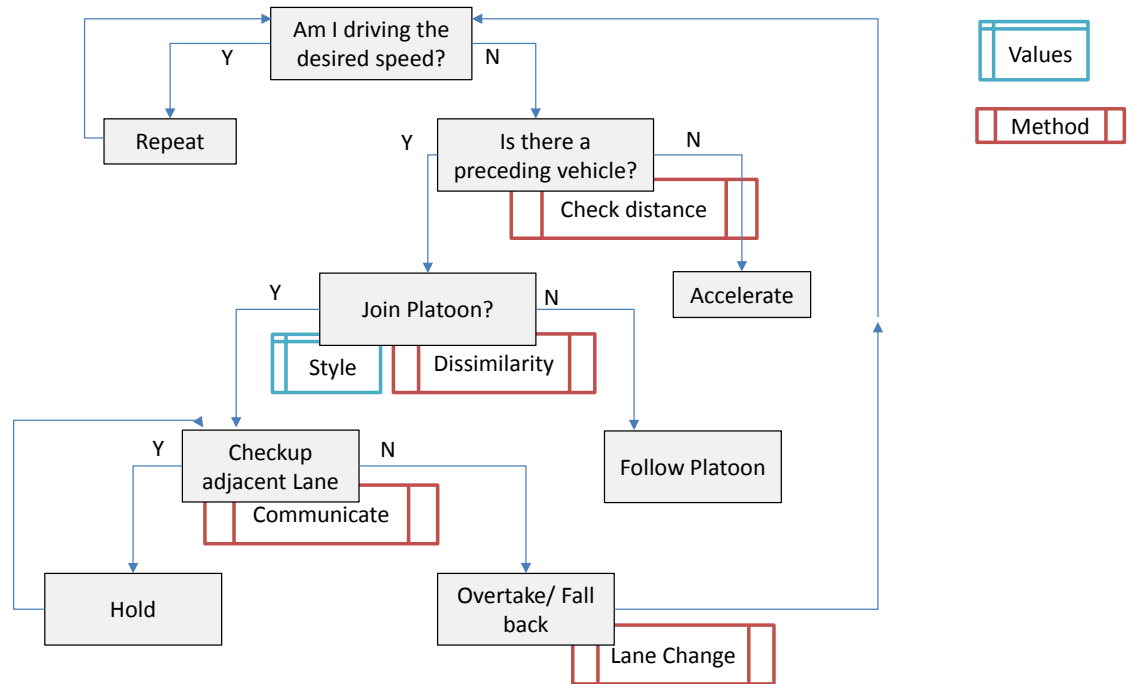

FIGURE 10 Behavioral rule set for the global layer

The possible scenarios of platooning can be various and complex. A clear guideline and boundaries need to be developed for feasible joining and detaching from the platoon, as well as the individual behavior of single cars. Therefore, developing a behavioral rule set for forming, joining or leaving a platoon is not the objective of this thesis. This section shall clarify the interaction of the layers.

5. DEVELOPMENT AND IMPLEMENTATION OF THE MICROSCOPIC SIMULATION

In the previous chapter, a general framework for platooning strategy has been presented. Thereby, the aptitude of Gipps Model and IDM has been discussed. For cooperative driving strategies, both models have components that are suitable for incorporating received data via IVC communication. On this account, a new model is proposed that dispose of advantageous properties of both models. The effect of this model, however, needs to be validated through an empirical study. Those can be generally carried out on available simulation packages that are discussed in 3.2 but they are limited in the modularity for implementing new models or they are cost-intensive. Besides, not every package offer the possibility to represent the vehicles as interactive agents. Against this background, a major contribution to this work is the development of the simulation framework in Python 2.7. Subject to the simulation framework is the modeling of vehicular agents that inhere properties and methods that are specific to those agents.

5.1. Development of the Microscopic Simulation

As discussed in 3.4 ABM is suited for problems that consist of many subsystems interacting in a dynamic environment. Vehicles are an optimal instance of agents as they can represent subsystems in a dynamic environment (traffic) where other agents (other road user) are sharing the same resource (lanes) and the interaction of each other (e.g. following or overtaking) changes the state of the environment constantly (position in road occupied). In light of these observations, it is only intuitive to resort to object-orientated programming language. Hereinafter, the composition of the simulation

framework is presented. The detailed explanation focuses on the classes FIGURE 11 and is followed by the procedure of the simulation execution.
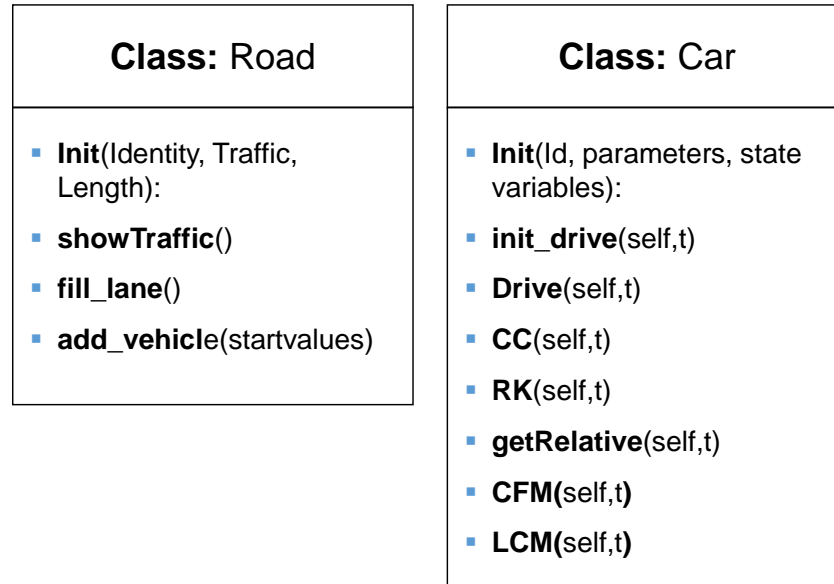
Class: Road	**Class:** Car
▪ **Init**(Identity, Traffic, Length): ▪ **showTraffic**() ▪ **fill_lane**() ▪ **add_vehicle**(startvalues)	▪ **Init**(Id, parameters, state variables): ▪ **init_drive**(self,t) ▪ **Drive**(self,t) ▪ **CC**(self,t) ▪ **RK**(self,t) ▪ **getRelative**(self,t) ▪ **CFM(**self,t**)** ▪ **LCM(**self,t**)**

FIGURE 11 Description of Classes in the Microscopic Simulation

The simulation environment hast two classes: Road and Car. The Road class serves for creating lane objects. A lane object has the property identity, traffic, and length that are constructed with the *init*-method. Identity is a consecutive number and length determines the total distance of the lane, whereas the Traffic is an empty array. The traffic-array is reserved for object instances for vehicles that are located in the assigned lane. With the method *showTraffic*, the current vehicle agents in the respective lanes can be returned so that one is able to determine at any time which specific vehicle is driving in which lane. *Fill_lane* executes a loop to create vehicle objects by invoking *add_vehicle* and passing start values for the class Car. The advantage is that creating a lane object automatically calls the *fill_lane*-method. Thereby, vehicles are instantly associated with the created lanes.

The blueprint for a vehicle is defined in the class Car. Beside its ID number, the state variables position x, velocity $\dot{x}$ and acceleration $\ddot{x}$ are declared that are one-dimensional arrays with the length of the simulation run time. Further related state variables specific to each vehicle agents are headway distance s, relative velocity to predecessor $vrel$, time gap to predecessor tg and the time gap change rate $tgRate$. Depending on the CFM, the model parameters are introduced that allows intervehicle variability to describe different type of drivers or vehicle capabilities. The main method is *drive* where the CFM is invoked and the state variables are updated. Detailed comments to the methods and sub methods are to be found in the following call-function.

Code 1 Simulation Call

```
init()      # Initialize Simulation variables
l1 = Road(1,3,60) # Create lane object with ID 1, create three vehicle
object inside and lead vehicle with CC at 60 kph
l2 = Road(2,3,80) # Create lane object with ID 2, create three vehicle
object inside and lead vehicle with CC at 90 kph
for t in xrange(len(timesteps)):# Simulation loop with running time
'timesteps'
  if t<skip:
    for vehicle1 in l1.traffic: # Exception for first two iterations
      vehicle1.initdrive(t)

    for vehicle2 in l2.traffic:
      vehicle2.initdrive(t)
    else: continue
# DRIVE-----------------------------------# Main Method
  for vehicle1 in l1.traffic:
    vehicle1.drive(t)

  for vehicle2 in l2.traffic:
    vehicle2.drive(t)
# LC--------------------------------------# Lane Change
  for vehicle1 in l1.traffic:
    if vehicle1.ident == 1:
      continue
    vehicle1.lc(l1.ident,l1,l2,t)

  for vehicle2 in l2.traffic:
    if vehicle2.ident == 1:
      continue
    vehicle2.lc(l2.ident,l2,l1,t)
```

FIGURE 12 Code 1: Simulation Call

The source code of the system call is shown in FIGURE 12. The Simulation Call starts with a global *init*-method that defines the simulation parameters. These include the runtime variable *time* and the difference in time (or iteration step) *dt*. Both variables are integers. The array *timesteps* is created that is sliced in equidistant steps of *dt* with the length of *time* (see FIGURE 13 Conceptual Design for Simulation Run). The simulation is then iterated over the difference of time that is scalable for any difference in time. By this means, the conceptual simulation framework is defined. It is a time-discrete mode that updates and determines the new state of the system at discrete point of time. To model dynamic changes, the value of *dt* should not exceed over 1 second. Note that *dt* is consistent with the time difference used for the numerical integration to update speed and position of each vehicular agent (see equation (4.1-4.2)).
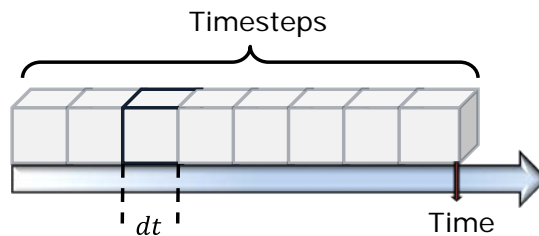

FIGURE 13 Conceptual Design for Simulation Run

The actual simulation is then executed in the for-loop. In detail, every vehicle object located in the class lane are concatenated in the array lane.traffic. In this way, vehicle objects become the iterable that invokes the *drive*-method successively. The *drive*-method is responsible for the updating state variables in the sub method *RK*. Moreover, it calculates the new acceleration at time t based on the CFM at hand. Within the *drive*-method, the vehicles are distinguished between the first vehicle object and last object. The first vehicle inherits the cruise control method *cc* to show deterministic

behavior for analyzing purposes. All other vehicles execute the CFM that is implemented. At the end of the drive method, the object is copied to a temporary variable *downstream*. This is necessary to get the relative state variables for any successive vehicle in order to make the calculations.

The code implementation of the CFM is straightforward and therefore not further explained in detail.

The lane change method *lc* is evaluated before the *drive*-method is called to see if there is an incentive given to change the lane. *Lc* is a call function that invokes a sequence of pre and post processing that consists of the sub methods *checkblock, checkfollowers, assessLC, incentive* and *performLC*. Until the last sub-method, the criteria for a lane change is repeatedly assessed. The associated Boolean variable is *lcdecision*. If the value switches to 1, perform LC is conducted

Checkblock assess if there is a feasible gap in the target lane. If there is an overlap with a neighboring vehicle, the lane change method can be aborted. Otherwise, the next method is called.

Checkfollowers is a method to determine the candidate of the potential successor on the target lane. Its position must be smaller than the subject vehicle's position minus the fixed car length of 7m. The first vehicle that suffices this requirement is set as the immediate follower. Having identified the ID of the successor, the direct preceding vehicle is then assigned as the potential predecessor in the target lane. For this method, there needs to be an exception for when there is no candidate for a lead vehicle or for follower. This case occurs when the subject vehicle with the lane change intention is

going to be the last link the first vehicle in the target lane. To overcome this problem, two dummy vehicles SmallM and BigM are created. They become the reference for computation of relative state values. They are not affecting the vehicles in lane as those two dummies are not placed in the lane objects.

AssessLC is the examining for the safety criterion as described in 4.2.3. For this purpose, the new acceleration of the back vehicle n shall not exceed a safety brake value $\tilde{a}_n > -b_{save}$. In order to calculate $\tilde{a}_n$, the position and speed require updating prior to the *drive*-method. An internal algorithm then determines the new acceleration of n and passes the value of *lcdecision* accordingly

Incentive ensures whether the subject vehicle will have a benefit by changing the vehicle. There are generally four vehicles involved that must be looked at. The subject vehicle *sv*, the preceding vehicle in the current lane *pvcl*, the back vehicle after lane change *bv* and the preceding vehicle in the target lane *pvtl*. The old and new acceleration rate of *sv* depends on *pvcl* and *pvtl* while the old and new acceleration of *bv* is defined by *pvcl* and *sv*. The back vehicle before lane change that is denoted with *o* in equation (4.9) is omitted as the implementation does not support aggressive driving behavior such as tailgating.

PerformLC is the actual method that executes the lane change. Once the incentive is given, the ID of *sv* and *bv* are passed to this method. The traffic array of the current lane will then be manipulated so that the *sv* vehicle is removed from the lane and afterwards inserted in the target lane with regards to the correct position in the new traffic-array. This closes the lane change method.

5.2. Implementation of the Microscopic Simulation

In the previous section, the general procedure of the microscopic simulation has been discussed. Moreover, longitudinal CFM and the MOBIL LCM have been implemented. the validity of this simulation needs to be examined. Qualitative analysis, legitimate

5.2.1.   Validation with Gipps

For the validation of the model, a basic scenario with both IDM and Gipps' model is considered. Here, a lead vehicle is driving in the cruise control modus with a constant speed of 60 kph. Three following vehicles are generated at distances between 20 to 60 meters and the lead vehicle is set at 80 meters (see TABLE 4).

TABLE 4 Setup for Validation

Scenario	Motion Profile	Initial Point	Initial Velocity
LV	Const. v= 60 kph	80m	0 kph
FV1		60m	
FV2	Gipps	40m	
FV3		20m	

In the first simulation, the performance of the Gipps' Model is analyzed using the model parameters in TABLE 5 that applies for all following vehicles. The desired speed is multiplied by the factor two of the lead car's speed so the followers have the chance to shorten the distance. FIGURE 14, FIGURE 15 and FIGURE 16 depicts on the x-axis the time and on the y-axis the position, velocity and acceleration respectively.

TABLE 5 Gipps Model Parameter

Gipps Parameter		
Desired speed v_0	$[kph]$	120
Reaction time T	$[s]$	1
Jam distance s_0	$[m]$	2
Max acceleration A	$[m/s^2]$	3
Max deceleration B	$[m/s^2]$	-8
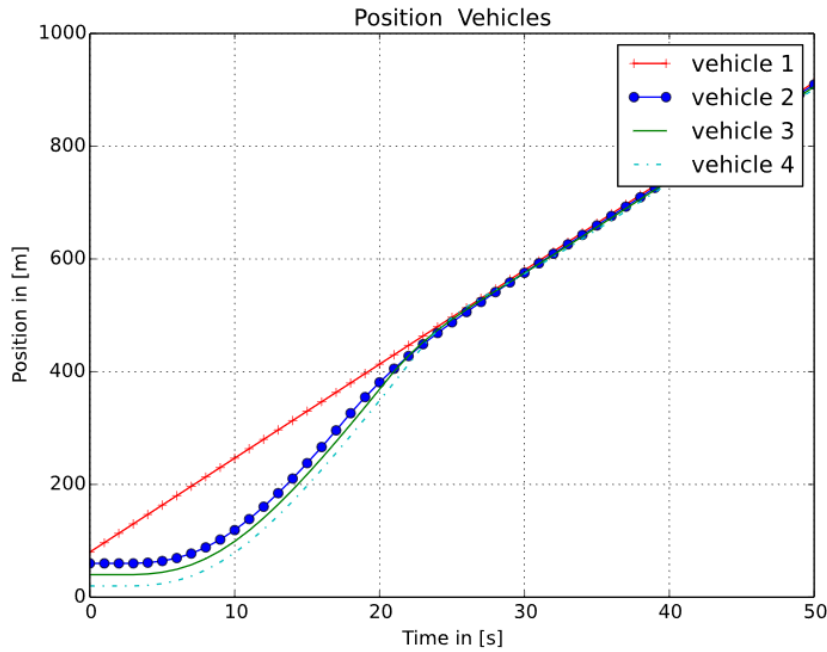
FIGURE 14 Validation with Gipps - Position over time

One can see the characteristic slope of vehicles 2 to 4 that is approaching the position of the lead vehicle. The smooth closing in is an expected outcome of the CFM model. Note that the vehicles take roughly five seconds to start shorten the headway distance and after 22 seconds they are in a steady-state following the lead vehicle. The fact that the curves align and do not exceed vehicle 1's curve is proof that the CFM is working properly.
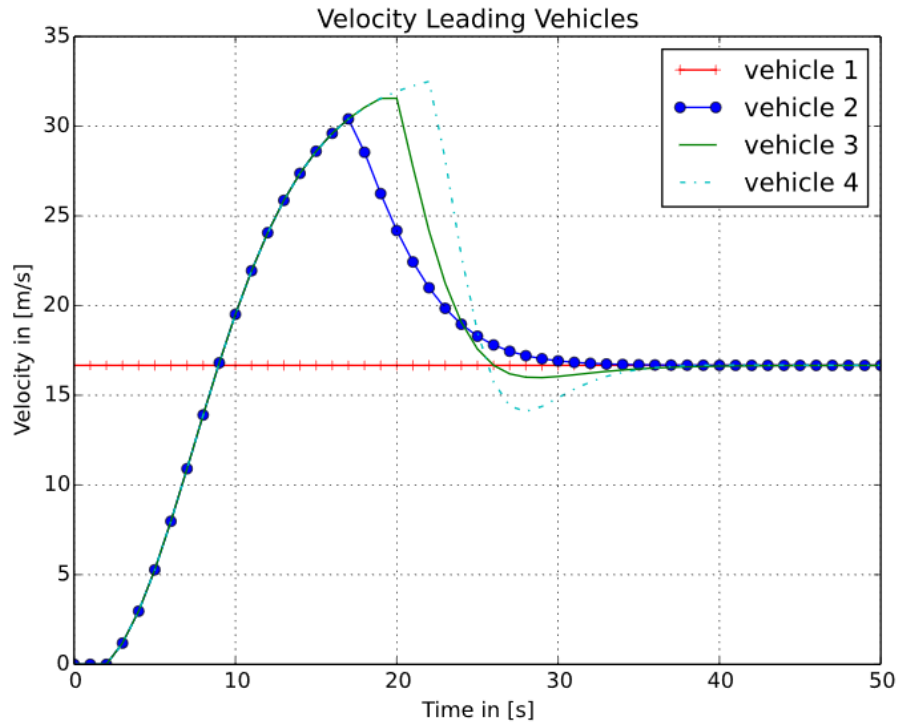
FIGURE 15 Validation with Gipps - Velocity over time

In FIGURE 15 is shown the velocity profile. The dashed straight line is the constant

speed of the lead vehicle at $16.67\ m/s$. It is apparent that the followers' velocity profile

grows constantly until the velocity reduces abruptly successively beginning at 17

sec with a delay of 2 seconds. Peculiar is that the acceleration of each follower is

identical. As the initial gap of 20 m does not activate the following algorithmV_i^{pre}, it is

logical that the algorithm reproduces the same value. The abrupt change in the speed at

17, 20 and 22 sec marks the activation of the Gipps following algorithm. The severity

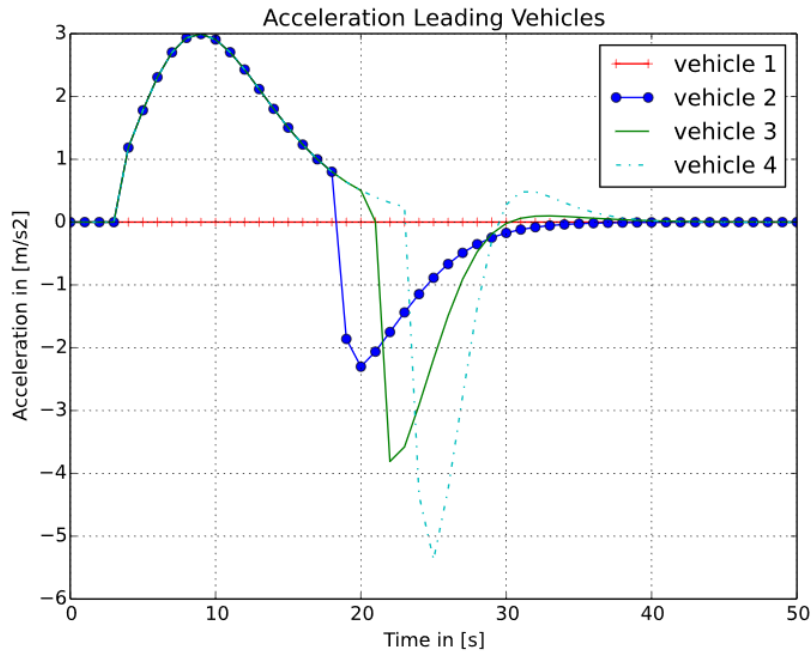of deceleration becomes obvious in FIGURE 16.

FIGURE 16 Validation with Gipps - Acceleration over time

Here, the brake applied by vehicle 4 is roughly twice as high as the deceleration of vehicle 2. Due to the latency of reaction, the remaining distance is short. Accordingly, the deceleration grows to the maximal assumed brake capability b_{max}. Here, the shortcoming of Gipps' model becomes apparent. Vehicles do only evaluate the gap and maximal deceleration of their predecessor. The lack of foresight leads that vehicle 4 takes five seconds until it reacts to the sudden deceleration of vehicle 2. It is worth mentioning that the 'smoothness' of the curve are impacted by the numerical differentiation which can be improved by higher order differential equations.

5.2.2. Basic Scenario with CPM

In this scenario, the behavior of the CPM shall be examined. Object of investigation is the spacing strategy of the CPM with varying parameters of the maximal braking

capacity that is wirelessly transmitted by the preceding vehicle. The parameters of the setup is given in TABLE 6.

TABLE 6 Setup for Basic Scenario

Scenario	Motion Profile	Initial Point	Initial Velocity
LV	Const. v= 60 kph	$80m$	$60\ kph$
FV1		$60m$	$30\ kph$
FV2	CPM	$40m$	
FV3		$20m$	

As the previous setup, the vehicle agents are created at fixed distances and the vehicle car drives constantly with 60 kph through the simulation run. Note that all following cars have an initial speed to ramp up the time until steady following. This scenario involves two runs with different conveyed maximal deceleration B_{i-1}^{IVC} of the immediate downstream vehicle to expose the influence of this parameter. The model parameters are presented in TABLE 7.

TABLE 7 CPM Model Parameter

CPM Parameter		Run 1	Run 2
Desired speed v_0	$[kph]$	120	
Reaction time T	$[s]$	1	
Jam distance s_0	$[m\ ]$	2	
Max acceleration A	$[m/s^2\ ]$	3	
Max deceleration B_{i-1}^{IVC}		-8	-12

The difference of both runs become apparent in FIGURE 17. In the first run, all following cars are in equilibrium at a gap of 11 m. Here, the first following vehicle start closing the gap after $7sec$ of simulation start. The high headway distance of roughly $48m$ is due to the initial velocity difference between the lead and all following vehicles. The second run shares approximately the same gradient as the first run, contrasting in

the magnitude. This is an expected observation as in the following procedure, the CPM activates the same algorithm as the Gipps' model. At run 2, the gap value settles at $36m$.
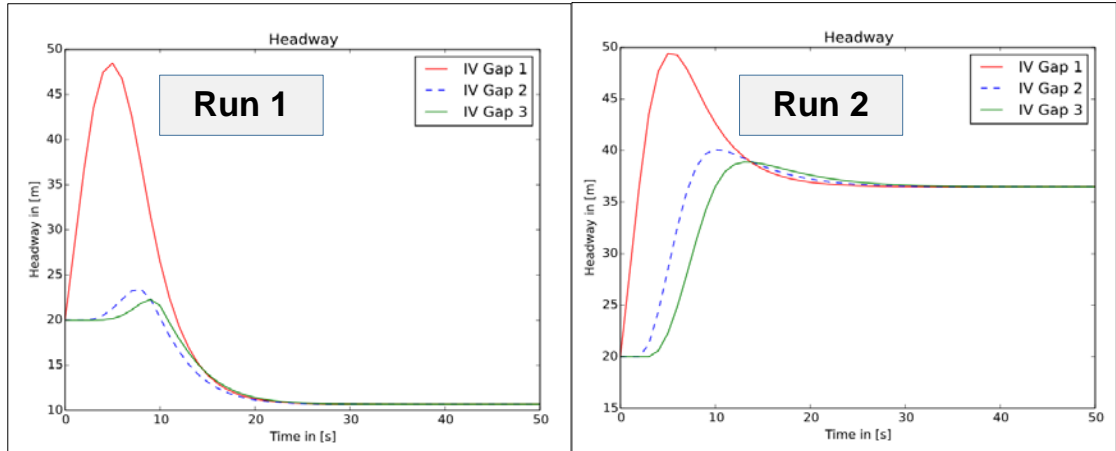

FIGURE 17 Basic Scenario – Headway Distance

The higher spacing strategy in run 2 supports the feature of the CPM. A higher braking capacity of the predecessor means it leaves less time for reaction in case of emergency braking. To ensure the passenger safety, a higher intervehicle gap is required that is reflected in the comparison. In the same manner, a car that has a lower braking force is characterized by longer braking distances. Given this information, the intervehicle gap can be minimized without endangering the passengers.

5.2.3. *Specific Scenario with CPM*

The structure of the scenario includes a cruise control vehicle at constant $60\ m/s$ that starts decelerating after $25\ sec$ with $3\ m/s^2$. When reaching a velocity of $30\ m/s$, it starts accelerating with $3\ m/s^2$. This setup can disclose the performance of the implemented models at nonsteady conditions. The specification of the scenario setup is

shown in the tab xx where the initial position and velocity of respective vehicles are assigned. Note that every agent has the starting acceleration of $\dot{v} = 0$.

TABLE 8 Scenario Setup

	Motion Profile		Initial Position	Initial Speed
LV	t=0: Const. v= 60 kph t= 25: $\ddot{x}(t) = -3\ m/s^2$ v=30kph: $\ddot{x}(t) = -3m/s^2$		$80m$	$60kph$
	Scenario 1	Scenario 2		
FV1			$60m$	$30kph$
FV2	Gipps	CPM	$40m$	$30kph$
FV3			$20m$	$30kph$

The models to be investigated are the Gipps' model and the CPM. The key parameter to be adjusted in this scenario is the maximal braking capacity B_{i-1}. This parameter decides over the spacing strategy of each follower. In case of Gipps' model, this parameter is estimated as the originally proposed and is denoted as B_{i-1}^*. In practice, estimations are imperfect and therefore afflicted with an error. The proposed CPM in this work, however, has full availability to individual maximal deceleration parameters due to the technology of V2V communication. Thus, the parameter B_{i-1}^{IVC} can be altered assuming the traffic consists of vehicles with mixed braking parameters. The expected outcome of this scenario is a varying spacing strategy according to the received parameter information for the CPM. TABLE 9 shows the chosen parameters.

TABLE 9 Gipps' and CPM Model Parameter

		Gipps' model	LV	FV1	FV2	FV3
				CPM		
Desired speed v_0	[kph]	120		120		
Reaction time T	[s]	1		1		
Jam distance s_0	[m]	2		2		
Max acceleration A	[m/s^2]	3		3		
Desired decel. b	[m/s^2]	-		3		
Max deceleration B	[m/s^2]	-6	-10	-8	-6	-4

Note that Gipps' model does not have a desired deceleration as it is a specific parameter of the IDM. In FIGURE 18 is depicted the travelled distance of both models. The slopes of the lead vehicle (dashed line) represent the short-term deceleration with the successive acceleration.
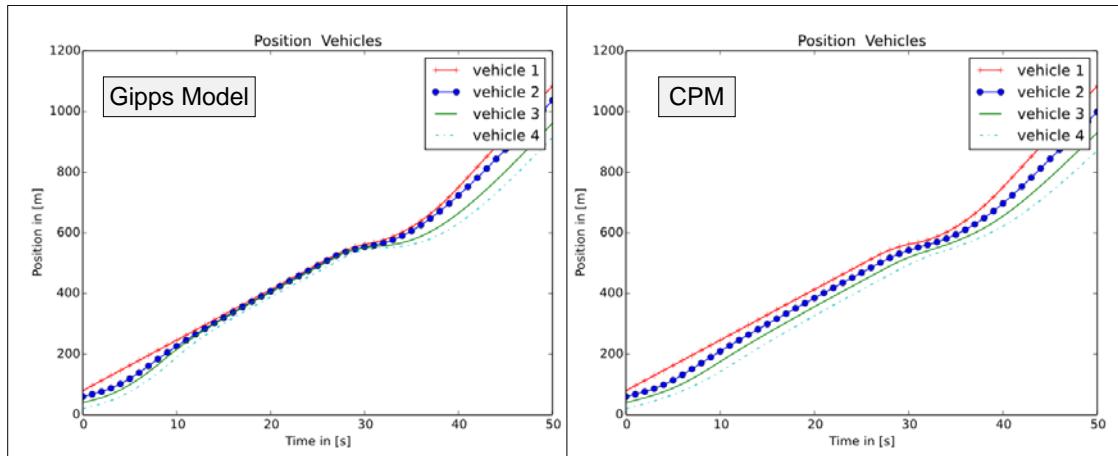

FIGURE 18 Specific Scenario - Travelled Distance

The signals of headway distance (see FIGURE 19) and time gap (see FIGURE 20) are more comprehensive to expose the individual mechanisms of the two models.
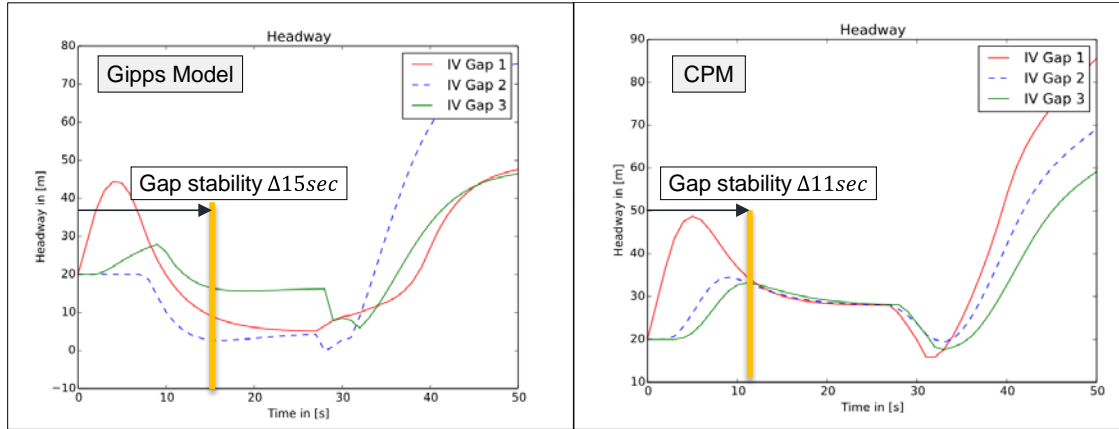
FIGURE 19 Specific Scenario – Headway Distance

The time until stability is achieved by the IV (i) gap is marked with a yellow bar in both plots. The criteria for reaching stability is fulfilled when the rate of time gap falls below $0.1 \frac{s}{s^2}$ (in absolute numbers). The stability is reached in Gipps' model after 15 seconds while the CPM takes 11 seconds as shown in FIGURE 19. Moreover, in FIGURE 20 is depicted the contrast in response to the changes in deceleration and acceleration beginning at 25 seconds.
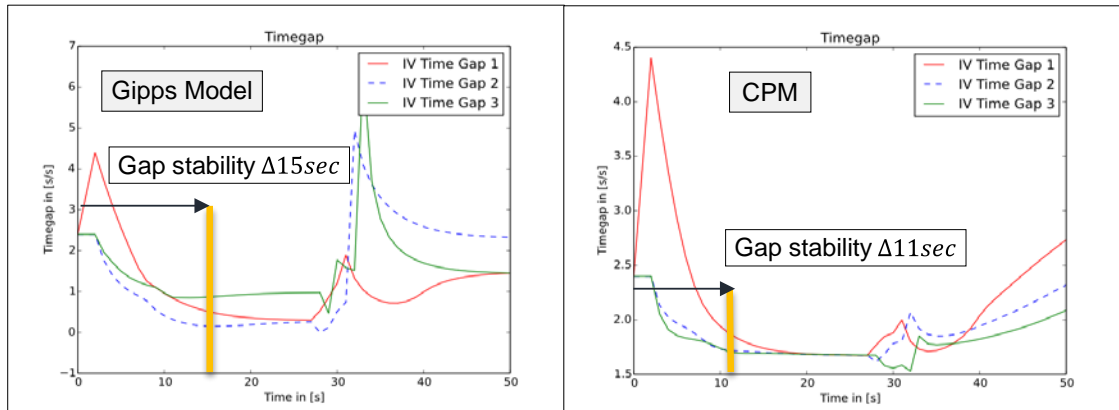

FIGURE 20 Specific Scenario – Time Gap

Peculiar is the magnitude of response between the two models. In the Gipps' model, the brake reaction is continued and amplified with each following vehicle. Again, the

lack of spatial anticipation results in more sensitive reaction of the vehicle. In contrary, the CPM shows a favorable response to the actions of the lead vehicle. His braking has no amplifying effect and is damped.

5.2.4. Discussion

In the frame of this work, contributing a traffic simulation environment is an integral part of the objective. This chapter presents the development of a flexible, object-oriented traffic simulation framework programmed Python 2.7. The aptitude of modeling the traffic with interactive as agents is discussed. Vehicles have a multitude of properties and states in common like the weight, acceleration capacity or desired velocity. They further are endowed with interactive traits, meaning they share the same resource (roads) in the environment and change its state dynamically. Against this background, representing vehicles as instances of an object-orientated platform is an intuitive step that is taken in the work.

The simulation environment consists of two classes: Car and Road where the instances are driven vehicles and lanes. Due to the object-orientation of the program, the number of vehicles and lanes are variables and can be extended to one's need. Further elements in the traffic as RSUs may also be implemented that will incorporate different properties and methods. The environment the vehicle are placed and share are the lanes. Due to their state of position in the lane, vehicles are in continuous interaction as spaces in the lane is a resource that can physically not be shared by more than one vehicle. The intelligence implied in the agent is able to process future states of foreign agents and response in a manner that the conflict is resolved.

Decisions about the conceptual design of the simulation framework are made. The program at hand is space-continuous and time-discrete. A continuous spatial dimension is regarded as a desirable in particular for microscopic traffic simulations, as the dynamic state transition are not sufficiently represented with space-discrete models. As regards the time dimension, discrete time steps has been shown to be sufficient when the iteration steps are chosen below $1sec$ (Manley et al. 2014).

Furthermore, a detailed insight of the simulation procedure is highlighted. Here, the process of the lane change is broken down as it exemplifies the complex mechanism cognition from perception to decision-making of a human that is projected in methods of the simulation. Apart from this, the implementation of the required assessment for the safety and incentive criterion is a design question for the programmer, since the identification of the relevant agents vary from program to program.

In the second part, two CFM are specifically implemented to validate the proposed simulation environment. With the aid of Gipps' model, elementary expectations of a car following model are proven. Here, the following car adapts to the speed and acceleration of the lead vehicle and omit their desired speed, thus guaranteeing a collision free simulation. Having verified the simulation environment, this chapter investigates the behavior and performance of the Cooperative Platoon Model. A basic scenario illustrates the desired variable behavior when receiving intelligence about the vehicle local braking force of the preceding vehicle. Tweaking the communicable individual parameter B_{i-1}^{IVC} controls the spacing strategy of the CPM. In the specific scenario, the lead vehicle varies its longitudinal control to assess the following behavior of the Gipps' model and the CPM in comparison. The CPM performs solid results with regards to

time until reaching stability and robustness against sudden changes in acceleration. From those observations, this favorable performance is explained by the 'foresight' of the CPM that is lacking in Gipps model.

6. SUMMARY AND OUTLOOK

In light of current progress in automotive-related technologies such as intelligent driver assistance systems and advanced telematics, new opportunities for a coordinated management of the traffic becomes feasible. First applications of coordinated driving systems will be the cooperative platooning. Longitudinal formation of vehicles has been subject of research for many decades. Coupled with the recent advents of intervehicular communication, the precise implementation of cooperative platoons gain continuously focus. The research around platoons is in many ways beneficial as it has positive effects on the safety, fuel consumption and traffic throughput. In particular, the heterogeneous conditions in the present traffic that result from imperfect human control or egoistic behavior may be eliminated once the on-board intelligence takes over the throttling and steering. The favorable outcomes of such automated systems are challenged by its implementation which is why research deal with question about the control strategy of such platoons.

The vision of such accident-free automated driving is a challenging task like for many safety-related systems. Guaranteeing safety requires a system to be maximal robust and it may not expose humans to additional danger. Conventional verification procedures like field operational test are commonly time-consuming and cost-intensive. To overcome this obstacle, simulation qualifies as a valuable assessment tool. Against this background, the thesis at hand has following objectives: (i) review and assessment of past and current approaches and implementations of vehicular platooning. (ii) presentation of a concept of an integral platoon model and (iii) development of a flexible and object orientated microscopic traffic simulation.

In chapter 2, related work to cooperative driving and platoons are discussed. Here, the boundary between cooperative systems and autonomous driving is pointed out. Autonomous driving is possible without the coordination by equipping vehicles with sophisticated environment sensors and complex algorithm in controllers. While the navigation through traffic is feasible, instances like the *DARPA Urban Challenge* contestants are not designed for optimizing traffic flow. Sharing information via VANET is one measure to make the environment predictable and coordinate the global behavior in the traffic. Therefore, current subjects of research around Vehicle-2-X communications are presented. The chapter proceeds with the overview of current collaborative research projects with regards to platooning. The scope of control, relevant vehicle types and the degree of traffic integration are examined. Many projects consider the mixed platoon of passenger cars and trucks and implement backup strategies for emergency situation. Moreover, a general classification of vehicle formations is outlined. This can be subdivided by the centralized or decentralized coordination. Prospective applications rely on distributed coordination where the communication and decision for action is incumbent upon individual vehicles. The chapter closes with coordination algorithms found in the literature. Here, different approaches of forming a platoon is presented. This can be done based on the spatial proximity or by the similarity of shared vehicle properties.

Chapter 3 deals with the theoretical background of traffic simulation and descriptive methods. Prominent commercial and open-source packages are introduced. This section is followed by an in-depth discussion about existing classes of CFM and LCM. Based on the key parameters for the following strategy, the CFM have various

advantages and disadvantages. All have in common that the models are assuming deterministic response to a given stimulus which is why many models lack of complex human behaviors such as spatial anticipation. This chapter closes with the overview of ABM and its applications in the context of traffic simulation. Agent technology gains growing focus as the representation of vehicle as agents is intuitive and large-scaled problems can be tackled that was not possible with past generations computing performances. The need for ABM rises also because human behavior can be modeled.

Chapter 4 is dedicated with the concept design of a platoon strategy. This introduces a layer perspective of a platoon control that is divided in the vehicle local layer, the platoon layer and the global layer. The bottom layer consists of the vehicle feedback controller that gives insight about the mathematical operations executed to return state variables. Two prominent CFM are considered that seems to be suitable options for the platoon strategy. This work does not consider lateral controls as it does usually not contribute to the stability or effectiveness of platoons. However, the lane changing model MOBIL is examined. It is interesting from the modeling perspective as it allows to represent different lane changing decision-making. The platoon layer then discloses actual strategies for platooning. The ACC-based swarm behavior is feasible with the state-of-the-arts technology, but lacks of information about specific vehicle properties of the downstream traffic. To overcome this suboptimal platoon strategy, the idea of coupled coordination is introduced. Here, the idea of vehicle internal brake force is transmitted to optimize the spacing strategy. The global layer depicts the interaction of vehicles before they engage to a platoon. With the aid of the dissimilarity function,

vehicles can evaluate the utility of forming a platoon. An internal behavioral rule set is steadily executed within each vehicle that decides to form, join or leave a platoon.

The development of a simulation framework and the implementation of the proposed CPM is subject to chapter 5. Programmed in Python, the simulation environment is capable of running different models as Gipps' model, the IDM or the CPM. Further, the LCM MOBIL has been implemented. Due to the design of this simulation program, further extensions can be installed easily. Subsequently, the models' behavior with different simulation scenarios are analyzed. The CPM proves to be adaptive to different transmitted information about the preceding vehicle's braking capability.

However, the outcome of the experiment requires careful assessment considering the underlying assumptions. The analysis in chapter five has a qualitative characteristic. To validate the observations in the scenarios, datasets should be collected and statistically analyzed.

Adjusting the brake capacity parameter of vehicles showed the expected behavior in the spacing strategy of the CPM. Examining the impact of different values might be an interesting approach for further research efforts. The spacing strategy is based on the criterion to avoid a collision when the predecessor applies full brake. This criterion may be relaxed for further research as the emergency brake on high ways are considered rare exceptions. A more relevant scenario is given when a neighboring vehicle cuts aggressively into the lane ahead and the lead vehicle is forced to do a sudden brake, but not until full stop. The spacing strategy should be adapted to fulfill the safety criterion

for this scenario rather than a full stop brake scenario. Using the developed lane change models, modeling aggressive and egoistic drivers are feasible owed to the algorithm design of MOBIL

Applying the CPM gives the vehicle further intelligence concerning the braking force of its immediate predecessor. Due to the knowledge of the braking distance, successors may choose an appropriate driving strategy: if the brake force is relatively low, the headway distance can be shortened without exposing the platoon members to additional danger. On the contrary, vehicles ahead with high brake forces are challenging the active safety when the gap is too close and an unexpected events happen. The adaptive strategy can propel the performance and stability of platoons. Further, the microscopic simulation environment in Python allows the modeling and simulation of vehicular agents and thereby present a powerful platform for future research. This thesis at hand has provided vital contributions for the research of coupled coordination and agent-based modeling.

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