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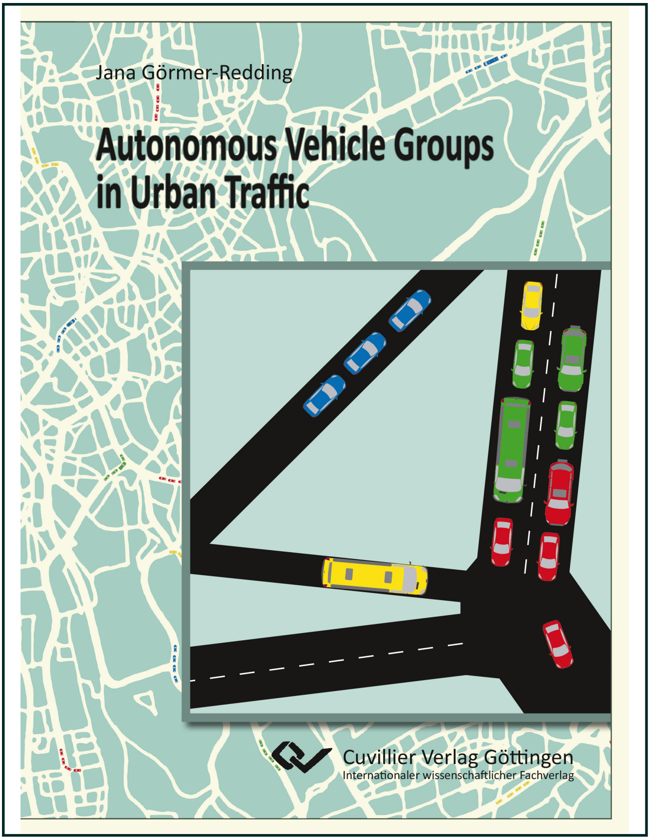
Autonomous Vehicle Groups in Urban Traffic



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The beginning is the most important part of the work.
Plato (s. IV aC)

Chapter 1

Introduction

This thesis addresses a new model of autonomous vehicle group formation (AVGF), which will benefit the flow of urban traffic in the future. Increasing population and cross-linked economies with incremental division of work trigger a growth in transportation processes and raises the question of where traffic management needs new constructive concepts. Passenger mobility has had a long tradition in our industrial society. Figure 1.1 illustrates the historical development and new modes of transportation such as rail, automobiles and aviation which have had impact on transportation. Self-driving vehicles are the (future) robots to simplify human lives and the next transformative technology, as once the introduction of the automobile, the traditional car, was.

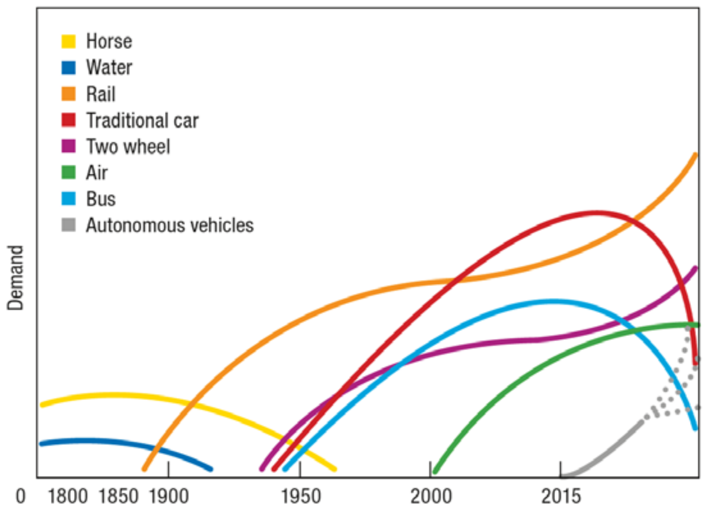

Figure 1.1: Indication of Historic and Future Passenger Mobility Trends (cf. [295]).

The news [275] [54] [311] [330] [58] insinuates [99] that the future of mobility lies in highly or fully automated vehicles. In the upcoming years, highly assisted vehicles (HAV) will be on the market, whereas fully automated cars are under active development and topical in transport research. Nevertheless, the development of self-driving cars that do not require human intervention, also referred to as autonomous vehicles (AVs), is accelerating as described by `Bertoncello and Wee` [41]. They discuss that, in 2015, the development of fully autonomous vehicles starts, in 2020 AVs are market-ready, and in 2030 the consumers start to adopt AVs. Finally in 2050 AVs become the primary means of transport.

The classification of automated driving levels provided by the Society of Automobile Engineers (SAE) [181] proposes six levels, starting from level 0 (purely manual driving) to level 6, where the automated system can perform all driving tasks under all conditions. The United States Department of Transportation applies the SAE levels with National Highway Traffic Safety Administration (NHTSA) [2] policies: On the one hand, it includes guidance for manufacturers, developers and other organizations for designing, developing, testing and deploying safe automated vehicles. On the other hand, it provides policies with a clear distinction between Federal and State responsibilities and existing and new regulative tools required for AVs. European mobility adoptions deal with automated driving [72] including various functions for daily traffic. There is a European study [135] which considers highly automated and connected vehicles and the necessary policies for sustaining research and development and bringing them to market.

Besides the above-mentioned technical and political achievements regarding autonomous vehicles, there are technologies and systems such as Cooperative Adaptive Cruise Control (CACC) and Intelligent Transportation Systems (ITS) in use. ITS aims at improving public transport, logistics and traffic management by utilizing new hardware infrastructures such as sensors and communication networks with modern information technologies. Examples of ITS are presented in different projects like PATH [354] or AUTO21 [238]. One important research area of ITS is the construction of intelligent autonomous vehicles, such as one driving in the competition of DARPA Grand Challenge or the construction of the Google Car 'waymo'[356], which are able to collaborate with each other to reach their destination safely and efficiently. CACC provides vehicles with the ability to cooperate, e.g., in order to avoid collisions. Collaboration in this context is the coordination and cooperation of individual vehicles in order fo them to reach their goals efficiently (further definition of keywords in the following Chapter 2).

1.1 The Argument

Autonomous vehicles (AVs) have recently been receiving much attention due to their promising prospects of social, political and economic benefits. AVs are capable of sensing their environment and navigating without human input. AVs interact with smart infrastructure and communicate with each other. The main features of AVs are the capability of autonomous operation like the Uber autonomous taxis [158], autonomous delivery of goods and persons [55], as well as automatic parking [217]. Here, autonomous indicates that the vehicles act independently of the driver's action and control, whereas automatic is defined as working by itself with little or no direct human control, but still initiated by the human.

AVs will act as individual robots, driving the demanded route using calculated decision making, while travelers will be able to sleep, eat, email, work or even meditate. AVs can be expected to become places of activity rather than just means of transport. AVs have many possible uses in the transportation field [390] [131] [250], including logistics, such as the trial of autonomous pods for home delivery [55] and also in economic use to maximize the safety and efficiency [249].

However, AVs are still heavily under development and manufacturers are more or less successfully striving to establish them on the market [2]. The rising technological standard [244] and increasing amounts of traffic burden the existing traffic management. New urban planning concepts and new technologies such as V2X (vehicle to exchange communication) and autonomous cars are research in progress and only rudimentary available.

Standard traffic situations include numerous heterogeneous participants (here: vehicles). There are many situations where communication between participants is beneficial, if not crucial. An example is a traffic jam, in which no individual vehicle can improve the situation by itself, other than by adjusting their speed to the conditions and waiting until the cause of the traffic jam has dispersed. In congested situations, information such as warnings to slow down and problem solving techniques for resolving the cause of conflict is helpful. Grouping vehicles as investigated in this thesis could be beneficial in order to increase the throughput of a network, but at the same time focus on the individual interests of vehicles to increase the driving comfort. The specifications of AVs are designed by engineers based on the model of human driving and decision making. Thus, AVs can have goals and interests.

Therefore, this work focuses on the investigation of how autonomous vehicles can be grouped and what effects such grouping may bring about in different traffic situations. One way to model AVs is in simulation [281] [215] by incorporating AVs into vehicle groups. Industrial fleets lead the way with the use of grouped AVs in mining, farming and in closed contexts like airports.

Two relevant concepts in this context are convoys [38] and platoons [354], where vehicles are joined for coordinated action. Convoys are a sequence of vehicles driving in the same lane in which every vehicle has a driver (usually they are military or logistical convoys). Vehicle platoons are an automated form of convoys in which a human driver leads a line of closely following vehicles. Each following vehicle autonomously measures the distance, speed and direction and adjusts to the vehicle in front. In more recent works `Saeednia and Menendez` [301], the term 'platoon' is defined by decreased gaps between consecutive trucks and identical speeds.

Automobile platoons are used for automated highway systems (AHS) only. It started with the first automated vehicle, which contained a computer and was built for research by Ohio State University in 1962. For implementation in the PATH project of automated vehicle platoons, the infrastructure needed to change, because it works with magnetized stainless-steel spikes in the highway which provide small amounts of digital data (describing lane changes, recommended speed). Vehicles use this infrastructure-provided information for sensing speed and their location. Thus, vehicles can organize themselves into platoons of eight to twelve cars and decrease the distances between each other to a conventional braking distance. Although the platoons were successful, investment has moved towards autonomous intelligent vehicles rather than building specialized infrastructure.

Nowadays, the AHS[1] platoons are conducted by the SARTRE Project (Safe Road Trains for the Environment) [67], which includes sensory technology in vehicles (mostly trucks) that can read passive road markings, and use radar and inter-car communications to make the vehicles organize themselves without the intervention of drivers. Being in the platoon, drivers can do other things than driving while the platoon proceeds coordinated towards its long distance destination. The vehicles in the platoon are physically detached and can leave the convoy at any time. Such an autonomous cruise control system has been developed by Volvo, Mercedes-Benz, BMW, Volkswagen and Toyota.

However, although the effect of vehicle platoons on highways was demonstrated (benefits of substantially shorter commutes during peak periods, reduced congestion, fewer traffic collisions, and greater fuel economy due to reduced air resistance) [67], in general little attention has been paid to the use of grouping vehicles in urban traffic.

1.2 The Example

One sample traffic scenario models traffic components in a four-way intersection as seen in Figure 1.2. The focus is on the individual vehicles, seen as autonomous agents (explained in Chapter 2.3.1) which coordinate their calculated behavior with other agents. The agent concept includes reactive, proactive and social behavior. Exchanging information pertaining to goals and route plans is essential for decentralized cooperative control in dynamic groups of vehicles.

From the point of view of agent design, this application example is appealing because, on one hand, it is easy to understand, while on the other hand, it offers a variety of interesting problems. The local planning of groups and the necessity of dealing with changes caused by the actions of other agents allow us to study the relationship between individual and collective group vehicles. The agents in urban traffic have to react in real time, they are resource-bound, and have incomplete knowledge about the world.

The main focus of this thesis is the integration of agent coordination and cooperation into urban traffic environments in the form of groups. Use cases of traffic scenarios make it possible to investigate various forms of vehicle grouping strategies using a variety of coordination and cooperation mechanisms. The mo-

[1] There exists a broad line of work on automated highway systems like the concept of managed lanes.

tivations for forming a vehicle group are less gaps, higher speed, less emissions, and higher traffic safety.

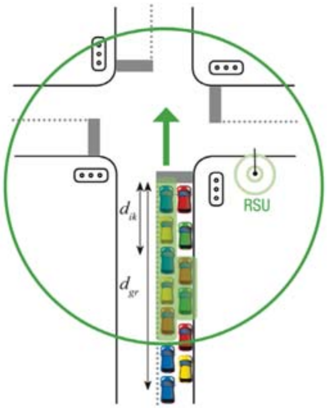

Figure 1.2: Vehicle Grouping (adapted Source: [110] p.12.)

For example, the mini scenario in Figure 1.2 illustrates a typical situation. There are two lanes in each direction with three vehicle options for the next action: turn left, go straight, and turn right, which would cause a resource conflict for lanes; thus, three lanes in each direction and three options to take means that preprocessing of the route plan is necessary. The situation needs vehicle coordination before arriving at the stopping line. Obviously, there are different ways of resolving those situations.

One method of vehicle group formation is illustrated in Figure 1.2. The first vehicle (blue in the illustration) at the stopping line is defined as the group leader. This group leader sends a speed recommendation, the maximum possible group size and information about the destination of his route. The maximum group size d_{gr} (the green area within the green communication circle) is measured as the spacial distance to the group leader and is determined by the predefined desired speed $v_{desired}$ and the rest time value t_{green}: $d_{gr} = v_{desired} * t_{green}$.

Potential group members which are within the communication coverage distance (blue circle) verify with transmitted information whether or not they are joining the group leader. For this purpose, the destinations of the routes need to coincide. In order that all vehicles within a group can pass the stopping line during the next green phase, the distance d_{ik} between the vehicle i and the group leader k should be within the maximum distance d_{gr}. Consequently, the group size is limited by the communication range, the rest time value of the traffic light and the predefined desired speed. Finally, all group members adapt their speed to the recommendation of the group leader (the movement is represented by the green arrow).

Infrastructure elements like traffic lights and message signs can help to control and coordinate vehicle actions or can even be extended by building another lane. But infrastructure changes are not always beneficial or possible. Thus, coordination is the key. For example, the vehicle agents could - each by itself - locally decide for some random action movement. Alternatively, the autonomous vehicles could communicate their goals, and agree on a joint plan to resolve resource conflicts (like one lane for two actions) or for coordination (like sorting depending on the route the vehicle agents have planned). Intuitively, the former option seems to generally be used to deal with the situation, whereas the latter alternative is more reasonable for cooperative traffic control and can bring benefits to the traffic system. Typically, this results in coordination and communication costs which should be minimized by the design of how vehicles are grouped. Vehicle groups should not use extra resources like a commuters' park and ride lot, and communication should be standard and kept to a minimum.

Do simulation tests confirm the intuition that grouping vehicles by route choice brings benefits to urban traffic? How will a traffic system consisting of a number of vehicles behave if the individual agents use group strategies? These are central questions that this thesis investigates.

1.3 The Approach

This thesis tackles the relevant research question of using AVs for a new mobility model by designing and implementing autonomous vehicle group formation (AVGF). In this work, the focus is on AVGF for fully autonomous vehicles (SAE Level 5) exclusively. Since fully autonomous vehicles do not exist, simulations are used to evaluate the vehicle groups. In an urban simulation environment, AVGF joins individual vehicles dynamically into vehicle groups based on their similarities to the surrounding ones. The goal is to prove that AVGF will contribute to a smarter, faster and more efficient mode of transport.

In this thesis, the procedure model of AVGF is addressed in three steps:

1. Functional Design
   In this phase of work, the entities in the traffic domain, i.e., traffic participants, especially vehicles, are defined. Then, the requirements for the simulation of traffic with focus on AVs are analyzed. Simulations are required for modeling AVs in urban traffic, because manufactured autonomous vehicles exist only as prototypes and are still under development; there are legal aspects as well. But simulations have difficulties reproducing interactions, i.e., the communication between drivers and other drivers or pedestrians. Humans often interact with eye contact or gestures and have many psychological influencing factors which are difficult to model. Due to the communicational and cognitive limitations in simulations, the model is simplified to use exclusively autonomous driver-less vehicles. Additionally for SAE level 5, human drivers are the users of the fully automated cars and are no longer active.
   Cooperation (defined in the Background Chapter 2.1.1) is a strategic approach to meeting the challenges of open complex systems. But this will be no universal solution: the choice of strategy depends on the individual situation, although it can be motivated by the infrastructure. AVGF is addressed in this thesis with cooperative coordination methods applied to dynamic environments. Cooperative traffic is considered in this thesis

under the assumption that AVs are cooperative and not competitive in the sense of economics. This means that the vehicles react as rational actors (not altruistically, but tending to be benevolent), considering their own preferences. The global goals are reached through their diametrically opposing group behavior . Malicious behavior or competitive aims are out of scope.

This thesis aims to use the paradigm of intelligent autonomous agents for grouping vehicles. The agents can interact with each other in a virtual simulation environment in an urban traffic context. These dynamic, interactive environments pose interesting challenges for research on specialized capabilities as well as on the integration of these capabilities.

With the paradigm shift [258] from static and centralized traffic systems to dynamic and decentralized traffic systems, modular subsystems can be designed and simulated with the focus on user optimum. The system optimum is not the focus of this research. The user optimum is challenging because, usually, the individual interacts with systems on that level. Individual goals and preferences can be respected by the design of vehicle groups. Then both internal and external validations of group preferences can be discussed. Individual preferences need to be clustered into groups. Then, statements about the system can be formulated, deriving from the decentralized perspective. This enables groups to fulfill and interact with the requirements of the system as a bottom-up approach.

Groups are psychologically inspired. During the development of human society, group formation was a helpful factor. Group formation phenomenons like termites building their society are transferred to technical systems as defined by socionics and bionics in order to investigate whether groups are also useful in the complex traffic domain. Group behavior facilitates information sharing and problem solving. There are two possible reasons why groups are formed. Firstly, joint tasks can be performed in groups, while, alone, they might not be completed. Secondly, each individual can reach the goal, but in a group it can be reached faster, better and/or with less effort. Groups are triggered in certain situations and the members have corresponding defined relations depending on the joint goal and task.

The idea is that, with a designed vehicle group model, the autonomous vehicles will drive cooperatively in groups with less gaps between vehicles and coordinated operational (e.g., speeds), tactical (route) and strategic (destination) goals, depending on their individual and group utilities. The vehicles are detached and can join or leave the group at any time. A group leader depends on the application and mechanism. Groups can have leaders which are dynamically elected; roles and their assignment within a group may change over time. A horizontal group concept is preferred, which needs to deal with group knowledge and the communication between members.

I define cooperative, decentralized traffic management as the processes of monitoring and optimizing network flows, taking the autonomy of networked traffic participants and communication between them (Car2X technologies) into account.

2. Technical Concept
In this step, I study the applicability of multi-agent models and methods of group formation and coordination with the focus on the requirements and constraints of decentralized traffic management, which means taking individual preferences of traffic participants into account.
The paradigm of agents, which derives from the field of artificial intelligence, can contribute tothe solution design of autonomous vehicles. According to `Russell and Norvig` ([300] p. 34f.), in the context of Artificial Intelligence (AI), an intelligent agent is

> an autonomous entity which observes through sensors and acts upon an environment using actuators (i.e. it is an agent) and directs its activity towards achieving goals (i.e. it is "rational", as defined in economics). Intelligent agents may also learn or use knowledge to achieve their goals. They may be very simple or very complex. (...) Intelligent agents are often described schematically as an abstract functional system similar to a computer program.

Most definitions of intelligent agents emphasize their autonomy, whereas `Russell and Norvig` [300] consider goal-directed behavior as the core of intelligence. For my understanding, I combine the autonomy concept with, especially for agent groups, goal-directed behavior. Agents are autonomous computer programs carrying out tasks on behalf of users. They are defined by the three main attributes of being

- reactive - meaning that they perceive the environmental context in which they operate and take action appropriately depending on it;
- proactive - meaning that they adapt to change and react to future situations; and
- social meaning that they are capable of interaction, communication and coordination; they may collaborate on a task.

Autonomous programs used for operator assistance or data mining are called 'intelligent agents' as well, but does not match with my understanding described above.
The agent paradigm extends into economics and cognitive science, as well as interdisciplinary socio-cognitive modeling and social simulations, which makes it a useful model for cooperating autonomous vehicles. Therefore, AVs are conceived to be operated by software agents.
Multi-agent Systems (MAS) combine AI methods with distributed systems and object-oriented programming. The assumption by `Müller and Pischel` [255] is that, with this MAS paradigm, it is easier to build systems which have the properties of agents.

MAS [268] are a paradigm for constructing complex, software-intensive systems, providing multiple methods for modeling and simulating. The complexity of computer processes in autonomous vehicles requires modeling and simulation methods for design and high level abstractions. Those new developments for software engineering are provided by multi-agent systems [136].

3. Implementation and Evaluation
   The prototypical implementation is carried out in Multi-agent traffic interface, called MATI, an agent-based simulation environment created in this thesis for modeling AVGF, by using scenarios which reflect realistic traffic situations. For instance, the urban network of Southern Hanover was analyzed, modeling morning rush-hour traffic. This combination of simulation and a vehicle group model form the novel aspects of this thesis in which the experiments in different urban traffic scenarios show significant improvements in traffic flows through the use of AVGF.

   After the group operation, the last process verifies the model with the assessment of the simulation data. The effects of the grouping models using selective routing for physically coordinated driving are investigated regarding the question of whether it is better for the vehicle to drive individually or in a convoy of vehicles with or without group formation on the same route in urban traffic. What are the influencing external and internal factors for manipulating the convoy of vehicles and their group coordination?

1.4 The Contribution

The paradigm shift to dynamic traffic control including autonomous vehicles is likely to take place in the near future. One part of the solution to address the challenges is the approach of autonomous vehicle group formation (AVGF): It models autonomous vehicles in the urban traffic environment, uses the multi-agent paradigm to describe capabilities in order to model driver behavior in an abstract yet realistic way, and simulates the vehicle groups in the urban networks for investigations. The focus is on studying local decision-making that takes individual preferences into account, as well as on sharing and distributing information.

This thesis makes two main contributions. First, it describes and specifies agent-based traffic simulators, resulting in a combination of an open-source traffic simulation environment with the MATI framework which applies the agent paradigm to the actors in the simulations. This simulation tool is designed for the general purpose of connecting exchangeable environments with multiple interpreters acting in the same environment. Specifically, MATI is designed for modeling vehicle group formation along with metrics for measuring the efficiency of the resulting grouping algorithm. This AVGF algorithm is implemented and tested in simulation. Second, this research proposes a multi-agent-based architecture and methods for AVGF, and shows that this combination dramatically outperforms an individual driving strategy in simulation.

The desired outcome is to show that street capacity utilization can be improved in rush hours (medium traffic density: Level of Service C or D) with decentralized vehicle groups in order to increase the throughput for more efficient urban traffic. This is done by adjusting the distance and speed within groups. The concept of agents and MAS enables the representation of traffic systems including traffic-independent signal plans for traffic management and Vehicle-to-X-change (X stands for any) Communication, same as C2X (V2X) communication to show the effects of decentralized groups in urban traffic. The hypotheses are stated in the Evaluation Chapter 7.1.

Therefore, vehicles are abstracted as agents that form groups inspired by human group behavior. Thus, the main objective is to study the benefits of AVGF. A realistic example shows the group phases and the effect that coordinated and cooperative driving has, namely, to improve traffic-dense situations in urban traffic. Coordinated operational (e.g., speed), tactical (route choice) as well as strategic (actual position in relation to the destination) criteria for autonomous grouping are the subject of investigation in order to answer the question of if and how vehicle grouping works in simulations.

In summary, the use of AVs in groups are for safety and comfort reasons, but, mainly, to improve the group efficiency for the benefit of individuals and global preferences thanks to the effect of collective knowledge. Autonomous vehicle groups will result in smoother, faster traffic flows, reducing and avoiding congestion. Additionally, vehicle groups promote efficient and smooth acceleration and enable optimal energy use and reduced emissions. The inherent safety of AVs reduces requirements for heavy protective equipment for coping with the collisions resulting from driver faults, thus shedding weight on the car body. Once again, this generates lower emissions both on the road and during manufacturing. Autonomous vehicle group behaviors and the related technological changes improve the quality of life by optimizing driving, which leads to better use of road capacity, improved road design and new methods for traffic management, decluttering of urban spaces, easier parking, investments in public transport, taxis and infrastructure, and better management of urban sprawl. Thus, the new method of autonomous vehicle groups alleviates existing problems. In future the concept will offer flexibility, is easy to use, and is applicable to loose and tight formations of various sizes, and to group formation with and without leaders.

1.5 The Structure

Based on the contribution and the overview illustrated in Figure 1.3, the structure of this thesis is outlined in the following. The Figure 1.3 shows that scientific contribution is based on the traffic system environment. The numbers indicate the contributions. In the theoretical chapter, a group model is presented which is materialized by the all-embracing simulation environment. The