Energy-optimized driving with an autonomous vehicle in urban environments

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Abstract*—A high percentage of deceleration and acceleration in urban traffic is caused by the stops at traffic lights. Reducing these required stops combined with an overall smoother traffic flow can reduce the negative effects on the environment in terms of less emissions, noise reduction, and energy consumption. In this paper a cooperative system developed in the research project KOLINE is introduced aiming at the reduction of delay and emissions by adjusting both the signal control and the vehicles' driving strategy. First, the overall system architecture including the wireless communication between traffic signals and vehicles is described. The paper focuses on the vehicles' reaction approaching a signalized intersection and presents a novel approach to optimize the driving strategy based on the traffic information received. The main feature of our approach is the optimization of both longitudinal and lateral guidance of the vehicle simultaneously. Therefore, the surroundings of the vehicles detected by the vehicles' sensors is combined with more precise information on the local traffic state such as tailback length or traffic volume for each lane and forms the basis for proper driving strategies. To handle the complexity of the optimization problem, a metaheuristic considering the possible actions of the vehicle is used to determine the optimal driving strategy in the current driving situation. The optimized strategy is finally realized by a test vehicle capable of driving autonomously in the dense traffic of urban environments.

I. Introduction

Especially in urban traffic networks, required stops at traffic lights causing braking and reacceleration have significant impact on network capacity and emissions of motorized traffic. An efficient coordination of the traffic can help to minimize the total amount of stops in order to reduce delay and emissions in urban networks [1], [2] complying with the European directives relating to limiting values of SO_2, NO_2, NO_x, and PM_{10} [3].

New approaches for optimized traffic coordination are encouraged by modern wireless communication and sensor technology. Today, various projects are working on the development of cooperative systems (e.g. Safespot, CVIS, sim^{TD}) based on car-to-infrastructure (C2I) communication and accurate traffic data.

Such systems often use driver information to coordinate urban traffic. Going one step further, adaptation of the vehicle's automatic cruise control based on current and precise traffic data can increase the traffic efficiency and emission reduction. Moreover, a fully autonomous vehicle offers the opportunity to optimize both longitudinal and lateral guidance simultaneously considering lane change maneuvers as well. The mentioned improvements can be achieved substantially by optimizing the traffic flow at signalized intersections.

The basic idea includes the adaptation of the traffic signal control to the current traffic flow as well as the vehicles' reaction according to optimized driving strategies. Aiming at a more energy-efficient mobility, the authors are contributing to the research project "Cooperative and Optimized Traffic Signal Control in Urban Networks" (KOLINE, www.koline.info). The project itself and a new approach for optimizing the vehicles' driving strategy are presented in the following.

II. Related Work

Already in the early 1980s, a system was developed that recommends an approach velocity allowing the driver to pass the next signal-controlled intersection without stopping [4]. Based on modern wireless communication an improved system could be realized in the project TRAVOLUTION funded by the German government [5].

Due to the growing availability of digital map data and C2X applications, research has started to focus on driver assistance systems for improving the overall mobility and traffic flow.

Another approach that calculates a recommended speed with regard to the current traffic light state and provides this information to the driver can be found in [6]. In [7], an ant colony optimization algorithm is used to optimize the vehicle's driving strategy on highways in terms of fuel consumption.

Research on further traffic improvements regarding supported or automated lane change maneuvers focused mainly on automated highway systems [8] - [10].

Generally, a very efficient vehicle driving strategy is driving at a constant speed [11]. Due to intersections, congestion, and other traffic disruptions, this simple strategy can only be realized in a few situations. To determine an optimized driving strategy for urban traffic the other road users, traffic lights, and upcoming tailbacks need to be taken into account.

III. System Architecture

The aim of the developed system is to adjust both the infrastructure and the vehicles' reaction enabling a mutual optimization. As an integral part of the project, the combination of detector counts and C2I information is used to realize a more reliable prediction of the current traffic situation.

The vehicles provide data about their current position and speed as well as data about surrounding road users which are detected by the vehicle sensors to improve the prediction. This data is collected for the signal control optimization and the tailback approximation. The processed data including information about the local traffic state for each lane and road geometry is then transmitted to the vehicles by I2C communication. Based on the received data the vehicles can determine a driving strategy which is optimized in terms of fuel efficiency and emissions.

A. Main Subsystems

The overall architecture of the cooperative system including all subsystems and signal flow is shown in Fig. 1. The complete system depicts an urban network consisting of multiple signalized intersections, a traffic control center, and specially-equipped vehicles. Therefore, the system is divided into three subsystems KOLINE-Signal Control, KOLINE-Center, and KOLINE-Vehicle.

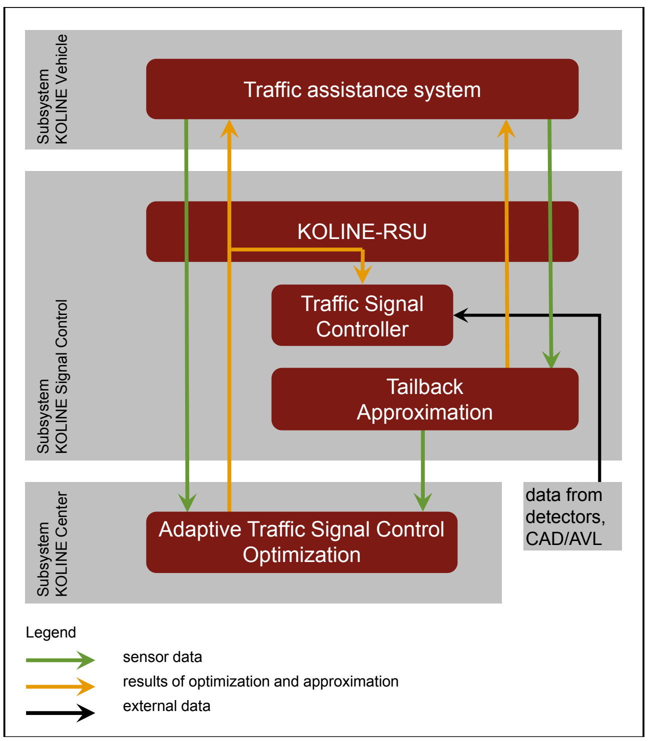

Fig. 1. Overall system architecture [12]

Using a model-based optimization [13], the KOLINE-Center determines the signal programs for all traffic signal controls within the network according to the current traffic demand. For this purpose, it receives the local detector data from every intersection and transmits the particular signal program.

The KOLINE-Road Side Unit (RSU) then forwards the signal program to the Traffic Signal Controller. The RSU is also in charge of transmitting the traffic data provided by the Tailback Approximation module and the signal information to the KOLINE-Vehicles which are currently in range of communication. The concept of the tailback approximation and the calibration of the underlying traffic model is described in [12] in more detail.

B. Communication

The optimization and therefore also the success of the project depend critically on the available data that is transmitted between the RSU and the vehicles. This short-range vehicular communication between the KOLINE-Vehicles and the KOLINE-Signal Control is based on wireless LAN in the 5.9 GHz band. The IEEE 802.11p communication standard which is used in the project was introduced in 2010. The interface of the used vehicular ad-hoc network (VANET) is compliant to the project sim^{TD} [14]. In the KOLINE project, four different types of telegrams are sent; three of them have already been defined in sim^{TD}. The vehicles send their current states including position and speed in the Coop Awareness Message (CAM) to the RSU; the other telegrams are received from the vehicles. The current state of the traffic signals and the next signal times are provided in the SignalphaseAndTimingData (SPAT) message. The topological information in the Intersection telegram including the complete geometry of an intersection, its incoming and outgoing lanes, and lane attributes like the allowed maneuvers is necessary; as a result the vehicles can be assigned to their current lane and the corresponding traffic signal. Additionally, detailed local traffic data such as current traffic volume, the prediction of tailback length with upper and lower deviations are provided for each single lane in a separately defined message using an application specific data structure in the communication protocol.

IV. Test Vehicle "Leonie"

A vehicle built with the intention to drive fully autonomously in urban environments serves as one of the experimental platforms in this research project (see Fig. 2). The test vehicle called "Leonie" has already performed its first autonomous runs in the real urban traffic of Braunschweig's inner ring road [15].

Fig. 2. Test vehicle "Leonie" is approaching a signalized intersection

The vehicle is a Volkswagen Passat station wagon equipped with an additional generator, a full set of automotive sensors and a special gateway to control the vehicle's electronic throttle control, braking system, gearbox, and electric power steering. Six automotive computers connected via Gigabit Ethernet provide the necessary computing capacity for all running software tasks. An INS/GPS bi-directional coupled inertial navigation system localizes the vehicle precisely so that a mapping to the vehicle's lane is possible while approaching an intersection. To fulfill the particular requirements of an autonomous vehicle, multiple sensors and sensor technologies are used. The detection range and the coverage of all sensors are substantially higher than standard sensor equipment in passenger cars.

To gain a significant benefit from the optimization it is important to detect other vehicles or traffic participants in a wide area around the vehicle. The sensor fusion merges the data of all sensors into a consistent representation of the vehicle's environment to combine the specific advantages of each used sensor technology. The processed sensor data and the received information from the road side unit are collected by a central module and are correlated with certain a-priori knowledge, i.e. digital map, speed limits, etc. (see Fig. 3). This allows assessing the current driving situation.

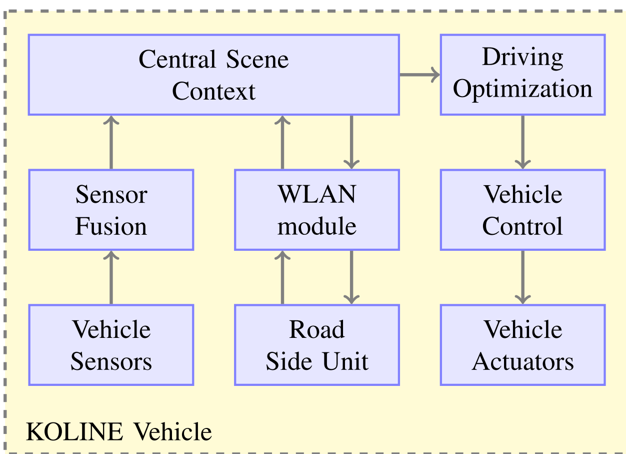

Fig. 3. Vehicle Systems

All recognized vehicles are assigned to specific regions of interest and evaluated in relation to the ego vehicle's scope of action. This information is provided to the driving optimization module and to the road side unit via C2I-communication to be used for optimizing the signal control. A more detailed description of the driving optimization follows in the next section of this paper. The realization of the driving strategy and the resulting trajectory is based on the low level control divided in lateral and longitudinal controller.

V. Optimization

The aim of the driving strategy optimization is to minimize the fuel consumption and the number of required stops at intersections. The result is a higher-level driving decision which adjusts both longitudinal and lateral guidance of the vehicle simultaneously. Safety-relevant tasks such as lane keeping and distance control are directly realized by the vehicle control. Although the optimization problem has continuous states, by modeling it as a discrete decision tree the complexity is significantly reduced. Every node of this tree represents a possible state of the vehicle consisting of the current position p, velocity v, acceleration a, and the lane l described in the state vector $\mathbf{x} = [p, v, a, l]$. The possible driving options in moving urban traffic are basically to adjust the speed, performing a lane change or turning maneuver. These options are defined as

$$O \in (-a_{min}, \ldots, a_i, \ldots, a_{max}, m_i) \tag{1}$$

where a_i represents a set of constant accelerations in the given time interval ΔT between the maximal allowed deceleration $-a_{min}$ and the maximal allowed acceleration a_{max}. m_i are the current possible maneuvers. One of the options has to be chosen for each time step of the prediction.

Based on detailed sensor data and the received information about the local traffic state including a precise traffic state prediction for each lane an adapted decision tree can be built. The chosen options represent the weight respectively the cost of each edge.

Fig. 4 shows an example of a decision tree. For purposes of clarity, only the four options a_{min}, a_0, a_{max}, and a possible lane change to the left m_{left} are modeled for each node.

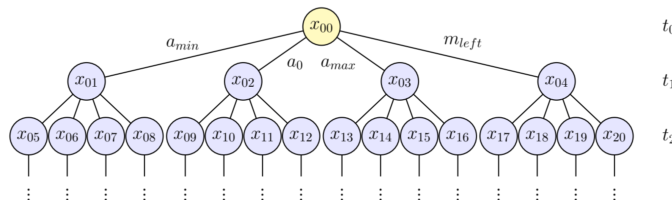

Fig. 4. Example of a decision tree with three time steps based on only four options for each node $O \in (a_{min}, a_0, a_{max}, m_{left})$

An optimal driving strategy corresponds to a set of chosen options, e.g. $S = (x_{00}, x_{02}, x_{11}, \ldots)$, and thus to an optimal path of the decision tree regarding previously defined optimization criteria. The number of possible nodes follows a geometric progression and the number of paths grows exponentially.

To narrow the solution space, some paths can be directly excluded which violate one of the following conditions: the driving strategy has to consider the traffic regulations (speed limits, traffic signs, and so on). The other road users have to be taken into account so that the resulting strategy does not cause hazardous situations. Furthermore, paths including unnecessary lane changes or frequent accelerations are also canceled.

Although the decision tree grows rapidly, a short computation time is essential due to the real-time capability. Therefore, an algorithm based on metaheuristic is used to find the best path. The used max-min ant system (MMAS) is an extension to the ant colony optimization algorithm proposed as metaheuristic for combinatorial optimization [16]. The metaheuristic is directly utilized to build the decision tree and simultaneously to determine the optimal path.

The basic idea of the metaheuristic is based on the behavior of “real” ants while looking for the shortest paths between a food source and their colony. Their route selection is influenced by the pheromone concentration laid down by the previous ants. The higher the concentration, the more likely it becomes that an ant chooses this path.

Therefore, the tendency of each ant to explore a new path in a graph is described as a stochastic model. This model uses the reciprocal of the costs of each edge, the so called heuristic desirability η_{ij}, as a measure how attractive the edge is. In addition to the desirability, each edge is weighted dynamically with an amount of pheromones $\tau_{ij}(t)$. The set of reachable and allowed nodes n from a node i is defined as J_i^k

This results in the transition probability $p_{ij}^k(t)$ that an ant k moves from node i to node j

$$p_{ij}^k(t) = \begin{cases} \frac{\tau_{ij}^{\alpha}(t)\cdot\eta_{ij}^{\beta}}{\sum\limits_{n\in J_i^k}\tau_{in}^{\alpha}(t)\cdot\eta_{in}^{\beta}}, & \text{if } j \in J_i^k \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

The two parameters α and β weight the influence of pheromone concentration and the heuristic desirability. When ants have finished their path, the update of the amount of pheromones is calculated by

$$\tau_{ij}(t+1) = \rho\cdot\tau_{ij}(t) + \Delta\tau_{ij}(t) \tag{3}$$

where ρ is the factor for the evaporation of the pheromones. However, only the edges $E(i,j)$ which are part of the best solution per iteration T_{ib} are intensified by

$$\Delta\tau_{ij}(t) = \begin{cases} \frac{1}{L(T_{ib})}, & \text{if } E(i,j) \in T_{ib} \\ 0, & \text{otherwise} \end{cases} \tag{4}$$

where $L(T_{ib})$ represents the total costs of the best solution per iteration. In order to preserve the tendency to explore new paths, the total amount of pheromones deposited on each edge is limited to the interval

$$\tau_{min} \leq \tau_{ij}(t+1) \leq \tau_{max} \tag{5}$$

at the end of each iteration. The total costs of a complete path can be calculated from the accelerations of each time step on the basis of the vehicle’s longitudinal dynamic. Using the equilibrium of forces along the vehicle longitudinal axis the needed work W_w performed by the driven wheels can be determined.

Assuming only planar vehicle movements, still air and a vehicle equipped with front-wheel drive [17], the necessary traction force F_t based on the equilibrium of forces along the vehicle’s longitudinal axis can be modeled as

$$F_t = f_R\cdot m\cdot g + \lambda_r\cdot m\cdot a + c_d\cdot A\cdot\frac{\rho_A}{2}\cdot v^2 \tag{6}$$

with the rolling resistance coefficient f_R, the vehicle mass m, the acceleration due to gravity g, the ratio of the rotating masses to the vehicle mass λ_r, the aerodynamic drag coefficient c_d, the frontal area A, and the air density ρ_A. Neglecting the longitudinal slip the power P_w of the driven wheels is given by

$$P_w = F_t\cdot v = \frac{\mathrm{d}W_w}{\mathrm{d}t} \tag{7}$$

Integrating (7) over the time period ΔT yields

$$\begin{aligned} W_w &= \int_0^{\Delta T} P_w \mathrm{d}t \qquad (8)\\ &= (\lambda\cdot m\cdot g\cdot a + f_R\cdot m\cdot g)\cdot\left(\frac{1}{2}\cdot a\cdot\Delta T^2 + v\cdot\Delta T\right)\\ &\quad + c_d\cdot A\cdot\frac{\rho_A}{2}\cdot\left(\Delta T\cdot v^3 + \frac{3}{2}\cdot a\cdot\Delta T^2\cdot v^2\right.\\ &\quad \left. + a^2\cdot\Delta T^3\cdot v + \frac{1}{4}\cdot a^3\cdot\Delta T^4\right) \qquad (9)\end{aligned}$$

The sum of the needed work for each time step yields the total costs of a complete path which has to be minimized for the optimal driving strategy.

VI. Experimental Results

The possible potential for optimization is shown with the help of the simulation of an intersection at an arterial road in Braunschweig, Germany. On this two-lane urban road the total volume of traffic is up to 18,000 vehicles per day in each direction [18]. In the simulation, only one direction has been considered to visualize the effect of the developed optimization algorithm. The simulation scenario is sketched in Fig. 5.

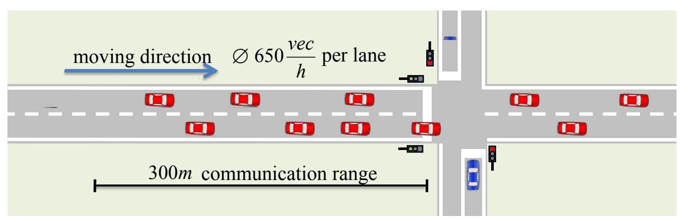

Fig. 5. Simulation scenario

The numbers of simulated vehicles per hour on each lane was set to 650 $\frac{\text{vec}}{\text{h}}$ which is close to the intersection’s maximum capacity. Based on the real traffic signal, the red phase takes 55 seconds and the green phase 30 seconds. The communication range is limited to 300 m which can be reached under good conditions.

Fig. 6 illustrates the velocity profile of a simulated vehicle while approaching a waiting tailback in front of the red traffic light which is located at $x = 0\,\mathrm{m}$. The color of the dots represents the current signal state and the color of the lines indicates the current acceleration of the vehicle. The vehicle’s speed is adjusted when it comes into communication range. To avoid an unnecessary stop, the velocity is reduced to $33.1\,\mathrm{km/h}$ so that the vehicle can pass the intersection when the other vehicles have already started moving.

Assuming that all simulated vehicles are equipped with the presented system, the simulation shows that the total number of required stops on this arterial road can be reduced by 25%.

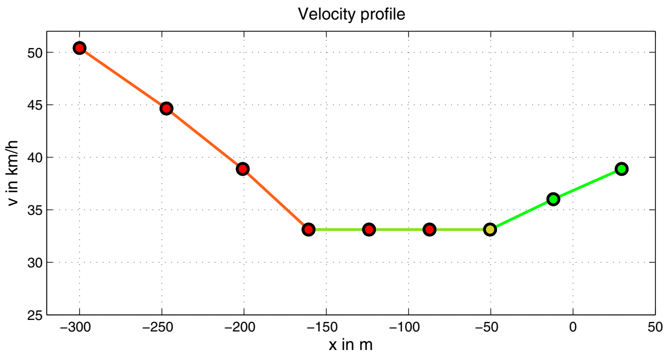

Fig. 6. Resulting velocity profile of the driving strategy while approaching to a red traffic light with waiting tailback

To compare the two scenarios, the work performed by the driven wheels is used again since this physical quantity is independent of the used engine technology and provides a valid comparison of scenarios. Using optimized driving strategies the needed work is reduced by 10% on average, for individual vehicles up to 35%.

VII. Conclusions and Future Work

The aim of the presented system is to reduce the delay and emissions as well as the fuel consumption in urban networks. The overall architecture of the project KOLINE funded by the German government was introduced. The research focuses on adjusting both the signal control and the vehicles' driving strategy in order to achieve these traffic improvements.

Based on C2I-communication a mutual optimization is realized. The data which is exchanged between the vehicles and the infrastructure is used to improve the performance of a traffic control system and to realize a more reliable prediction of the current traffic situation. Furthermore, the vehicles can determine a driving strategy which is optimized in terms of fuel efficiency on the basis of the traffic information received from the infrastructure. The authors presented in detail the vehicle's optimization based on the modified max-min ant system which enables a real-time capable optimization of driving strategy for the entire driving situation. The approach is realized by an autonomous driving vehicle which offers the opportunity to optimize both longitudinal and lateral guidance.

The simulation results give a first impression of the potentials of the optimized vehicle guidance. Currently, the presented overall system is being tested under conditions close to an urban reality on a non-public testing ground. The prepared test site covers an urban network consisting of three signalized intersections modeled after existing ones at an arterial road in Braunschweig. The future work aims at the implementation of the system on an arterial road of Braunschweig, Germany, as part of a test bed called "Application Platform Intelligent Mobility" (AIM) [19] to analyze the impacts of the developed cooperative system on the overall traffic flow.

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