Slipstream Cooperative Adaptive Cruise Control - A Conceptual ITS Application for Electric Vehicles

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***Abstract*—The Electric Vehicle is seen to be one of the most important enablers for a more environmentally friendly mobility of people. Unfortunately, state of the art electric vehicles suffer from a series of problems, with facing a very limited traveling distance compared to gasoline vehicles being one of the most relevant ones. In this paper we present an approach how to reduce the energy consumption while traveling over longer distances by using the slipstream effect behind a vehicle ahead. We show how this can be implemented as a specialized form of cooperative adaptive cruise control, one of the innovative Intelligent Transportation System applications. The paper elaborates in detail on the reliability of the application from the perspective of the current ITS communication technology, by means of two example scenarios, and outlines also on other aspects of implementing *Slipstream Cooperative Adaptive Cruise Control* for electric vehicles.**

I. Introduction

One Million Electric Vehicles (EV) on the roads of Germany until 2020, that's one of the great plans of the government to be able to achieve the strong goal of climate control. Because of several major drawbacks, EVs are currently not attractive enough for most of the potential customers. Thus, for example, equivalent EVs are still more expensive than usual cars. One further important drawback of EVs is their short range, which is typically between 100 and 200 km. This property makes them reasonable for inner city trips, but not for traveling over longer distances.

Information and Communication Technologies for Intelligent Transport Systems (ITS), such as the European ETSI ITS-G5 [5] , can be considered as one of the most important enabling technologies for making EVs more attractive to potential customers. The ITS-G5 communication technology is based on IEEE 802.11p, which is an amendment of IEEE 802.11 (ordinary wireless LAN) to adapt this well known technology for vehicles and their dynamic environment [1], [2], [3]. For radio transmissions a dedicated spectrum in the 5.9 GHz frequency band is used, split into 3 channels (ITS-G5A) for safety related applications and 2 channels (ITS-G5B) for non-safety related applications with 10 MHz bandwidth for each. An additional frequency band (ITS-G5C) can be used for further applications. The access technology makes use of the probabilistic Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism. It allows a fully decentralized control of the medium access without any dependency on infrastructure components. As a result, VANETs span a very flexible network structure. This technology form the basis for ITS applications which can provide more safety, comfort and infotainment to the driver.

In this paper we present a concept to reduce the energy consumption and extend the range for EVs in case of traveling over longer distances, based on ITS communication. The idea is to use the occurring slipstream effect, in case of driving behind another vehicle at a short distance and with a minimum speed. This leads to a reduction of the air drag for the following vehicle. Consequently, the energy consumption can be reduced and the EVs are able to travel longer distances. The application which realizes this idea is called Slipstream Cooperative Adaptive Cruise Control (SCACC).

The remaining paper is structured as follows: In Sec. II more details on the basic concept will be shown, regarding the air drag phenomenon, measuring results and ITS applications. An approach for the reliability analysis of Slipstream Cooperative Adaptive Cruise Control using the current ITS communication technology is described in Sec. III. Sec. IV describes the different stages of SCACC by using the full potential of ITS-G5. Sec. V discusses further improvements with regard to other important aspects. Finally, Sec. VI concludes this paper and gives an outlook for future work.

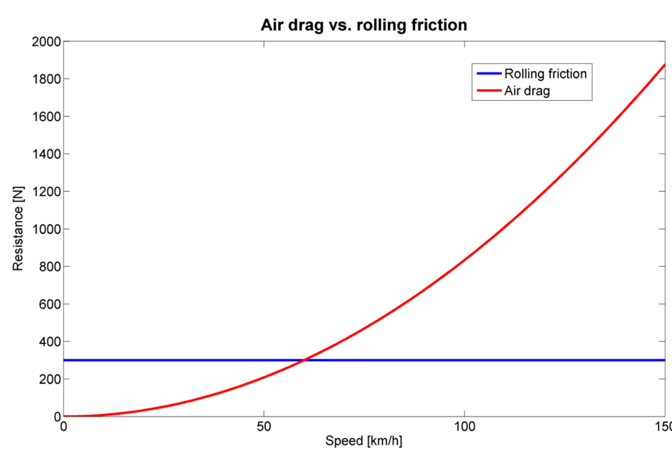

Fig. 1. Air drag versus rolling friction with increasing speed calculated for the research vehicle at DLR.

Distance apart	Reduction
30 m	21 %
3 m	60 %
2 m	80 %
1 m	93 %

TABLE I
MEASUREMENT RESULTS OF AIR DRAG REDUCTION AT 80 KM/H [6].

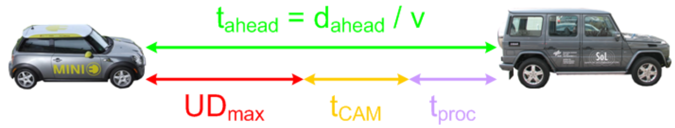

Fig. 2. The time ahead distance and its shares.

II. BASIC CONCEPT

The concept presented here is physically based on the phenomenon of the air drag which is presented in Fig. 1. It depicts the behavior of the air drag versus the rolling friction dependent on the vehicle speed. The curves represented here have been calculated from the specification for our research vehicle, a Mercedes G-400, by using the simplified equations given in [4]. The figure shows very clearly the quadratic ascent of the air drag with an increasing speed of the vehicle. From a speed of 60 km/h the air drag resistance starts to exceed the resistance for the rolling friction. Consequently, air drag reduction seems to be a very good starting point for reducing the energy consumption while driving with higher speeds, e.g. on highways or freeways.

Some first measurements described in [6] show, that it is actually possible to decrease the energy consumption by slipstreaming. Their results are summarized in table I and II. The scenario there was slipstreaming behind a rig by varying the distances between the rig and the car behind. These results show to some extent which safety distances are needed to be able to use the slipstream effect.

The starting point for our idea is Cooperative Adaptive Cruise Control (CACC), a current ITS application, based on the exchange of so called Cooperative Awareness Messages (CAM) [7]. These messages are broadcasted periodically by each vehicle using the ITS-G5 communication technology. CAMs are messages containing information about the current status of the vehicle. Thus, by broadcasting CAMs, each vehicle is aware of all the other vehicles in the vicinity. CACC enables safe platooning for a convoy of several consecutive vehicles by means of ITS communication and forms the ITS basis of our idea.

The challenge of our concept is to reduce the safety distance in such a way, that an efficient use of the slipstream effect is possible. This requires robust and reliable ITS communication as a key technology for safe driving at short distances. In a next step, additional sensors, like RADAR, LIDAR or camera can be used to further increase safe driving at short distances as well as the reliability of the application. Due to the long reaction time of humans, the driver has to be removed from the control loop and autonomous driving and control is necessary, at least in longitudinal direction. The new resulting ITS application is called Slipstream Cooperative Adaptive Cruise Control (SCACC) and is able to reduce the energy consumption and extend the range of EVs while driving with higher speeds over longer distances.

Distance apart	Reduction
30 m	11 %
15 m	20 %
6 m	27 %
3 m	39 %

TABLE II
MEASUREMENT RESULTS OF FUEL CONSUMPTION AT 89 KM/H [6].

III. CURRENT STATE RELIABILITY CONSIDERATIONS

A reliable SCACC application, i.e. driving at very short distances, requires robust ITS communication. A detailed reliability analysis of the current ITS-G5 communication technology in a freeway scenario with high dense traffic was done by Kloiber et. al. in [8]. The approach presented there can be used to analyze the reliability of a possible Slipstream Cooperative Adaptive Cruise Control based on ITS-G5 only. Thereby, the important performance metric for CAM based ITS applications is the so called *Update Delay*, which is defined as the time interval between two consecutive received CAMs from the same transmitter. The approach explained there for the reliability analysis of CAM based ITS applications is to calculate a maximum allowed Update Delay for CAM receptions, by analyzing the application requirements for a correct application functionality. Fig. 2 shows the relation between the maximum Update Delay UD_{max}, the interval of the periodic CAM transmissions t_{CAM}, the time t_{proc} which is needed for processing and finally the distance d_{ahead} or rather its timely representation t_{ahead}.

This leads to the following equation for the maximum Update Delay:

$$UD_{max} = t_{ahead} - t_{CAM} - t_{proc} \qquad (1)$$

For the reliability analysis of SCACC we consider two scenarios: Slipstreaming behind a car at 130 km/h and slipstreaming behind a truck at 80 km/h.

A. Slipstreaming behind a car

For this scenario we assume a constant speed of 130 km/h, a distance of 30 m according to tables I and II, a CAM transmission rate of 10 Hz and a general processing delay of 100 ms. According to the equation above, these values can be used to calculate the maximum allowed Update Delay for the SCACC in that case. Insertion of the given values into equation 1 results in 0.63 s for the maximum allowed Update Delay. By means of the performance curves provided in [8], the probability for exceeding the maximum allowed Update Delay can be determined and is shown in Fig. 3. Thereby one has to take care of choosing the correct curve according to the assumed CAM transmission rate. According to the CAM transmission rate of 10 Hz as assumed above, the graph shows, that the probability for exceeding a maximum allowed Update Delay of 0.63 seconds is in the range of 9×10^{-3}. Exceeding the maximum allowed Update Delay means that the application requirement for a proper functionality is not fulfilled, and the SCACC is not working reliable. With regard to safety aspects, where failure probabilities of 10^{-8} and less are intended, this value is absolutely not acceptable. If considering a more effective slipstreaming distance of even 3 m, the maximum allowed Update Delay is negative and not applicable any more.

B. Slipstreaming behind a truck

For the truck scenario we assume a constant speed of 80 km/h, the same distance of 30 m, a CAM transmission rate of 10 Hz and again a processing delay of 100 ms. Using these values equation 1 results in 1.15 s for the maximum allowed Update Delay. Fig. 4 shows the determined probability for exceeding that maximum allowed Update Delay by means of the respective performance curve for the 10 Hz CAM transmission rate. The probability of exceeding the maximum allowed Update Delay of 1.15 seconds in this case is in the range of 4×10^{-4}, a still too high value, having the safety aspect in mind. Considering here a more effective slipstream distance of 3 m, too, leads still to a negative maximum allowed Update Delay, which is not applicable using the assumptions above.

More details on the procedure of the reliability analysis of CAM based safety applications are given in [8].

IV. Using the Full Potential of ITS-G5

The investigations above have shown that SCACC is not feasible using current ITS-G5 control channel only. CACC is the ancestor of our SCACC application and is based on broadcasting CAMs. But broadcasts in ITS-G5 have some major drawbacks according to the reliability of information transmission:

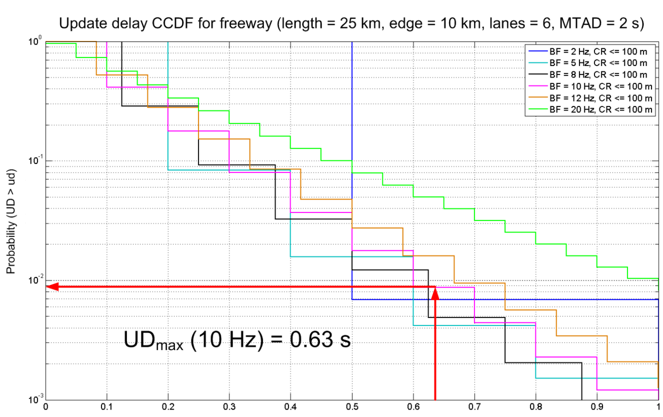

Fig. 3. Reliability analysis method for SCACC behind a car.

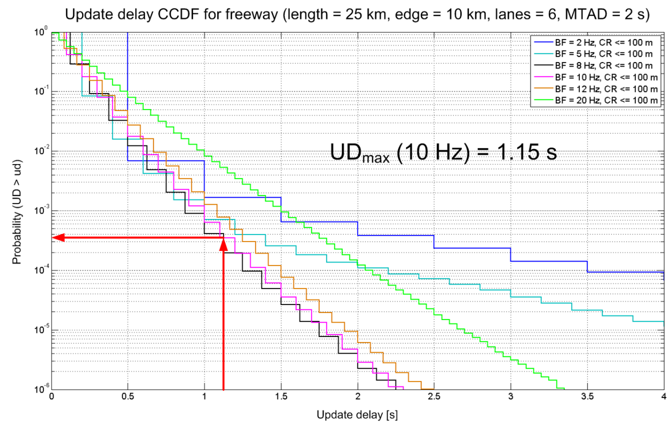

Fig. 4. Reliability analysis method for SCACC behind a truck.

During unicast transmissions, the receiver is able to acknowledge the correct reception of the packet. If the transmitter doesn't get an acknowledgement in time, the packet will be retransmitted again. Acknowledging packets is not possible during broadcast transmissions, because the packet is not addressed to one specific vehicle, but to all within the communication range. Thus, the transmitter cannot even be sure, that at least one vehicle has received the packet correctly.

Moreover, unicast transmissions are allowed to use the Request To Send (RTS) / Clear To Send (CTS) collision avoidance mechanism [9], to reserve the channel for the following data packet transmission. This mechanism, too, cannot be used during broadcast transmissions, which leads to the well known hidden terminal problem [10], causing additional packet collisions.

Because the loss of packets is the main reason for an increasing Update Delay during the periodic broadcast of CAMs, our proposal is to use dedicated unicast communication between the in tandem driving cars running SCACC. Hence, the information exchange between the corresponding vehicles can be made more reliable by using acknowledgements and the RTS/CTS mechanism if necessary[1]. To avoid congestion on the Control CHannel (CCH), we further propose to use a dedicated Service CHannel (SCH) only for SCACC. The existence of a dedicated SCACC SCH could be proclaimed by so called service announcement messages broadcasted on the CCH [11]. This approach, too, can reduce packet collisions and increase the reliability of information transmission, because there is no additional contention with other message types not used by SCACC.

Running SCACC may be done in a platoon of 2 vehicles or more, following each other at a short distance. Platoons of multiple vehicles have been analyzed in the German national project KONVOI [15], which aimed at the automation of truck platoons on highways for a better utilization of the road network and increasing road safety. The distance was controlled to the desired 10 m by means of automatic distance and lane

[1]If the packets are small, the RTS/CTS communication overhead doesn't pay

keeping systems. For their truck platoon scenario, they provide four different steps: Platoon-organization, -formation, -drive and -brake-up [16]. In the following subsections, we describe the different steps and show the connection to SCACC for electric vehicles.

A. Platoon-organization

The first step is to organize a SCACC platoon, if there is no existing platoon, or to find an already existing SCACC platoon with the possibility to join it. Finding other vehicles to form a new platoon, or finding an already existing platoon, can be realized by using the broadcast of standard CAMs and service announcements on the CCH. The SCACC announcement, in our case, may contain information about the necessary capabilities and the dedicated SCH, which will be used for reliable SCACC. If at least two vehicles have been encountered, they have to arrange the order of the platoon. In case of joining an already existing platoon, the vehicles have to negotiate at which position in the platoon the joining vehicle is allowed to merge.

B. Platoon-formation

If the leading vehicle has been determined, the merging of the SCACC participating vehicles can be started to form an ordinary platoon. After the establishment of the reliable unicast connections on the dedicated SCH, as discussed before, the vehicles can start to shorten the distance in a controlled way, until the safety and slipstream efficiency aspect are at the appropriate rate. In case of a new vehicle intending to join an already existing platoon, the platoon has to brake up at the corresponding position, to free up space for the joining vehicle. After the vehicle has merged, the gaps will be shortened again for efficient using of the slipstream effect, by using the dedicated unicast communication.

C. Platoon-drive

In this stage the platoon is in a steady-state. To be able to keep the very short distances, the mean human reaction time is too long, so that the driver has to be taken out of the loop. That means, at least all following vehicles, have to be controlled automatically in longitudinal direction. Sometimes it could be necessary for the platoon to perform a lane change maneuver, thus it could be better even to control the lateral direction of the vehicles automatically.

D. Platoon-brake-up

If one or more vehicles have reached their destination, they have to leave the platoon. If not all vehicles are leaving, the remaining part of the platoon can still go on. Only the gaps have to be closed by the vehicles in the remaining platoon. Otherwise, the platoon brakes up completely.

V. Further Improvements

This section discusses further improvements regarding other important aspects to bring SCACC closer to realization. Thereby, the support by additional sensors and the user acceptance play a significant role.

A. Additional Local Sensors and Positioning

A very important implementation aspect for the SCACC application, is the relative position between the platoon members. The vehicles must have accurate knowledge about the relative position towards the vehicle driving in front, but also to the other vehicles driving ahead. Additionally, information about the vehicles dynamics (speed, acceleration, turn rate, etc.) are of advantage in order to foresee the movement maneuvers and predict the future relative position of the surrounding vehicles.

An SCACC message may contain the geographical position (latitude, longitude, elevation), position confidence, speed, speed confidence, heading, curvature, longitudinal acceleration, etc., as also defined for ETSIs CAM specification [12]. GNSS is based on the measurement of the distance to a set of satellites that orbit around the Earth in order to calculate the position of the receiver in global coordinates. In this process a series of error sources will have a negative impact on the accuracy of the calculated position. For instance, errors in the satellite ephemeris and clock, propagation delays in the atmosphere, offset of the receiver clock as well as receiver noise yield in sum an error of σ_{rms} = 6 m [13].

To be able to fulfill the demands imposed on the relative position regarding accuracy, availability and integrity, we propose to follow a sensor fusion model where multiple sources of information are merged in order to provide an accurate image of the surrounding traffic situation. This leads to a design, where a range sensor, as for instance RADAR or LIDAR, are combined with the sensor measurements available inside the received messages. The information on the vehicle dynamics along with a state transition model for the vehicles can yield an accurate prediction of multiple targets in the platoon. The combination of this with the ranging sensor can overcome GPS drop-outs due to shadowing and obstructions and thus increase the availability of the system. The filter outputs a posterior for the system state, which can be seen as the current integrity measurement of the system. If the uncertainty of the relative position to the other targets gets too high the system might fall down to the user controlled mode.

Given the fact that the SCACC application requires accurate knowledge of the relative position towards other vehicles rather than accounting for their absolute location in a global frame a further improvement is suggested. Due to their vicinity, the vehicles forming a platoon see the same set of satellites and are subjected to the same ephemeris and satellite clock errors, as well as the same atmospheric errors. These common errors in the receivers can be canceled by following differential techniques. Making use of the communication channel between the vehicles, raw-GNSS data as code and carrier phase ranges and Doppler measurements might be exchanged. Mid-range GNSS receivers are able to provide raw-data measurements at 5 to 10 Hz rate. A further advantage of exchanging raw data is that the SCACC fusion engine benefits from using unprocessed data. Usually, automotive GNSS receivers filter the calculated GNSS position using a movement model for the dynamics of the vehicle. The noisy

Fig. 5. Looking through vehicle effect by projection of the scene ahead onto the head-up display to increase the drivers comfort in SCACC [14].

GNSS output is smoothed and is not prone to sudden changes. The SCACC however, requires sensor outputs to be consistent with each other (e.g the GNSS output and the INS values) in order to apply its own state transition models.

B. User Acceptance

Another issue which should be addressed for the realization of SCACC is the user acceptance. One can easily imagine, if driving behind a truck at a few meters distance with a speed of 100 km/h or more, seeing nothing but the backside of the truck, the driver must feel very uncomfortable, despite the automatic control of the vehicle by the SCACC application. The driver would feel much more comfortable, if he could see what happens in front of the truck. As we discussed cameras as possible additional sensors before, it is quite imaginable to transmit video data of the scene in front of the truck to the vehicle behind using ITS communication. The data could be processed and projected in a user acceptable form onto a head-up display. In a possible scenario as shown in Fig. 5, the comfort of the driver can be increased significantly, despite of driving behind a van at a short distance.

VI. Conclusion and Future Work

This paper describes a conceptual idea of the new ITS application SCACC which makes it possible to follow other vehicles at short distances in order to use the slipstream effect and reduce the energy consumption. This can make EVs more attractive according to the current range limitations if traveling over longer distances. The presentation in this paper includes reliability considerations of the SCACC application with respect to the current communication technology ITS-G5, as well as ideas on further improvements for other important implementation aspects.

In future works the conceptual ideas presented here should be investigated in much more detail, i.e. improvement of the communication reliability, integration of additional sensors, increasing the user acceptance and finally putting all things together to build up a complete SCACC application, with it's different stages.

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