Vehicular Communication Performance in Convoys of Automated Vehicles

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Abstract—The combination of automated driving and Inter-Vehicle Communication (IVC) allows automated vehicles to drive cooperatively, thereby greatly enhancing their safety and traffic efficiency. Convoys are groups of automated vehicles which keep a multi-lane formation with decentralized control supported by IVC. The vehicle control algorithm of convoy vehicles requires up-to-date information about the neighbor vehicle dynamics; fast and efficient convoy communications enable the cooperative maneuvering of the automated vehicles. For this reason, we evaluate IVC in convoys of automated vehicles by defining performance metrics which quantify the reliability, latency and data age of convoy communications. Our results explore the trade-off between the convoy message frequency and the communication performance; whereas a high message frequency results in a higher number of lost messages and delay due to channel congestion, a low message frequency yields a higher data age of the information available to the vehicle controller. As a result, convoy algorithm designers should choose carefully the optimal value for the convoy message frequency as a function of the required communication performance and the convoy size.

I. INTRODUCTION

Road vehicles are increasingly equipped with various driver assistance systems, which make driving safer and more comfortable. Typically, these systems warn drivers about imminent danger or support them in critical driving situations, for example when the driver unintentionally departs the lane. Extensions of these assistance systems can execute specific driver tasks in some situations. Adaptive Cruise Control (ACC) automates the driver’s longitudinal control (acceleration and braking) of the vehicle by adjusting the vehicle speed to maintain a safe distance to vehicles ahead. ACC can be regarded as an important step towards fully automated driving, where the vehicle is capable of driving autonomously without driver intervention in all situations. It is a base functionality for automated convoy driving [1], where vehicles with common trajectories drive in a multi-lane formation and coordinate their maneuvers in a decentralized way.

State-of-the-art ACC systems typically rely on a single or multiple radar installed in front of the vehicle, which may be combined with lane keeping and power steering. The radar, jointly with other sensors, provides their sensor measures to an in-vehicle perception sub-system, which constructs a consistent real-time model of the vehicle’s surrounding. Based on this local environmental model, the vehicle controller executes the algorithms for longitudinal and lateral motion control of the vehicle. In general, the sensors of an ACC system have a limited perception range (i.e., they can only see the directly adjacent vehicles) [2] and do not work reliably in adverse weather conditions. These limitations result in an inaccurate model of the vehicle environment and potentially erroneous output of the vehicle controller.

Inter-Vehicle Communication (IVC) may allow to overcome the limitations of ACC by direct communication between nearby vehicles. Convoys of automated vehicles enable safe and efficient cooperative driving by providing three key features [3]: (i) real-time exchange of vehicle dynamics (position, speed, heading and acceleration), (ii) cooperative sensing to enhance the environmental model of autonomous vehicles by means of the mutual exchange of sensed data, and (iii) cooperative maneuvering to allow vehicles to drive coordinately according to a common decision-making strategy.

Whereas in conventional Cooperative ACC (C-ACC) systems a vehicle transmits its dynamics data to its follower vehicle only [4], an automated vehicle in a convoy exchanges information and cooperates with all its neighbors, including those on adjacent lanes. This cooperation allows a better estimation of the dynamics of neighboring vehicles and prevents oscillations in the inter-vehicle spacing, which potentially lead to the instability of the vehicle formation.1

The present paper studies the performance of IVC for convoys of autonomous vehicles by means of a bidirectionally-coupled vehicle and network simulation. After outlining the trade-offs between message transmission frequency, reliability and delay, we provide quantitative results of the communication performance in convoys of automated vehicles. These results may serve as guideline for the design of efficient and robust vehicle control algorithms for convoys.

The effects of IVC on C-ACC and convoys of autonomous vehicles have also been studied in other publications. [5] and [6] model a convoy as a networked control system that takes into account communication effects and analyzes its string stability. [7] shows measurement results from a field trial with WiFi/OCB-based communication in a non-line-of-sight (NLOS) environment for convoys. [8] develops a C-ACC system that gracefully degrades to conventional ACC

1This is also referred to as string (in-)stability, where the convoy is modeled as a string of vehicles and analyzed from a control theory perspective [5].
II. CONVOYS OF AUTOMATED VEHICLES

Cooperative driving among nearby vehicles is achieved by vehicle groups which exchange information by means of IVC. Convoy vehicles exchange information by means of IVC. These messages include the vehicle position, speed, acceleration, heading and maneuver intentions (e.g., lane change), amongst others. Given the typical transmission range of WiFi-based IVC, the neighbor vehicles in a convoy are located within the single-hop range. The required frequency for the transmission of convoy messages will depend on the convoy size, speed and the specific vehicle formation, and it will have a direct impact on the maneuvering performance of the control algorithm.

In addition to keeping the desired formation, vehicles can join/leave the convoy dynamically without jeopardizing the group stability by exchanging dedicated convoy management messages [3]. Furthermore, the vehicle control strategy integrates a lane-keeping algorithm which allows the convoy to follow the road geometry.

The interested reader may find further details about the convoy algorithm in [1].

III. INFLUENCE OF INTER-VEHICLE COMMUNICATIONS IN THE VEHICLE CONTROL

An important requirement for the control of convoy vehicles is their information exchange by means of inter-vehicle communications. Most vehicle control algorithms in C-ACC systems are based on minimizing an objective function which quantifies the error between the desired and the actual distance to the vehicle in front

\[ e_i = |d_i - d_{r,i}| = |(q_{i-1} - q_i) - h_i v_i| \]  

where \( d_i \) and \( d_{r,i} \) are the measured and desired distance, respectively, between the ego-vehicle \( i \) and the preceding vehicle \( i - 1 \). \( d_i \) is calculated as the difference between the measured vehicle positions \( q_{i-1} \) and \( q_i \), and \( d_{r,i} \) is equal to the desired time headway \( h_i \) (i.e., the temporal spacing between consecutive vehicles) multiplied by the \( i \)-th vehicle speed \( v_i \).

One of the main challenges in the calculation of this objective function by the ego-vehicle is the correct estimation of the dynamics of the vehicle in front, such as its position, speed and acceleration. The position of an adjacent vehicle can be obtained from the local vehicle sensors, applying a technique known as sensor data fusion [13]. However, other parameters, such as the speed, acceleration and planned maneuvers of neighbor vehicles, are best obtained by means of information exchange through inter-vehicle communications.

A critical aspect for the accurate estimation of the neighbor vehicle dynamics via IVC is the data age of the received information [9], defined as the time interval between the instant when the data is generated in the source vehicle until it has been processed by the ego-vehicle. In essence, the data age \( t_{age} \) is mainly influenced by three main factors, namely, the communication delay \( t_d \), the message transmission period \( T \) and the number of lost messages \( N_p \), with minimum and maximum values as follows:

\[ t_{age} \in [t_d, t_d + T(1 + N_p)] \]  

\(^2\text{Constant time headway is a popular policy, where the desired speed of the vehicle is proportional to the inter-vehicle distance, with the specified headway being the reciprocal of the constant of proportionality.}\)
In the best-case scenario, the data age is equal to the communication delay, which includes the time to gather the local sensor data, to generate and process the message, the duration of the packet transmission, and the time to decode and process the message at the receiver. In a general case, the data age also depends on the elapsed time since the last message transmission reception from the neighbor vehicle, which is on average proportional to the message period $T$. Furthermore, a number $N_p$ of lost packets will considerably increase the age of the received data.

Since the data age of information received by IVC is always greater than zero, the ego-vehicle controller is required to function with outdated (and probably inaccurate) information about the neighbor vehicle dynamics. Even though some parameters can be estimated (e.g., the new vehicle position based on its previous position, speed and heading), outdated data presents an additional challenge for the vehicle controller.

In order to minimize the data age, data should be transmitted with the highest possible frequency and with minimum packet loss and delay. Considering WiFi-based ad hoc communication operating in the 5.9 GHz frequency range, it is commonly assumed that 10 Hz is an upper bound for the periodic safety message rate. However, for a given convoy size, a very high message rate may result in long delay and high packet loss. Contrary, decreasing the message rate may improve packet loss and delay, but comes at the cost of the overall data age at the receiver. Therefore, convoy control algorithms will need to cope with the inefficiencies of IVC. We analyze next the performance and trade-offs of IVC in a convoy of automated vehicles, focusing on the aspects that determine the data age: reliability, communication delay and message frequency.

IV. PERFORMANCE EVALUATION

This section presents the simulation environment selected to evaluate the performance of convoy communications. Next, the considered communication metrics are described and the obtained results are discussed.

A. Simulation framework

Our proposed approach combines a vehicle simulator and a network simulator to analyze the communications among convoy vehicles with a high realism. This approach provides an accurate model for the vehicle dynamics together with a precise implementation of the protocol stack. As a result, the obtained results will be very close to an experiment with real vehicles, with the advantage that scenarios with a large number of vehicles can be considered without cost concerns.

As network simulator we have selected ns-3 [14], a widely-used tool by the research community for the simulation of communication networks and Internet systems. ns-3 is a discrete-event simulator particularly well suited for the simulation of IVC, due to its highly accurate model of the IEEE 802.11 physical and MAC layers for IVC, its flexibility and extendability. We have implemented the convoy messaging protocol in ns-3, as well as the standard Cooperative Awareness Messages (CAM, EN 302 637-2), Decentralized Environmental Notification Messages (DENM, EN 302 637-3), and the GeoNetworking algorithms of the European protocol stack for inter-vehicle communication [15].

The chosen vehicle simulator is Webots 4, a powerful, sub-microscopic, high-fidelity simulator originally developed for mobile robotics, which has recently been upgraded to support automotive platforms. Webots provides a useful framework for faithfully reproducing multiple intelligent vehicles based on the Open Dynamics Engine (ODE) library.

B. Simulation scenario

In order to evaluate the communications of automated vehicles in a convoy, we have designed a scenario consisting of a vehicle convoy in a freeway with the Webots PRO simulator, version 8.3.0, as shown in Fig. 2. The convoy vehicles drive along a ring-shaped freeway with 8 lanes following a multi-lane formation, eventually returning to their initial position.

The vehicles are controlled by the convoy algorithm described in Section II, implemented in Webots, which allows them to perform lane-keeping and cooperative maneuvering in a fully distributed manner through the exchange of convoy messages. These periodic single-hop messages are transmitted with a common transmission frequency; the time instant of the first transmission is randomly chosen by each vehicle. Convoy messages are broadcast on a single channel with the ITS-G5 (IEEE 802.11p) protocol, with standard parameters for IVC. The radio propagation model considered is a log-distance path loss model with Nakagami fading, which has been validated experimentally [16].

The convoy communication protocol is modeled in the network simulator ns-3, version 3.19. The simulation results are calculated as the average of 30 simulation runs with a duration of 30 seconds. The main parameters of the simulation are summarized in Table I.

In addition to the convoy vehicles, the simulation includes 160 vehicles driving within transmission range of the convoy (approximately 400 m [17]) which broadcast periodic CAMs every 500 ms, thereby increasing the load in the wireless communication channels.

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3Outside the Context of a BSS (OCB) in IEEE 802.11-2012.
4http://www.cyberbotics.com/
channel. For the convoy vehicles, the transmission of CAMs is no longer needed, since their content is included in the convoy messages.

The design parameters that have been considered to evaluate the communication performance of convoy are the convoy message frequency (i.e., the inverse of the time interval between the transmission of convoy packets) and the number of vehicles in the convoy.

C. Communication metrics

We have selected four relevant communication metrics to evaluate the performance of convoy communications:

- The Node Coverage Ratio (NCR) measures the reliability of a message dissemination in a vehicle group. It is defined as the ratio between the number of vehicles which receive a message and the total number of vehicles in the convoy. There are two main reasons for lost messages, namely, collisions between packets whose transmissions overlap, and a high path loss among vehicles located far away from each other.

- The communication delay for all convoy transmissions is defined as the time between the packet transmission and its reception by each of the vehicles in the convoy. It is determined by the time required to encode, transmit and decode the message. In case of channel congestion, the communication delay is expected to increase due to the backoff intervals introduced by the random channel access scheme CSMA/CA.

- The global transmission rate is calculated as the total number of convoy messages sent by all convoy vehicles per second. It mainly depends on the number of vehicles in the convoy and the message transmission frequency of the individual convoy vehicles.

- The data age, defined in Eq. 2, measures the freshness of the information received by IVC which is available to the convoy vehicle controller. In order to guarantee an efficient performance of the vehicle controller algorithm, the data age should be kept as low as possible.

D. Simulation results

We describe next some of the most relevant results obtained with the simulations, which evaluate the influence of the convoy size and the message frequency on the communication performance of the convoy. We consider several values for the convoy size, ranging from 6 to 40 vehicles, and a transmission frequency of convoy messages between 0.5 and 15 Hz.

As we can see in Fig. 3 (top), the average NCR of convoy messages is near 100% for small convoys, but it decreases progressively for larger convoy sizes. We also observe that a higher NCR can be achieved by lowering the convoy message frequency, especially in large convoys. The main cause for the lost messages are collisions among (nearly) simultaneous transmissions by different vehicles. It is also important to note that the fact that all vehicles transmit convoy messages with a common frequency leads to a high standard deviation in the NCR among different simulation runs; in case that several vehicles randomly choose a similar time instant for their initial message transmissions, also the following transmissions will collide repeatedly, leading to a greatly decreased NCR with respect to the case when all convoy message transmissions do not overlap in time.

In summary, there is a trade-off between the convoy size and the message frequency on one side, and the communication reliability of convoy messages on the other. In consequence, the convoy message frequency must be chosen appropriately as a function of the convoy size in order to guarantee a certain communication reliability. For instance, in a convoy with 40 vehicles, the convoy message frequency needs to be set to a value of at most 5 Hz in order to keep the average NCR above 85%. The vehicle controller should therefore be resilient to an adaptive transmission frequency of convoy messages depending of the convoy size.

Fig. 3 (bottom) shows the global transmission rate of convoy messages. As expected, this value is directly proportional to both the convoy size and the convoy message frequency, with a very low variability among different simulation runs. We observe that the degradation in the NCR is correlated to the global transmission rate; therefore, the convoy message frequency should be adjusted in order to keep the transmission rate below this value as far as possible.

Fig. 4 (top) shows that the average communication delay of all transmitted convoy messages also depends on the selected convoy parameters. Most importantly, we observe that the delay increases in large convoys with a high convoy message frequency. Such scenario yields a high global transmission rate of messages and results in a higher number of packet collisions, which increase the communication delay of convoy messages more than 100% with respect to the case of a small convoy or a low message frequency. Therefore, it is important to choose carefully the message frequency as a function of the convoy size in order to keep a low communication delay.

Finally, Fig. 4 (bottom) plots the average data age of the information received by all convoy vehicles. As we can observe, the data age is mainly determined by the transmission

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
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</thead>
<tbody>
<tr>
<td>Freeway length</td>
<td>2 km (8 lanes)</td>
</tr>
<tr>
<td>Convoy size</td>
<td>6 – 40 vehicles</td>
</tr>
<tr>
<td>Average vehicle speed</td>
<td>25 km/h</td>
</tr>
<tr>
<td>Convoy message size</td>
<td>2048 bytes</td>
</tr>
<tr>
<td>Convoy message frequency</td>
<td>0.5 – 15 Hz</td>
</tr>
<tr>
<td>PHY / MAC protocol</td>
<td>ITS-G5 (802.11p)</td>
</tr>
<tr>
<td>Data rate</td>
<td>6 Mbit/s</td>
</tr>
<tr>
<td>Transmit power + antenna gain</td>
<td>20 dBm + 9.1 dB</td>
</tr>
<tr>
<td>Receiver sensitivity</td>
<td>-95 dBm</td>
</tr>
<tr>
<td>Channel bandwidth</td>
<td>10 MHz at 5.9 GHz</td>
</tr>
<tr>
<td>Simulation runs / duration</td>
<td>30 / 30 s</td>
</tr>
</tbody>
</table>

TABLE I SIMULATION PARAMETERS
frequency of convoy messages; in order to have up-to-date information about their neighbors, all vehicles must broadcast convoy messages with a high frequency. The data age also increases slightly with the convoy size, due to the previously discussed delays and collisions associated to a higher channel load. Although high convoy message frequencies lead to a lower NCR and higher communication delay, they also provide the vehicle controller with the most up-to-date information, i.e., with the lowest data age.

V. CONCLUSIONS

Convoys of automated vehicles allow the creation and management of multi-lane formations of vehicles which maneuver coordinateely thanks to the exchange of information by means of Inter-Vehicle Communication (IVC). Convoy vehicles require fast and reliable communications in order to ensure a safe and smooth driving for all convoy vehicles.

In order to quantify the communication performance of convoys of automated vehicles, we consider the bidirectional coupling of the vehicle simulator Webots and the network simulator ns-3. This approach allows the use of highly realistic models both of the vehicle dynamics and the communication protocols.

We have evaluated four communication metrics of convoys using this simulation framework: the Node Coverage Ratio (NCR), the communication delay, the global transmission rate and the data age of convoy messages. The results show that the performance of IVC in convoys (NCR and delay) progressively deteriorates as the number of vehicles in the convoy increases. Both communication metrics can be improved, to some extent, by reducing the convoy message frequency; however, this increases the average data age of the received information, i.e., it requires the vehicle control algorithm to operate with more outdated data about its neighbor vehicles. Therefore, it is important to select a convoy message frequency appropriate for the particular scenario, which provides up-to-date information to the convoy vehicles while avoiding the congestion of the wireless channel.

The obtained results serve as guidelines for designers of
control algorithms for convoys of automated vehicles, as they quantify the trade-off between the delay, reliability and data age of messages transmitted by the convoy vehicles. The impact of these communication metrics on the convoy performance (e.g., the duration of an overtaking maneuver or the required separation distance between neighboring vehicles) remains to be analyzed; we consider this a promising area for future study.

ACKNOWLEDGMENT

This work was supported by the European Commission under AutoNet2030, a collaborative project part of the Seventh Framework Programme for research, technological development and demonstration (Grant Agreement NO. 610542). The authors would like to thank all partners within AutoNet2030, and in particular David Mansolino and Iñaki Navarro, for their cooperation and valuable contribution.

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