Strategic Coordination of Cooperative Truck Overtaking Maneuvers

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Abstract: This paper demonstrates how a cooperative truck overtaking maneuver can be coordinated and synchronized via V2X. This is relevant because the classical truck overtaking maneuver imposes high stress on truck drivers, which can lead to work absences or accidents. We define which abstract/atomic tasks are involved in the truck overtaking maneuver and assign them to a distributed state machine. With the help of a V2X message we then synchronize this state machine and exchange all information relevant for the overtaking maneuver. The simulation of 600 overtaking scenarios demonstrates that the developed concept is adequate and that a transmission frequency of 5 Hz offers the best trade-off between channel load and maneuver quality.

1 INTRODUCTION

In Germany, the volume of freight transport has increased since 2015 from 4,470,468 kt annually by 1.5-2 % to 4,726,810 kt in 2018. In the same period, the share of the total volume transported by road transport increased from 78.1 % to 79.2 % (Statistisches Bundesamt, 2020). Of this again, about 90 % is transported by truck (Statista, 2020). Thus, a trend toward an increasing need for transportation by truck becomes obvious. The Covid-19 pandemic has also highlighted the need for and our dependence on truck transportation. In March 2020, shortly before the first lockdown in Germany, fears of supply chains breaking down due to the effects of the pandemic were already being fanned and an extreme strain on truck drivers was predicted (Hecking, 2020). Shortly afterwards, the MAN Truck & Bus SE for instance, had to stop production, partly due to supply chains breaking down (MAN Truck & Bus SE, 2020). However, for the fact that despite the extreme conditions the basic supply of goods in Germany could be secured, Federal Minister Scheuer expressed a big gratitude to all truck drivers and emphasized their importance (Bundesministerium für Verkehr und digitale Infrastruktur, 2020).

While the need for truck drivers is undisputed for a sustainable supply and economy, Germany is also faced with a severe driver shortage (Schlamp, 2020). In addition, existing truck drivers are under extreme stress during their working day, often caused by time pressure and conflicts with other road users (Evers, 2010). The consequences of these strains are illnesses (Bergrath, 2011) and accidents (Evers, 2010) For example, the recent health reports of the insurance companies show a peak of days-off-work per year in transport and logistics occupations (approx. 30 % above the average) and especially for vehicle drivers: 25 days per year, 70 % above the average (Bessel, 2020). Among the transportation professions, 27 % of the days off work were caused by back pain, while 13 % were caused by mental illnesses categorized according to ICD-10.

However, stress not only leads to illness, but also to risky and error-prone driving (Evers, 2010). In 2018, 61 % of accidents with personal injuries involving trucks on highways were caused by driver error (Statistisches Bundesamt, 2018).

Our short-term goal is therefore to relieve truck drivers through a cooperative truck overtaking assistant in order to reduce lost working days and accidents and to promote sustainable truck traffic. The long-term goal is to prepare trucks for cooperative autonomous driving functions. For these goals, we have already published the concept of the cooperative truck overtaking with optimized starting points, velocity profiles (Mertens, Hauenstein,

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Diermeyer, Jahn, & Kraus, 2020) and reduced safety distance (Mertens, Hauenstein, Diermeyer, & Kraus, 2020).

This paper starts in Section 2 with an overview of V2X, Cooperative Truck Overtaking, and the Collaborative Maneuver Protocol. In Section 3, it continues to introduce the distributed state machine for the strategic planning level and specify the message for coordination. The following Section 4 describes our simulation setup and present the results and discussions in before ending with a conclusion in Section 5.

2 STATE OF THE ART

This section, gives a briefly review of V2X and analysis of trends in this field over the last 20 years. Afterwards it states approaches for cooperative truck overtaking before presenting the Collaborative Maneuver Protocol as a possibility for strategic coordination. Afterwards a brief introduction to the project IMAGinE with the participating partners and goals is given.

2.1 V2X

An important step toward autonomous road traffic is connectivity and cooperation between vehicles (Mertens, Knies, et al., 2020). While it is still unclear which technology will prevail for data exchange in the future (WLAN or cellular based (Vukadinovic et al., 2018)), the standardization of the messages to be transmitted is progressing successfully. In Europe, the Cooperative Awareness Message (CAM) (ETSI - ITS, 2014a) and Decentralized Environmental Notification Message (DENM) (ETSI - ITS, 2014b) have already been specified by ETSI and the first vehicles such as the VW Golf 8 or the VW ID.3 are sending them as part of their standard equipment via ITS-G5 (ADAC, 2020).

In addition to these so-called Day 1 messages, the development of the Day 2 message Collective Perception Message (CPM) (ETSI, 2020) is already well advanced and will enable the exchange of sensor information in the future. Following on from this, the Maneuver Coordination Message (MCM) is being developed for coordination and maneuver planning via trajectories (CAR 2 CAR Communication Consortium, 2019).

2.2 Cooperative Truck Overtaking

During truck overtaking maneuver, the safety distances between the trucks before and after the lane change are often greatly undercut and conflicts arise with the car drivers because the truck blocks the overtaking lane. As already mentioned in the introduction, this can lead to high stress for the truck drivers and to accidents. V2X may be used also between trucks to optimize the truck overtaking maneuver and there are four steps (Mertens, Hauenstein, Diermeyer, Jahn, & Kraus, 2020):

- Find an optimized overtaking position
- Secure the reduced safety gap
- Perform a cooperative lane change
- Adjust the velocities during overtaking

While maneuver planning on a trajectory level could e.g. coordinate the cooperative lane change with MCM, agreeing on a certain overtaking point is a strategic decision that requires a much longer planning horizon than MCM allows. Therefore, a different message type is needed which is discussed in this paper.

2.3 Collaborative Maneuver Protocol

Oliver Sawade et al. have developed the Collaborative Maneuver Protocol (CMP) with the corresponding Collaborative Maneuver Message (CMM) for the negotiation of cooperative maneuver in ad-hoc networks between vehicles in 2018. The objective of the CMP is to enable robust coordination under byzantine network conditions. For this purpose, function-specific distributed state machines are designed in which each state assigns tasks for different roles. For example, in a platooning scenario the roles "leader" and "follower" could be implemented, where the follower in one of the states has the task to "follow with a small distance". To synchronize the vehicles in a distributed state machine, a session with all involved vehicles is started and the roles are assigned. Within the session each participant can start a vote for a state transition. In case of a uniform decision, the chosen state is transitioned and each participant takes over the task assigned to its role there. To detect a desynchronization or the failure of a session participant, each vehicle sends a heartbeat message with the hash of the current state (Sawade et al., 2018).

The advantage of the CMP is that no specific maneuver has to be planned in detail, but the coordination takes place on a higher strategic and abstract level. This increases robustness, since, for example, deviations from specific trajectories can occur more quickly and then lead to an abort of the maneuver. In addition, the vehicles can be kept in a synchronized state over a long period of time, which makes it possible to make long-term strategic decisions together. The individual function implementation of the corresponding vehicle is then responsible for the implementation of the role-specific tasks. Thus, the CMP can be set on top of an existing trajectory planning, which may differ from vehicle to vehicle. The disadvantage is that the specific trajectories are not coordinated between the vehicles, so especially in highly dynamic scenarios, maneuver can be planned better on trajectory level than on a strategic level. Furthermore, although the coordination and synchronization concepts are generic, the distributed state machine must be developed specifically for each function and initially distributed to all vehicles.

2.4 IMAGinE

The IMAGinE project (Intelligent Maneuver Automation - Cooperative Hazard Avoidance in Real-Time) addresses cooperative driving maneuver in 6 different scenarios, including turning on rural roads, merging onto highways, and truck overtaking (IMAGinE, 2016). The 12 consortium partners (Opel Automobile GmbH, BMW AG, Mercedes-Benz AG, MAN Truck & Bus SE, Volkswagen AG, Continental Teves AG & Co. ohG, Robert Bosch GmbH, IPG Automotive GmbH, Nordsys GmbH, WIVW GmbH, Hessen Mobil - Straßen und Verkehrsmanagement, Technische Universität München) are funded by the German Federal Ministry for Economic Affairs and Energy and aim to implement a collective perception with subsequent cooperative maneuver planning in simulation and real vehicles. Central to this is the agreement on common and uniform message specifications, in particular the CPM and MCM, with which important experience is being gained in the project for further specification and applications of the messages.

In IMAGinE, the MAN Truck & Bus SE is focusing in particular on the cooperative truck overtaking maneuver. For this purpose, two test vehicles were equipped with advanced sensors, actuators, computing units and a communication module for WLAN 802.11p.

3 METHODS

This section describes how the strategic planning layer for the cooperative truck overtaking maneuver is implemented and how the distributed state machine is designed. It is also determined what information needs to be exchanged and how it can be specified in a message. At the end, our simulation setup as well as the experiments are described. The main purpose of the experiments is to demonstrate that the cooperative maneuver coordination works and to investigate what transmission frequency of the described message is needed.

3.1 Strategic Planning

The truck overtaking maneuver requires a long planning horizon, since the low differential speeds of the trucks mean that long distances are covered from the first contact via V2X to the completion of the overtaking maneuver. A truck with a constant speed of 80 km/h overtaking a 70 km/h truck travels from the first contact via V2X at a communication range of 400 m about 3 km to the lane change into the overtaking lane and further 1.1 km to the second lane change. Such a long cooperative maneuver needs to be coordinated at a strategic planning level (also called behaviour or tactical level) (Gu et al., 2016), since the planning horizon of an MCM at a trajectory level is around 20 s, i.e. 440 m. Even though longer MCMs can be constructed, it is impossible to predict the position and velocity at 4 km distance accurately enough for a trajectory planning level. On a strategic level, it is enough to coordinate:

- About where lane changes are to be made
- How long the overtaking maneuver will take
- What safety distances are necessary
- Which type of cooperation is chosen

With this compact information, an unambiguous overtaking maneuver can essentially be described. It is not yet important, for example, to calculate the exact trajectory for the lane change, but to formulate abstract tasks that enable the execution of the overtaking maneuver. The following distributed state machine summarizes these tasks.

3.2 Distributed State Machine

As described by Sawade et al., a cooperative maneuver can be broken down at the strategic level into abstract tasks, which are then executed in a coordinated manner by the participating vehicles (Sawade et al., 2018). Execution in this context can mean, for example, that the underlying trajectory maneuver planning is parameterized accordingly. For the truck overtaking maneuver two roles are defined, whose tasks differ per state: the overtaker and the overtaken. Passenger cars, which of course also have to be considered in the truck overtaking maneuver, are not considered on the strategic level, since the cooperation between passenger cars and trucks is limited to the trajectory level during the first lane change. In the following, the ten states with the corresponding tasks are described:

1. **Solo** (not synchronized) - No truck in the surrounding area or for all trucks determined that overtaking is not practical.
2. **Initialization -** Information is exchanged and an attempt is made to establish the roles for Overtaker and Overtaken. If the assignment is successful switch to 3.
3. **Planning -** Both: The overtaking maneuver is planned and described by lane change, duration, safety distances and cooperation mode. If both trucks agree on the same overtaking maneuver, switch to 4.
4. **Approach -** Overtaken: Follow your originally planned Velocity-Profile. Overtaker: Adjust speed continuously so that the overtaker reaches the overtaken approximately at the time of the planned lane change. If the safety distance to the overtaken is ≤ 60 m change to 5.
5. **Secure Gap (pre) -** Overtaken: Transmit during emergency braking, brake signals via V2X. Overtaker: Reduce the safety distance secured by the V2X messages and react to possible emergency braking of the overtaken. Plan the cooperative lane change with the vehicles in the overtaking lane. When safety distance is reached, change to 6.
6. **Lane Change (to 2) -** Overtaken: Send braking signals via V2X in case of emergency braking. Overtaker: Perform lane change to overtaking lane and react to possible emergency braking. When lane change is finished change to 7.
7. **Pass -** Overtaken: Reduce your speed within the hysteresis. Overtaker: Increase your speed within the hysteresis. When safety distance is reached after overtaking maneuver change to 8.
8. **Lane Change (to 1) -** Overtaken: React to possible emergency braking from the overtaker. Overtaker: Execute the lane change to the first lane and send brake signals via V2X in case of emergency braking. When lane change is finished switch to 9.
9. **Secure Gap (post) -** Overtaken: React to possible emergency braking from the overtaker and accelerate again to the desired speed. Overtaker: Slow down again to desired speed and send brake signals via V2X in case of emergency braking. If the safety distance to the overtaker is ≥ 50 m change to 10.
10. **End -** Overtaking maneuver is completed, both continue at desired speed and reset all states.

In each state there are abort conditions, so that if an overtaking maneuver is no longer useful or a participant ends the cooperation prematurely, the system returns to state 1. It should be noted that the state changes do not depend on an absolute condition specified in state 3. For example, the transition to the lane change state does not depend on an absolute position on the road, but on the relative position to the overtaken. This allows that the overtaking maneuver can be adapted dynamically even after the initial planning and does not have to be aborted if minor deviations occur.

3.3 Required Information

As already mentioned, it is not useful to use an MCM over such a long planning horizon, since for example the lateral location component can be reduced to the two lane changes. However, for example, it is indispensable to determine when the first possible overtaking time point is, i.e. when the distance between the overtaker and the overtaken has reached the safety distance. To predict this point, the current positions and the upcoming velocity profiles of both trucks must be known. In “Cooperative Truck Overtaking on Freeways” (Mertens, Hauenstein, Diermeyer, Jahn, & Kraus, 2020) we investigated how velocity profiles can be exchanged over V2X and designed an ASN.1 specification that allows 7 km long velocity profiles to be transmitted in a 33 Byte message. The compression used resulted in an average deviation of 0.1 m/s between the original and the received velocity profile.

Now we want to go a step further and consider how the velocity profiles were determined in the first place. Most trucks today are equipped with a GPS cruise control system that calculates an energy-efficient velocity profile depending on the topology. The main factors that go into this calculation are (Passenberg et al., 2009):

- Road topology
- Position of the truck
- Desired speed: V_{set}
- Hysteresis with speed variation: H_{min} H_{max}
- Weight of the truck: W
- Engine model: E

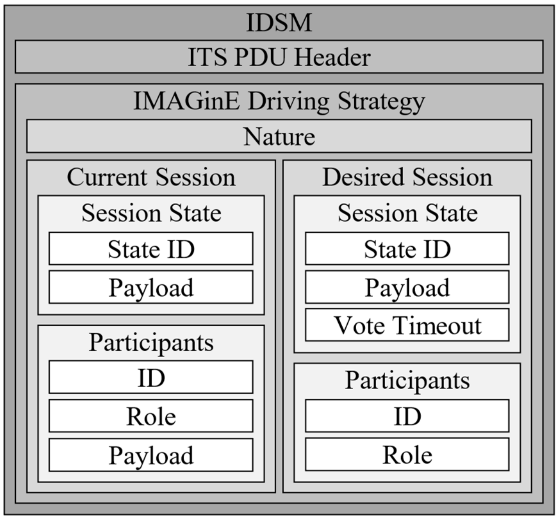

Figure 1: IMAGinE Driving Strategy Message specification.

Under the assumption that both trucks have a GPS cruise control that deliver approximately the same results with the same input, it is sufficient to transmit only the initial parameters for its calculation instead of the complete velocity profile. Since the road topology is already available in both trucks and the position is sent via the CAM, only V_{set}, H_{min}, H_{max}, W and E remain, which can be transmitted more compactly than a velocity profile. This information also allows us to determine the reduced safety distance, which depends mainly on the weight and the velocity. In the next step, we will embed this required information into a message to synchronously run through the distributed state machine and plan the overtaking maneuver.

3.4 IDSM Message

In order to synchronize the vehicles in the distributed state machine and exchange the required information for planning the overtaking maneuver, a message needs to be specified. Building on the CMP and the CMM of Sawade et al., the IMAGinE project designed the IMAGinE Driving Strategy Message (IDSM). Figure 1 shows the main elements of the IDSM. Beside the header it contains the IDS which indicates via Nature which function and thus which state machine is active. Furthermore, the current session and an optional desired session are included. These contain in each case a state with the ID and Payload of the current and the desire state. In the desired state there is also a timeout, for how long can be voted for it. The last elements of the sessions are the participant lists with the corresponding IDs and their roles. In the current state, each vehicle can add a payload to its participant entry to share details about itself. This message is thus generic in the sense that arbitrary state machines can be traversed synchronously. Once a session is initiated, each participant in the session can send a desired state in addition to the current state. As soon as all participants send the same desired state, the system switches synchronously to this state.

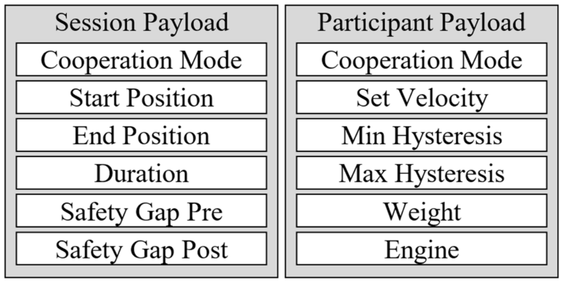

Figure 2: Payload for Cooperative Truck Overtaking.

The payloads in the IDSM are defined as a byte array so that specific content can be appended depending on the function activated. Figure 2 shows the payload for the Cooperative Truck Overtaking Maneuver and contains the information derived in Section 3.1 and Section 3.3.

3.5 Simulation

To test the coordination of the cooperative overtaking maneuver between two trucks with the IDSM, we implemented a simulation environment and a dashboard for visualization. The simulation of the two trucks is implemented in ROS-Kinetic (ROS, 2018) and ego data as well as simulated CAMs are provided as ROS-topic. For each truck one instance of the Cooperative Truck Overtaking Assistant is running which receives the data and provides IDSMs as ROS-topic for the other truck. Except for the lane changes, the trucks always drive on lane center and the speed of the trucks is directly controlled by the Cooperative Truck Overtaking Assistant. The calculation of the speed profiles is based on the already published tool "Truck Overtaking Analyser" which has now been extended by the coordination with the Distributed State Machine and the IDSM.

3.6 Experimental Setup

With the described simulation a series of tests with two objectives has been performed. Firstly, we wanted to see whether the strategic coordination concept works and whether the overtaking maneuvers as planned by the "Truck Overtaking Analyzer" are actually realized. On the other hand, we wanted to investigate which transmission frequency is necessary to achieve this. For this purpose, 100 scenarios for cooperative truck overtaking maneuvers with 1, 2, 3, 5, 7 and 10 Hz each were simulated while logging details like lane change positions, duration, number of messages sent and time in each state. The 100 scenarios were set up so that all were performed in Active Cooperative mode, both trucks had a total mass of 25 t, and the overtaken started 200 m ahead of the overtaker. The starting position of the overtaker went in 1 km steps from 3 km to 102 km on a 116 km long section of the A8 from Ulm to Munich with original elevation profile. 50 % of the scenarios were to be performed with reduced safety distance and the speeds were set at 20 % each as follows (Overtaker [km/h] / Overtaken [km/h] / Hysteresis [±km/h]): 80/70/5, 85/75/5, 75/70/7, 80/77/7, 85/80/7. The order of all overtaking maneuvers remained the same, so that they differed in the six runs only by the transmission frequency of the IDSM.

4 RESULTS AND DISCUSSON

The described tests were carried out at real speed and no problems or failures occurred. In total, about 30 hours of truck driving were simulated and 600 overtaking maneuvers were successfully coordinated and executed. Now we need to determine which IDSM frequency provides the best trade-off between message count, i.e. channel load, and coordination quality. For this, it is assumed in the following that the overtaking maneuver can be coordinated best with a high frequency, since queries can be exchanged more frequently and the delay is low. Therefore, for our experiments, 10 Hz is selected as reference.

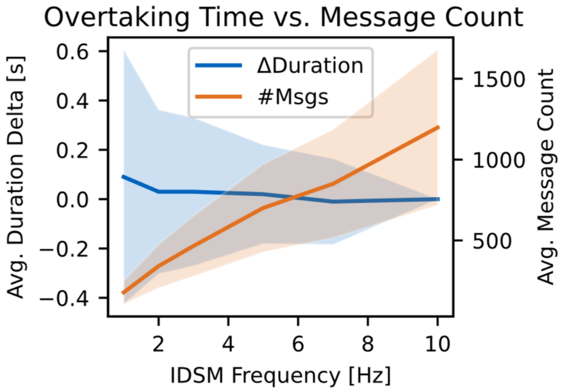

Figure 3: Mean±Sigma for overtaking duration and message count at different IDSM Frequencies.

Figure 3 shows the influence of the IDSM frequency on the average overtaking time and the average number of messages transmitted. As the frequency increases, the number of messages increases and so does the channel load. Further, it is noticeable that the average overtaking time differs from the reference by only 0.08 s even at 1 Hz. It is obvious, however, that the standard deviation of the average overtaking

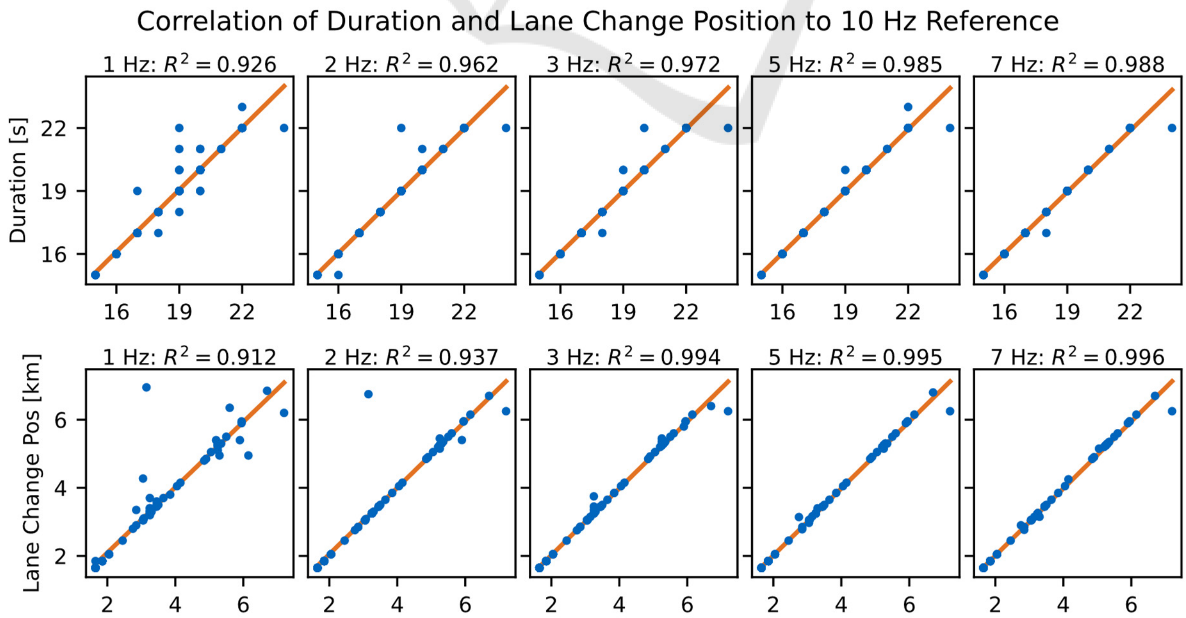

Figure 4: The correlation of overtaking duration and lane change position between lower IDSM Frequencies and 10 Hz.

duration increases with falling frequency. Thus, deviations from the optimal overtaking maneuver occur more frequently

Since this can have an effect on more than just the overtaking duration, we also considered the position of the first lane change in the next step. Figure 4 shows the correlation of the overtaking time and lane change position at 1, 2, 4, 5 and 7 Hz to our 10 Hz reference. While there is a strong correlation of $R^2 = 0.98$ for duration and $R^2 = 0.99$ for position for 5 Hz and 7 Hz, the correlation drops steadily to $R^2 = 0.92$ and $R^2 = 0.91$ at 1 Hz.

We conclude that the best trade-off between tuning and channel load is established at an IDSM frequency of 5 Hz. However, as a kind of dynamic congestion control, the frequency can be reduced to 3 Hz or 2 Hz if the current channel load requires it. While the coordination with 1 Hz still worked successfully, more frequent overtaking maneuvers were performed which deviated from the optimal overtaking maneuver. The coordination of the cooperative truck overtaking maneuver with 1 Hz should therefore be avoided. This is also confirmed by our last investigation. Figure 5 shows how the average time spent in each state differs from the references. In particular, at 1 Hz there are large deviations that clearly stand out from those of the other frequencies.

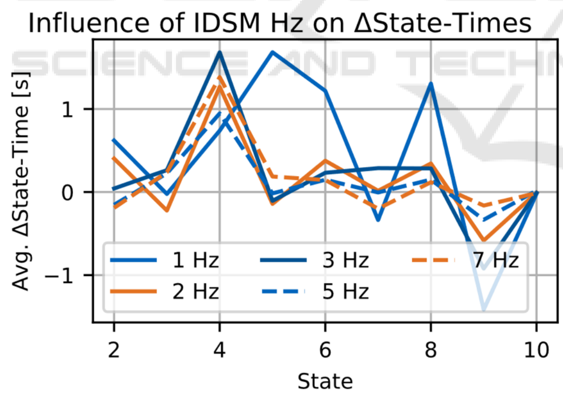

Figure 5: Average time spent in each state at different IDSM frequencies compared to 10 Hz.

5 CONCLUSIONS

It was demonstrated that the truck overtaking maneuver can be coordinated and executed cooperatively at a strategic level using a distributed state machine. To synchronize the vehicles in the distributed state machine, a message is required that groups the participants in a session and enables coordination for a transition to a new desired state. For this, the IMAGinE project specified a generic message on which we built and added a truck overtaking specific payload. Using this message, 600 overtaking maneuvers at different transmission frequencies were simulated, and all overtaking maneuvers were successfully planned and completed. Our subsequent investigation showed that a transmission frequency of 5 Hz provided the best trade-off between channel load and overtaking maneuver quality.

Having demonstrated in “Cooperative Truck Overtaking on Freeways” how a cooperative truck overtaking maneuver can be optimally planned, we now have the capability to coordinate this planning between two vehicles via V2X. The next step will be the integration of our system into two trucks to investigate the cooperative truck overtaking maneuver not only in simulation but in real field tests.

A resulting assistance system would have the potential to relieve the truck driver and lead to a more sustainable working environment and is a step towards autonomous truck traffic in the long term.

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CONTRIBUTIONS

J.C.M. (first and corresponding author) initiated the idea of the paper and contributed to the conceptualization, methodology, software, investigation and writing of the original draft. J.H. supported the methodology and investigation with insights and discussions. F.D. and A.Z. made an essential contribution to the conception of the research project and revised the paper critically for intellectual content. F.D. and A.Z. give final approval for the version to be published and agree to all aspects of the work. As a guarantor, F.D. accepts responsibility for the overall integrity of the paper.

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