Organization and Control of Autonomous Railway Convoys

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Subject of the RailCab project is the development of autonomous railway vehicles which can dynamically group to convoys without mechanical coupling. This enables an on-demand use of these vehicles while retaining the cost and ecological advantages of public transport. In this paper, we present (1) the convoy communication with respect to joining and leaving a convoy as well as (2) the convoy control strategy. We strongly emphasize the safety of the developed software.

Topics: Intelligent Transportation System, Vehicle Control

1. INTRODUCTION

In terms of ecological values, public transport by bus or railway is deemed superior to individual transport by car. Unfortunately, today's public transport cannot keep up with individual transport in terms of flexibility and comfort. The RailCab project was founded at the University of Paderborn in 1998 in order to develop a new railway system that features the advantages of both techniques in terms of cost and energy efficiency as well as flexibility and comfort [1].

The novel system is characterized by small autonomous vehicles traveling on demand instead of trains operating on a fixed schedule. For real-life validation of the complex mechatronic system, a test track in a scale of 1:2.5 was built at the University of Paderborn in 2002. The rail vehicles, so-called RailCabs, can align with others without mechanical coupling [2]. Best energy saving is achieved with distances between the RailCabs below a meter.

The employed motor, a doubly-fed linear motor [3] enables relative motion between vehicles cruising on the same stator section. Thus, it is possible to merge and split convoys while driving. Furthermore, the active steering allows grouping of convoys at passive track switches. Consequently, dynamic convoy driving is possible which offers the following possibilities:

- Increasing the track capacity
- Decreasing the energy consumption

In the past, most of the research activities about the control of vehicle platoons dealt with automotive applications and discussed the problem of nonlinear vehicle models. [4], [5] described the influence of the communication topology on convoy stability. In case of very small distances, a communication of lead vehicle information is mandatory. Otherwise driving within small distances cannot be handled. Several controller designs ensuring safety are presented in [6]. The different controller designs are chosen depending on the current driving mode. They also include lane changes and lateral control.

However, in case of rail-bound vehicles, only the control of the longitudinal dynamics is required with respect to drive control. The mentioned linear motor provides constant thrust in the operating range. Consequently, in contrast to road traffic, an advanced convoy control strategy allows safe driving with small distances between vehicles. We employ a single controller design and distinguish the different operating modes by adapting reference values.

The crucial point for the control of longitudinal dynamics and distance control is the reference generator, which must include limitations of speed, acceleration and jerk. The adherence to these limitations has to be ensured for all vehicles involved in a convoy.

Therefore, the individual limits of each vehicle are communicated to a vehicle which coordinates the convoy. This vehicle computes the limits for the whole convoy and sends them back to all vehicles. Thereafter, the vehicles are allowed to build a convoy under the condition that they respect the communicated limits.

The communication between the vehicles in a convoy is presented in Chapter 2. The control system shown in Chapter 3 enables a position control of an individual vehicle. The control structure of a vehicle convoy is described in Chapter 4. The maneuver control laws for a safe operation in convoy mode are presented in Chapter 5.

2. CONVOY ORGANIZATION

Convoy organization deals with building a RailCab convoy out of single RailCabs. A convoy operation is clearly safety-critical, a rigorous development approach is required which specifically targets mechatronic safety-critical systems. Besides testing, formal verification techniques like model checking should be employed to formally prove safety-critical properties.

Systems with thousands of elements and dynamic structural changes as in the RailCab project do not allow the specification and verification of the whole system. Instead compositional approaches have to be employed, where parts are precisely defined. Each system part is individually specified and verified with respect to safety conditions. The compositional approach then guarantees that the whole system is safe with respect to the safety conditions when the system is correctly assembled from the base parts.

The Mechatronic UML [7] is a modelling language which supports the compositional specification of structure and hybrid (continuous/discrete) behaviour. Additionally, the specifications are compositionally checked by the Uppaal model checker [8] whether they satisfy safety-critical properties.

In addition to previous work on convoys of only 2 RailCabs [9], we extended the specifications to support convoys consisting of (a fixed number of) *N* RailCabs. In a convoy, one RailCab is appointed to coordinate the convoy by periodically distributing reference values to the other RailCabs for convoy control and dealing with joining and leaving RailCabs.

In [10], we presented a formal specification and compositional verification approach for collaborations with an unknown number of participants. We build on this foundation and derive the software models from it.

Fig. 1 shows the structure of the convoy operation part of three RailCabs, the first one is the coordinator of the convoy and, in addition to the coordinator component, does also contain the component for driving in a convoy. This component does receive reference values. These include how to behave in case of a hazard [9]. The coordinator component of the two other components is currently not active. Both RailCabs also receive periodically reference values for driving in the convoy.

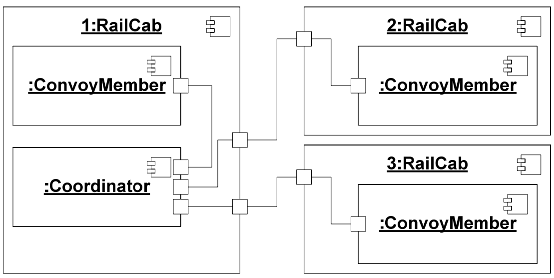

Fig. 1 Software structure of a convoy of three RailCabs

We identified the following use cases for the convoy operation: (1) joining a convoy, (2) leaving a convoy, and (3) changing the coordinator of a convoy. The communication protocols for these use cases must be specified for the individual RailCab as well as the coordinator.

The identified use cases are implemented by communication protocols between the participants. Fig. 2 shows the communication between a single RailCab and an existing convoy of two RailCabs. The single RailCab sends a request to join a convoy including its maximal velocity, and normal and maximal brake forces to the coordinator.

The coordinator checks whether it is possible (and beneficial for the convoy) that the additional RailCab joins the convoy. If that is the case, the coordinator computes new values concerning the maximal velocity and normal and maximal brake forces for each RailCab in the convoy as well as the potential convoy join position and velocity for the new RailCab. If the new RailCab agrees with these values, the coordinator relays them to all RailCabs in the convoy (including itself). Finally, the coordinator sends brake delay times to all RailCabs which enables a coordinated convoy braking in case of a hazard.

The messages are sent using data link layers which mask value and omission faults of the employed wireless network [9].

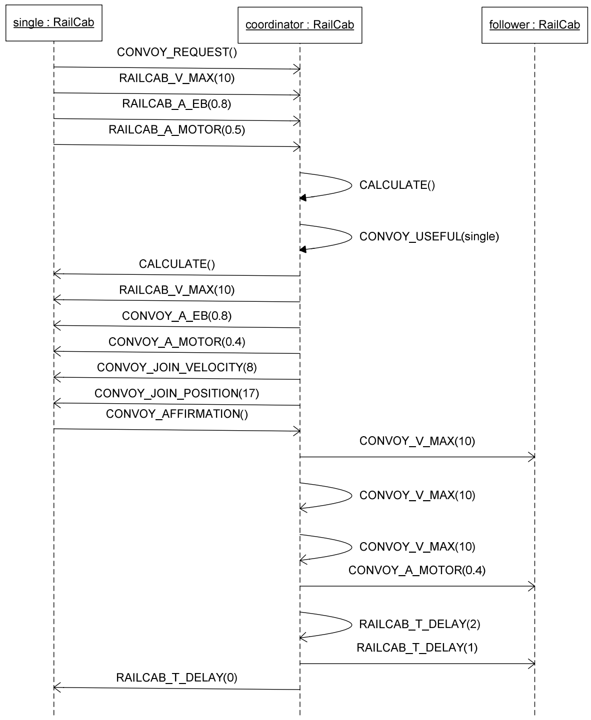

Fig. 2 Communication protocol concerning the use case: Joining a convoy

The components' behaviours are specified in Matlab Stateflow. The generated code is executed on the rapid prototyping hardware deployed on the RailCab.

The negotiation of the parameters for convoy mode is done by evaluating the vehicle properties $a_{\mathrm{motor,n}}$ and $v_{\mathrm{max,n}}$:

$$a_{\mathrm{motor}} = Min\{a_{\mathrm{motor,n}}\}, \qquad \mathrm{n} \in \{1..\mathrm{N}\} \tag{1}$$

$$v_{\mathrm{max}} = Min\{v_{\mathrm{max,n}}\}, \qquad \mathrm{n} \in \{1..\mathrm{N}\} \tag{2}$$

The defined parameters are binding for all convoy vehicles. The time delay $T_{\mathrm{delay,n}}$ is different for each RailCab. It depends on the vehicle mass m_{n} in relation to the force of the emergency brake system $F_{\mathrm{eb,n}}$ (which is communicated as $a_{\mathrm{eb,n}}$):

$$T_{\mathrm{delay,n+1}} = T_{\mathrm{delay,n}} + \Delta T_{\mathrm{n+1,n}} \tag{3}$$

$$\Delta T_{\mathrm{n+1,n}} = \frac{v_{\mathrm{n+1}}}{a_{\mathrm{eb,n+1}}} - \frac{v_{\mathrm{n}}}{a_{\mathrm{eb,n}}} \tag{4}$$

3. CONTROL OF LONGITUDINAL DYNAMICS

The longitudinal control of a vehicle requires a model of the vehicle dynamics and the actuators which are presented first in this section. With this mathematical description the controller can be designed.

3.1 Vehicle Dynamics

A mathematical model of the vehicle dynamics is mandatory for the controller design. It includes the dynamic behavior of the electric drive and the vehicle kinematics. The following assumptions for the vehicle dynamics are made:

- Complete decoupling of longitudinal and lateral dynamics
- No slip in longitudinal direction between wheels and rail

The vehicles represent a moving mass m_n with the second order dynamics

$$\ddot{x}_{\mathrm{n}} = \frac{1}{m_{\mathrm{n}}}(F_{\mathrm{M,n}} - F_{\mathrm{roll,n}} - F_{\mathrm{drag,n}} - F_{\mathrm{slope,n}})\,,\ \mathrm{n} \in \{1..\mathrm{N}\} \quad (5)$$

whereas $F_{\mathrm{M,,n}}$ represents the motor thrust and F_{roll}, F_{drag}, F_{slope} are disturbances. Crucial for the longitudinal control are the limitations. The motor thrust for the test vehicles is limited to 1100 N. The vehicle mass of about 1250 kg results in a maximal acceleration of 0.8 m/s^2 on plane track sections. The maximum speed is 10 m/s due to the tight curves on the test track.

The roll resistance of railway vehicles is small and can be approximated here to be less than 30 N. The air resistance is proportional to v^2. It is less than 50 N because of the low speed of the test vehicles. It is approximated to be nearly independent of the vehicle speed when head wind and down wind are also considered. However, the downhill slope force cannot be neglected. It constitutes 570 N at the biggest incline.

The applied linear motor is a direct drive which results in a linear model with the motor voltage $U_{\mathrm{M,n}}$ as the sole input and the vehicle position x_{n} as the single output as shown in Fig. 3.

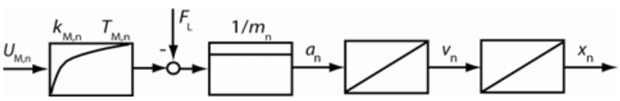

Fig. 3 Modeling of a longitudinal dynamics

3.2 Control Structure

A controller for the longitudinal dynamics has to be designed considering the following constraints:

- Automatic adaption to the vehicle mass
- Desired driving comfort

Therefore the control system includes a reference generator which considers the vehicle mass m_{n} and the limits of the acceleration $a_{\mathrm{n,max}}$ and the jerk $r_{\mathrm{n,max}}$. The feedback of current position and speed is mandatory for the position control (see Fig. 4). A follow-up control is applied with set point tracing $x_{\mathrm{n}}^{*}{}' = x_{\mathrm{n}}^{*} - d_{\mathrm{n,brake}}$. The braking distance $d_{\mathrm{n,brake}}$ is calculated by the speed v_n and the maximal acceleration a_n. The acceleration a_{n} depends on the vehicle mass m_{n} and the position x_{n} as well as the gradients of the track given by a digital map.

A cascaded control structure has been realized for the longitudinal control. The cascaded structure allows limiting the inner control variables. The innermost loop is the motor current control with a superordinated speed control loop. The outermost control loop constitutes a position control. The time pattern for the control of longitudinal dynamics is 1 ms. The linear motor provides a constant traction independent of external perturbations. Therefore jerk and acceleration limits can be guaranteed without employing an acceleration control loop.

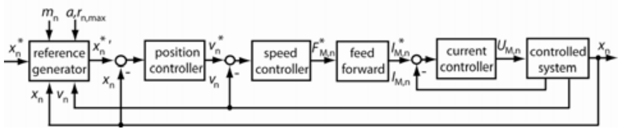

Fig. 4 Structure of longitudinal control

4. STRUCTURE OF CONVOY CONTROL SYSTEM

The convoy control requires a wireless network between the RailCabs. Consequently, an extension of the control system is required as shown in Fig. 5.

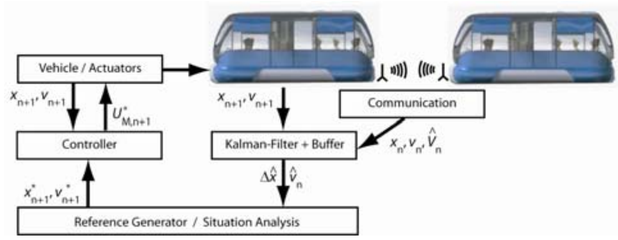

Fig. 5 Structure of the control system

4.1 Network Controlled System

Driving within a distance between vehicles of less than a meter requires information from the in front driving vehicle as well as from the convoy leader. If a communication to the leader exists, convoy stability can be ensured [4] even in case of speed independent reference distances [12]. Additionally early reactions on disturbances can be achieved [13] when the desired trajectory of the leader and its acceleration is known.

The absolute position of the vehicles is very precisely measured. Therefore, it is used for distance control in addition to the distance information measured by the distance sensors. However, the transmitted data also includes the speed information. Furthermore the desired trajectory of the leader is transmitted.

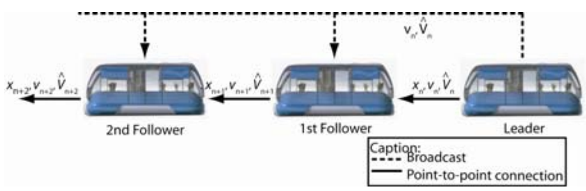

Fig. 6 Communication structure

The leading vehicle communicates its data via broadcasting to all involved vehicles. All other vehicles only provide data to the direct following vehicle (see Fig. 6). The cycle time T for the radio communication is 40 ms.

The effects of the wireless communication network like varying latencies in data transmission and packet losses cannot be neglected. Additionally an algorithm for generating data in the step time of the controller has to be implemented. The principle is shown in Fig. 7.

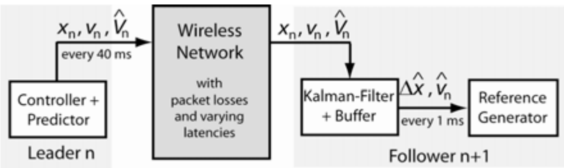

Fig. 7 Principle of network controlled system with predictor and buffer

A predictor is implemented in addition to the controller of the leading vehicle which includes a precise model of the vehicle dynamics. The predictor estimates the progress of the speed trajectory $\hat{V}_{\mathrm{n}}$ for a defined prediction horizon based on the track topology. The prospective development of the speed is then partitioned into the time pattern of the data communication

$$\hat{V}_{\mathrm{n}} = \{\hat{v}_{\mathrm{n}}(T)..\hat{v}_{\mathrm{n}}(kT)\} \tag{6}$$

The predicted vector of the speed is sent to the follower. The following vehicle is then able to estimate precisely the behavior of the leader in case of packet losses or high latencies.

The follower is expanded with a Kalman-Filter and a buffer. The filter is used for estimating the position $\hat{x}_{\mathrm{n}}$, respectively the distance $\Delta\hat{x}_{\mathrm{n,n+1}}$, and the speed $\hat{v}_{\mathrm{n}}$. The filter also includes a buffer for the received speed trajectory $\hat{V}_n$. Even if packet losses occur, the filter gets its input every period T within the prediction horizon of kT. The buffer is overwritten with each accurately received data. Within a prediction horizon of 10 transmission cycles (400 ms) the accuracy of the determined position can be improved up to 8 cm.

4.2 Reference Generator

The reference generator of a follower RailCab is different than the leader's one. Additionally, a situation analysis is executed inside by evaluating the current position and the speed of the leader *n* and the follower *n+1*. An additional input comes from the configuration control which evaluates the system state information. Either a normal state or a hazard occurrence [9] is identified. The set values for the position control are calculated by evaluating the braking distances with knowledge of the track topology [7].

The reference generator also outputs a signal of the convoy state which is needed for switching between the controllers. However, at the switching instant T_{switch} a continuous transition is required between speed and position control. Therefore the output of the position controller has to be equal to the input of the speed controller. With the gain K_{p} of position controller the following equation has to be fulfilled

$$\Delta x^*_{\mathrm{n+1}}(T_{\mathrm{switch}}) \cdot K_{\mathrm{p}} = v^*_{\mathrm{n+1}}(T_{\mathrm{switch}}) \tag{7}$$

In order to avoid discontinuities the distance will be reduced by a ramp signal.

A feed forward control improves the dynamic behavior of the following vehicles. In case of convoy mode, the current speed of the convoy leader, which is sent to all followers by broadcast communication, is applied in the feed forward line of all followers and is only activated in position control mode (see Fig. 8).

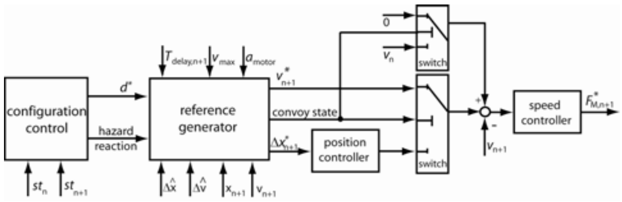

Fig. 8 Structure of convoy controller

Fig. 9 illustrates the behavior with the feed forward control which ensures convoy stability.

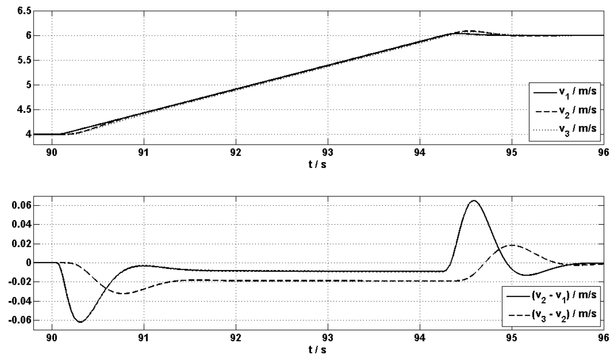

Fig. 9 Proof of convoy stability

5. CONVOY CONTROL

The objectives of the convoy control law are a fast formation of a convoy under safety requirements and the safe operation in platoon mode. A distance control as well as a speed control is applied for convoy control depending on the current situation. In this section, the distance control is described first. Furthermore maneuver control laws are presented.

5.1 Distance Control

The reference position of the follower is defined as

$$x^*_{\mathrm{n+1}} = x_{\mathrm{n}} - d^*(v_{\mathrm{n}}, v_{\mathrm{n+1}}, a_{\mathrm{n}}, a_{\mathrm{n+1}}) \tag{8}$$

where the distance reference d^* depends on the current operating mode and includes the length of the vehicle (3.5 m).

Some fundamentals of safe vehicle operation are defined first. Absolute and relative braking distances are distinguished. The absolute braking distance of the follower $d_{\mathrm{abs,n+1}}$ is an uncritical distance and defined as

$$d_{\mathrm{abs,n+1}} = \frac{v^2_{\mathrm{n+1}}}{2a_{\mathrm{n+1}}} \tag{9}$$

This distance also defines the inter-platoon distance. In contrast, the relative braking distance $d_{\mathrm{rel,n+1}}$ is the difference if the absolute braking distances of two RailCabs and is defined as

$$d_{\mathrm{rel,n+1}} = \left| \frac{v_{\mathrm{n+1}}^2}{2a_{\mathrm{n+1}}} - \frac{v_{\mathrm{n}}^2}{2a_{\mathrm{n}}} \right| \tag{10}$$

It is safety critical to drive within the relative braking distance. In order to avoid crashes, the vehicles must a priori agree upon the maneuvers. However, this cannot be ensured in all cases. Therefore maneuver control laws have been designed which minimizes risks while driving within distances of less than one meter.

5.2 Maneuver Control Laws

In general three kinds of maneuvers in case of convoy mode can be distinguished: merging and splitting of convoys and driving in a platoon. The maneuver control laws are based on the longitudinal control described above. The reference generator adapts the reference values depending on the current situation and outputs a convoy state signal for switching between the operating modes as described above.

The control strategy is realized as a state model with the three main states NOCONVOY, MERGING/SPLITTING and PLATOON as shown in Fig. 10.

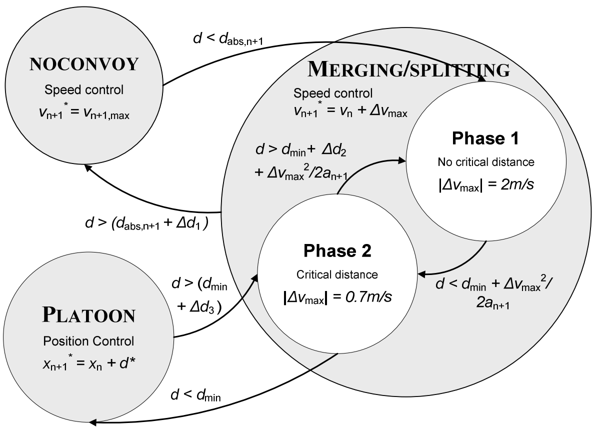

Fig. 10 State machine of the convoy control strategy

Merging

Merging of vehicles to a platoon is the most safety critical operation because of unavoidable speed differences while driving within small distances. Therefore a control strategy is applied which limits the speed during this process. Phase 1 of the merging process begins with undershooting the absolute braking distance. Here the speed controller limits the speed difference between follower and leader to 2m/s. The speed has to be reduced before the phase begins.

The safety critical process starts with reaching the relative braking distance. In phase 2, the speed difference is limited to 0.7m/s. A maximum speed difference of 1 m/s when the time delay of activation and engagement of the hydraulic emergency brake (approximately 300 ms) is considered. This speed difference is assumed to cause no remaining damages in case of a collision.

In order to avoid permanent switching between states, the conditions additional include a margin. A complete merging process is shown in Fig. 11. Whereas the effective distance of 4 m has to be reduced by the vehicle length of 3.5 m.

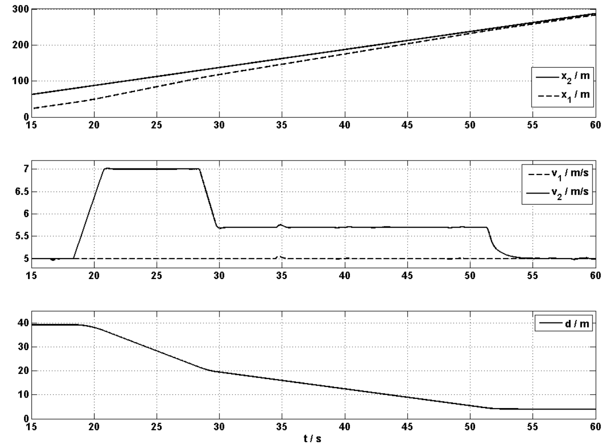

Fig. 11 Convoy formation (complete process)

Platoon

The platoon phase is activated by the transition from speed to position control. The criterion is a minimal distance d_{min} which is needed for reducing the speed difference between the two vehicles. Thus, the desired distance is smoothly adjusted (see Fig. 12).

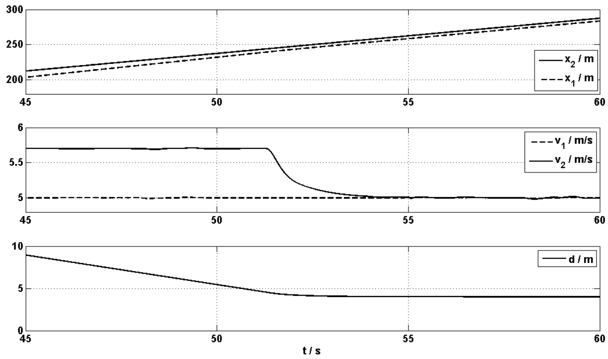

Fig. 12 Convoy formation (transition from speed to position control)

In platoon mode, a fixed distance reference is applied independent of the current vehicle speed. The desired distance is shortly undershot due to a braking procedure without propagation by the leader as shown in Fig. 13. This can be avoided with the a priori propagation of changes of the operational profiles.

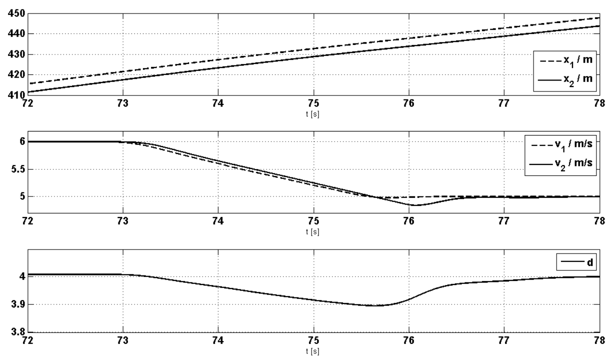

Fig. 13 Reaction of follower after braking of the convoy leader in normal case

However, the mentioned propagation cannot be ensured in all cases. Therefore the platoon mode is generally safety critical. However, in case of small distances resulting speed differences will be minimal. Consequently in case of system failures or emergency situations, a crash does not cause total damages on the vehicles. Routines for emergency cases are pre-defined and transmitted from the convoy coordinator as described in Chapter 2 to avoid accidents as far as possible. Fig. 14 illustrates a braking procedure after detecting a bad communication. Both vehicles decelerate to the final speed whereas the follower applies the negotiated maximum acceleration. Though the performance of the inter-vehicular communication is limited driving within the relative braking distance provides safety.

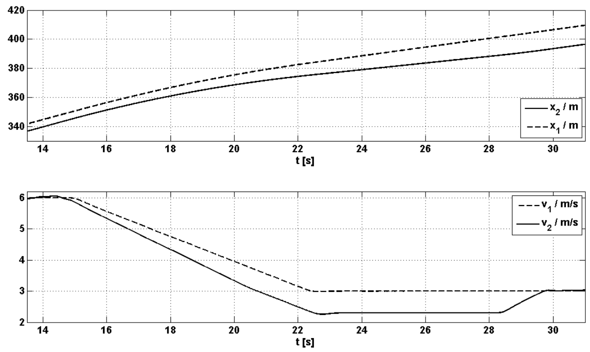

Fig. 14 Reaction of follower after braking of the convoy leader in emergency case

Splitting

The splitting process is very similar to the merging process. The state model for merging is reversely executed. The transition conditions are shown in Fig. 10. After splitting vehicles from a convoy, a distance greater than the follower's absolute braking distance is adjusted.

6. CONCLUSIONS

We presented the concepts for a safe operation of autonomous railway convoys. The developed system consists of two parts. The first one deals with the communication protocols between the convoy vehicles with respect to merging and splitting a convoy. The second one contains the networked control structure which ensures convoy stability. The control structure employs a predictor and a buffer. This results in a more precise control.

Control strategies for merging, following and splitting convoys are presented. The different control strategies are managed by a state machine. In spite of small vehicle distances independent of vehicle speed, the safety is ensured in all operating modes by the limitations of speed differences between vehicles and predefined emergency routines.

We currently verify the presented control algorithms by generating test cycles for all operating modes in order to refine control laws and control parameters. Additionally, we test the vehicle behaviors for longer convoys using augmented reality.

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