Simulation and Evaluation of Platooning Algorithms

With platooning, several trucks move automatically behind each other in a convoy, which allows smaller distances between the vehicles and therefore reduces fuel consumption. Important factors are the exchange of information about the individual positions and the stability of the platoon itself. IPG Automotive explains how to develop and validate the required algorithms using simulation.

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Platooning describes a system to couple multiple vehicles without a mechanical link. Especially for heavy-duty vehicles, it represents a promising assistance system which has been under development for multiple years. The vehicles communicate with each other (Vehicle-to-Vehicle, V2V) and autonomously follow the platoon lead vehicle. Relevant data such as breaking signals, steering commands, speed, and acceleration are transmitted directly to the following vehicles. They can react without delay and drive with much less headway than human drivers would need operating the vehicles.

The shorter distances between the vehicles reduce air drag for the following vehicles which significantly improves fuel economy. In times of great driver shortages and elevated personnel costs, further advantages arise specifically for heavy-duty vehicles. The following vehicles can either be operated by one safety driver each or, with adequate system maturity, even fully autonomously without a human driver. This would lead to significant reductions in cost and effort for freight companies. Furthermore, platooning results in a more efficient use of the available traffic space on the highway, which can in turn reduce traffic jams and increase traffic safety.

To enable platooning, two preconditions need to be met. Firstly, the systems of the individual vehicles need to reliably exchange their position and headway distance in real time. Secondly, it has to be ensured that the underlying control algorithms safeguard the stability of the platoon as a unit; commonly called string stability. This is why communication as well as control systems are to be continuously tested thoroughly during development.

As with all assistance systems, development and testing of platooning should be carried out with virtual test driving by performing simulation-based full vehicle tests in virtual driving scenarios. This makes it possible to both achieve a high level of test coverage and depth at an early stage and to rule out all safety risks in the simulation, for example the instability of the platoon controller which, in the worst case, can lead to accidents during testing.

TEST SETUP

A basic Proportional-integral-differential (PID) controller is used for longitudinal vehicle control. It was modeled with Matlab/Simulink, embedded as a virtual control unit into the open integration and test platform TruckMaker from IPG Automotive and subsequently tested, **FIGURE 1**. The simulation solution allows to transfer real test scenarios accurately into the virtual world and performs all tests without any risk. The virtual prototypes, exact virtual representations of physical vehicle prototypes, were simulated with full-vehicle models of 40-t trucks (tractor unit including trailer). As environment perception or inaccuracies in detection of vehicle distances are not the focus of this investigation, ground truth information was used for this purpose.

As part of an example test, the string stability was tested considering the parameterization of the PID controller. To this end, a stability-optimized PID controller was first tested with identical trucks. This was then compared to a changed payload of 10 t to examine the influence of varying vehicle masses on the string stability.

Afterward, the V2X communication was simulated. Here as well, the impact of transmission delays on the stability of longitudinal control was investigated by simulating artificial transmission errors or delays. In this context, the tests simulated errors in distance measurement as well as transmission delays of 10, 100 and 500 ms and analyzed their impact on the control quality.

Finally, the stability of control in slow-moving traffic was examined. Stop-and-

FIGURE 1 Platoon vehicles in the simulation environment TruckMaker (© IPG Automotive)

go traffic in particular represents a critical test case for string stability. In testing, the lead vehicle was stopped periodically and put into motion again in order to evaluate the control quality of the following vehicles as a reaction to the impulse.

The full-vehicle simulation in the test scenario is characterized by multiple connected simulation entities. Each vehicle was simulated by its own TruckMaker entity in order to simulate the vehicle dynamics of every individual vehicle in real time with the required level of detail. Depending on the required computing power, the different entities were distributed on one or multiple computers and communicated with each other via network connections in real time. This enabled a synchronous calculation of the simulation environment. If sufficient computing capacity is available, the simulation calculation can also be performed in multiple real-time speed. As a result, it is thus possible to calculate multiple seconds of simulated time in one real-time second.

RESULTS

FIGURE 2 depicts the deviation regarding headway as well as the absolute speed of the three following vehicles to each other. In the event of delays, no differences were noticed between unloaded and loaded vehicles in the deviation. After initial adjustment of headway, the strong delay at timepoint 40 s only resulted in a very small deviation. For acceleration, the deviations of loaded vehicles were more significant. Especially the third vehicle had difficulties to keep up with the platoon with a higher payload. However, overshooting, which describes the significant shortage headway compared to the target distance, did not occur. During or rather after acceleration was completed, the speed curve shows small bends that are not caused by poor control quality. They are the result of gear changes in the following vehicles.

A closer look reveals the cause for the deviation in the acceleration process considering the progression of engine power of the vehicles in **FIGURE 3**. The loaded vehicles reached their performance limit faster which results in deviations. Therefore, this case is not an instability: A change in payload only requires the front vehicle to adapt to the performance limits of the weakest following vehicle. Furthermore, every gear shift results in the disruption of acceleration. This fact also needs to be considered in the context of payload, as a change in payload requires a different gear shifting strategy and thus result in stronger deviations of vehicle speed profiles.

In stop-and-go traffic, there were no critical deviations even with different impulses from the lead vehicle, as depicted in **FIGURE 4**. However, timepoint 75 s hints at a shortfall in the target distance that grows the further behind in the platoon the respective following vehicle is located. Even larger platoons entail the risk of critical shortfalls in headway up to the collision of a following vehicle. This should be considered especially regarding the layout of actuators as well as the communication transmission and reaction times of the platooning system. Here again, it has to be noted that gear shifting may lead to deviations in the speed profile as described above. These deviations cannot directly be controlled by the actuators which is why instabilities may occur.

For this reason, a realistic V2X communication with according transmission latencies and noise was also simulated. The results are presented in **FIGURE 5**. Interestingly enough, the impact of a lagged synchronization can already be seen at the beginning of the simulation by the following vehicles braking first, which results in a delay in the first 30 s. Reacting to this, the lead vehicle brakes, which in turn results in an extremely

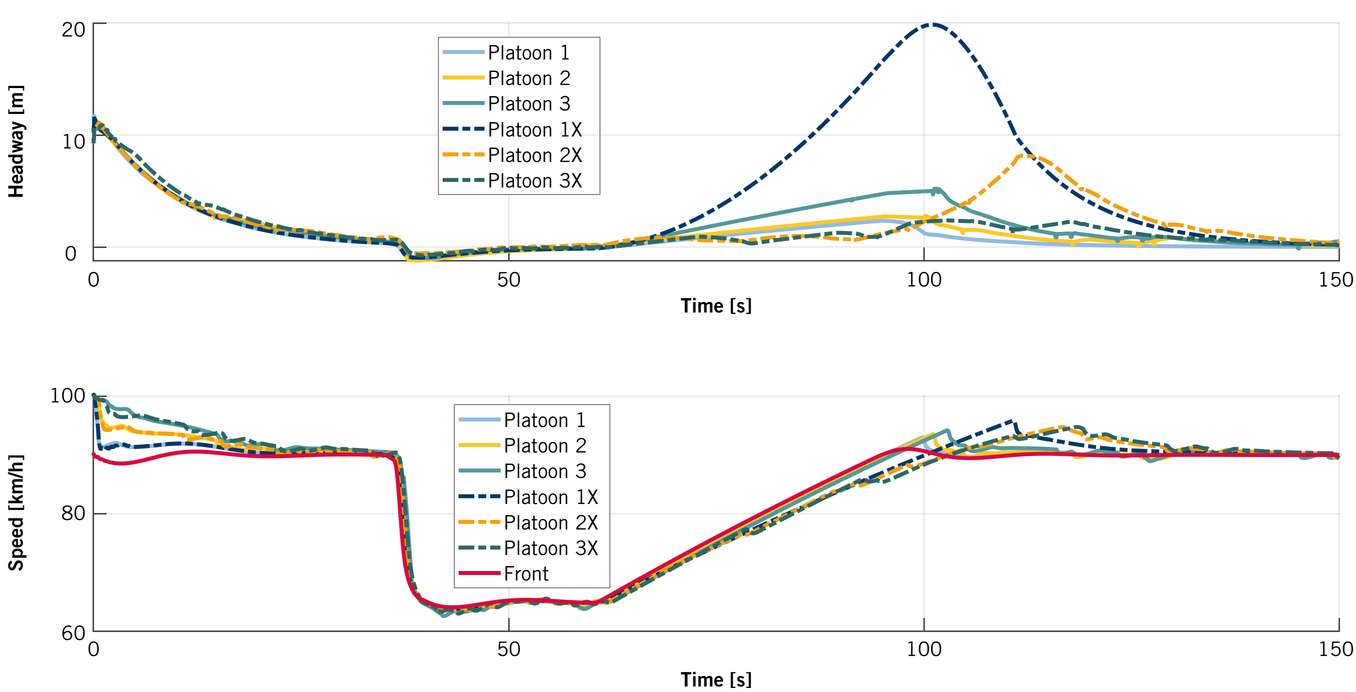

FIGURE 2 Comparison of headway and speed of the three following vehicles with and without payload (© IPG Automotive)

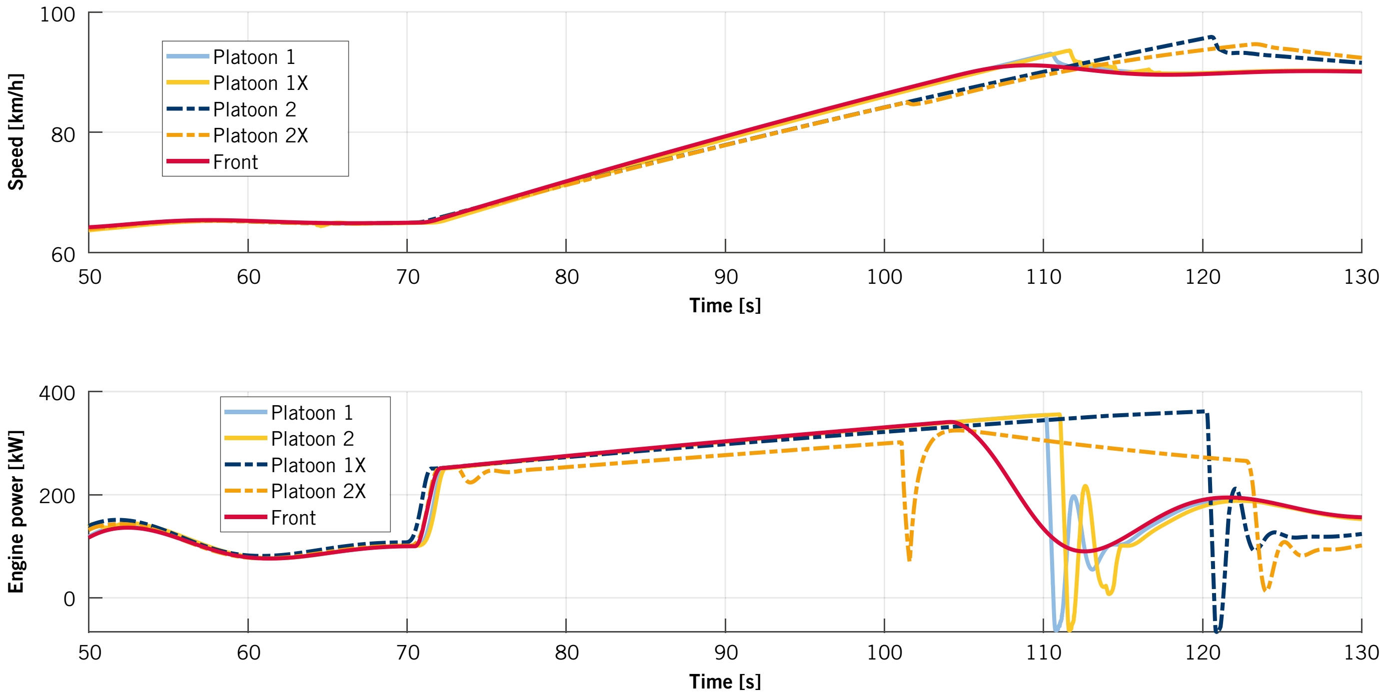

FIGURE 3 Comparison of speed and engine power of the following vehicles with and without payload (© IPG Automotive)

shortened brake reaction of the following vehicles, depending on how pronounced the transmission latency is.

If no larger headway had been created initially, the delayed reduction of speed would very likely lead to the collision of the following vehicle with the lead vehicle at timepoint 40 s. A significantly positive deviation, in this case a significantly larger headway distance, has a negative impact, too. Occurring distances of 80 m between the vehicles will with great probably lead to other road users merging into the gaps in between the following vehicles.

This event is not provided for platooning and complicates validation as other vehicles do not send information to the

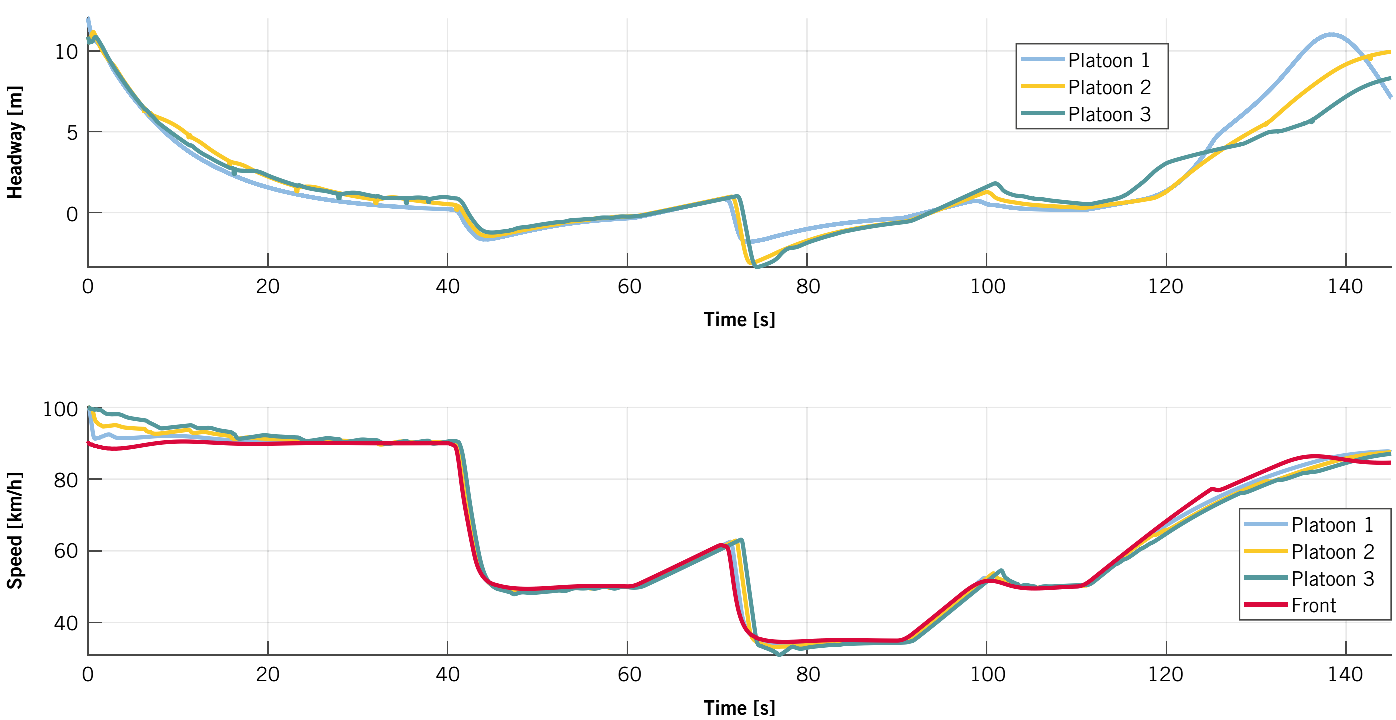

FIGURE 4 String stability in stop-and-go traffic (© IPG Automotive)

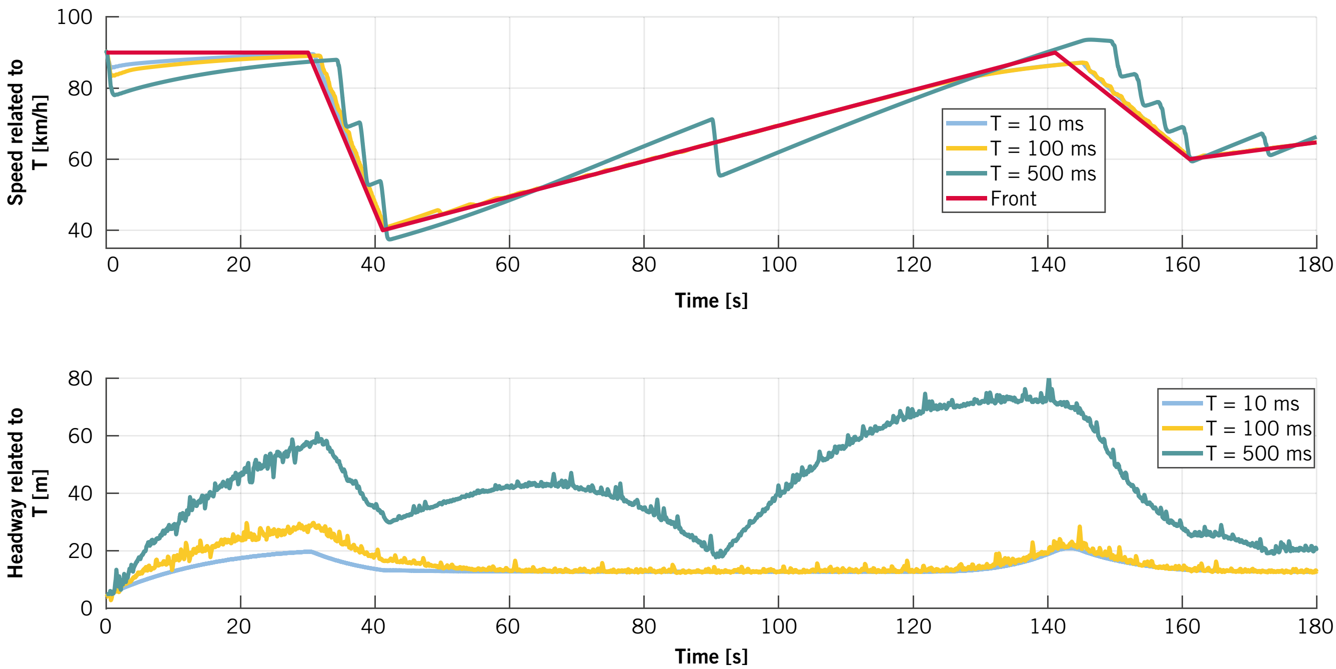

FIGURE 5 Impact of different transmission times (T) on the control quality (© IPG Automotive)

platoon vehicles and the distance between the platoon vehicles and the other vehicles thus needs to meet statutory framework conditions. As a result, the following vehicle separated by the other vehicle could lose contact to the platoon and, in the worst case, become unable to maneuver. Larger distances hence also represent deviations to prevent, which are mainly caused by the latencies.

All in all, the latencies and the artificial noise lowered the control quality significantly. This underlines the need for a realistic simulation environment even in early layouts of the control algorithms.

EVALUATION AND CONCLUSION

This article analyzed the development and validation of platooning systems for heavy-duty vehicles using simulation. It was shown that a change of payload of one platoon vehicle results in issues to follow strong accelerations of the less loaded lead vehicle. However, an instability resulting from this was not detected. Respective control criteria can therefore be laid out easily.

The analysis of the impact of realistic V2V communication showed the necessity of a powerful simulation environment. Especially the transmission delay and the resulting noise of distance determination lead to a significant reduction of control quality. The use of simulation allows for analysis of system properties and an early and robust layout regarding transmission errors and latencies. In this way, more issues can be solved and more layout issues handled in early development stages, even before the first physical prototype is available for testing.