A Modular Simulation Framework for Analyzing Platooning Coordination

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ABSTRACT

Recent developments by companies as Waymo, Uber, or Tesla show that autonomous driving is no science fiction anymore. Coordinated driving applications such as platooning, i.e., driving in convoys of coordinated vehicles, use the full potential of the automation. In this paper, we present a simulation framework for analyzing platooning coordination strategies which can be used by domain experts without experience in simulation as it abstract from the details of the underlying simulation. We show the applicability of the simulation framework to support the analysis of platooning coordination strategies in a case study with three coordination strategies.

CCS CONCEPTS

• **Computing methodologies** → **Simulation tools**; **Simulation evaluation**; • **Human-centered computing** → **Ubiquitous and mobile computing**; • **Computer systems organization** → *Self-organizing autonomic computing*; *Embedded and cyber-physical systems*;

KEYWORDS

platooning coordination, coordinated driving, simulation

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1 INTRODUCTION

The fast development of Adaptive Cruise Control (ACC) systems and self-driving vehicles in the last years enables new applications such as platooning, in which vehicles use ACC and vehicular communication to drive with small inter-vehicle distances [1]. Besides an increase of driver's comfort, the small distances in platoons (i) increase the efficiency in utilizing the roads, (ii) reduce the fuel consumption and, hence, the emissions due to slipstream effects as well as (iii) have social implications as platooning increases safety by eliminating the likeliness of accidents thanks to the ACC and to coordination through communication.

Platooning requires two types of organization. We distinguish the platoon management from platoon coordination: where the first targets the intra-platoon level, i.e., the adjustment of the inter-vehicle distance, the latter focuses on vehicle-platoon and inter-platoon interactions.

In this paper, we target coordination of platooning, hence, the assignment of vehicles to platoons based on individual factors as well as the coordination of platoons especially in scenarios with a small amount of platoonable vehicles, i.e., the pioneering phases of platooning. We present a simulation framework that integrates the platooning simulator Plexe [10] which is based on Veins [12] (including *SUMO* and OMNeT++) with the *Platooning Coordination System (PCS)* for platooning coordination [6]. The simulation framework integrates two components for (i) a simplified definition of the platooning coordination strategies and the configuration of the simulation as well as (ii) a web interface based analysis of the simulation results. This enables user without experience in programming / simulation to use it. The modularity of the simulation enables to integrate another simulation environment not depending on the *PCS*. We show the applicability in a case study. Hence, experienced programmers

might benefit from the easy to use web interface to understand details of the simulation while enabling them to use their favorite simulation tool.

The remainder is structured as follows: Next, Section 2 discusses related approaches. Section 3 introduces the *PCS* for platooning coordination. Section 4 explains the components of our modular simulation framework. Section 5 describes the example use of the system within a case study. Lastly, Section 6 summarizes the paper and mentions future work.

2 RELATED WORK

This section compares some tools for simulating platooning. For comparison we included Veins [12], Plexe [10], *VSimRTI* [9], the *iTETRIS Control System (iCS)* [7], and *Simpla* [11].

Veins [12] is a framework for vehicle simulation that provides both a realistic simulation of (i) wireless networking[1] using OMNeT++ [13] as well as (ii) realistic vehicle mobility based on the traffic simulator *SUMO*. Veins synchronizes these two simulators in a bi-directional way.

Plexe is an extension of Veins [10] that adds functionality to implement platooning. It features additional car-following models implementing ACC and Cooperative Adaptive Cruise Control (CACC), i.e., an enhanced ACC that exploits communication to reduce the inter-vehicle distance without harming safey. Simulation results can be analyzed using *R* [10].

The *V2X Simulation Runtime Infrastructure (VSimRTI)* [9] provides an infrastructure for coupling every discrete-event based simulator that supports the so called federate ambassador, e.g., network simulators like *OMNeT++* or *ns-3* [8] with *SUMO*. Such a setup can simulate platooning. Additionally, *VSimRTI* provides a GUI for analysis vehicles on the map and calculating statistics; however, this requires a commercial license. Alternatively, *VSimRTI* offers the *WebSocket Visualizer* for showing vehicles in a Google Maps View.

The *iCS* is part of *iTETRIS* [7] and permits to integrate *SUMO* and *ns-3*. As in Veins, every user can implement a custom vehicle behavior, e.g., for simulating platooning.

Simpla [11] is a plugin for *SUMO* that exploits its TraCI interface to control the simulation. It implements a basic platooning logic and supports configurable parameters, such as the distance between vehicles of a platoon. In contrast to Veins, it does not integrate a network simulation.

We compare the presented approaches for simulation of platooning and platooning coordination using the following criteria: (i) effort to setup and run a simulation; (ii) effort for testing custom platooning coordination strategies, (iii) visualization of a simulation, and (iv) possibility to compare the results of different platooning coordination strategies.

[1]Through configuration of the network simulator, it is possible to consider issue of realistic communication such as packet loss.

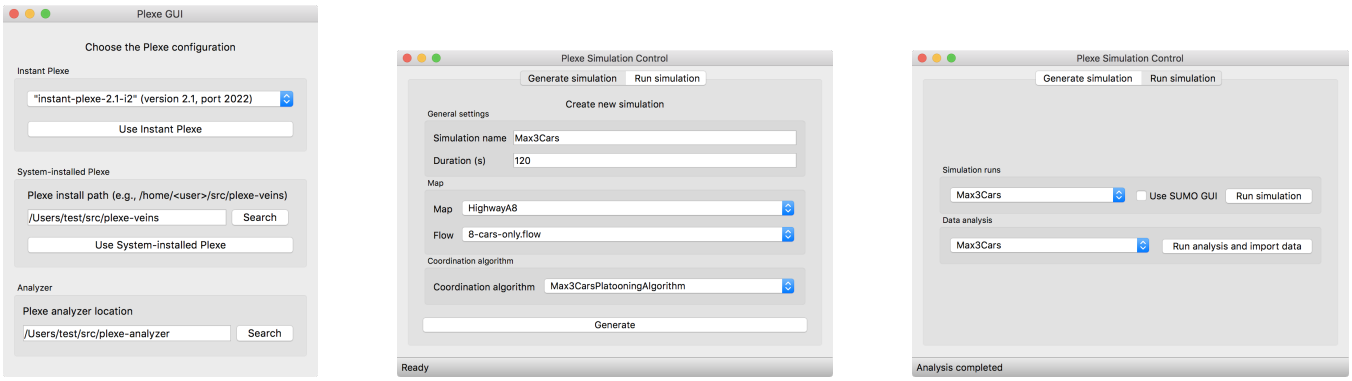
The effort to setup and run a simulation differs for the approaches. For example, *Simpla* offers a quite easy setup process while Plexe, Veins, and *iCS* require not only *SUMO* but also additional software for the network simulation. *VSimRTI* offers the built-in Simple Network Simulator. However, it does not provide the complete IEEE 802.11p stack, which is only present when using an external network simulator such as *OMNeT++*. The developers of Veins and Plexe offer virtual machine images to simplify this process.

Second, we analyze the possibility to implement and test custom platooning coordination strategies. In theory, every project supports this as all are open source and a developer could implement any required functionality. However, the projects can be split into two groups: Veins, *VSimRTI*, and *iCS* do not target platooning specifically, but might be extended for it. Plexe and *Simpla* are originally meant for platooning simulation. So these two projects offer platooning functionality, e.g., the CACC controller. In contrast to Plexe, *Simpla* offers only a limited extensibility because it does not implement custom controllers such as CACCs to enable platooning but uses different *SUMO* vehicle types for the purpose. The leading vehicle of a platoon need thus to be different than the following ones. Besides this issue, *Simpla* does not support (realistic) Vehicle-to-Vehicle (V2V) or Vehicle-to-Infrastructure (V2I) communication [11].

The third characteristic targets the visualization of a simulation. Most of the approaches use the traffic simulator *SUMO* that offers a Graphical User Interface (GUI) for observing a simulation. Large scale simulations, however, do not run in real time or are parallelized on a server, where the GUI is not used. This solution thus does not provide the best user experience. *VSimRTI* offers different solutions for a graphical representation of a simulation; however, as it does not focus on platooning, it does not display platooning-related information.

Finally, we analyzed the comparability of the results of different platooning coordination strategies. None of the approaches offer a complete solution. All projects that use *SUMO* are able to provide raw log files that contain data, such as the velocity. This data can be analyzed using *R* or other tools, requiring manual effort. These tools are essential for complex statistical analyses, but there is also the need of performing rapid qualitative analyses.

Overall, there are different tools that can be used to show how platooning works. But when it comes to the implementation of different platooning coordination strategies and especially the visual analysis and comparison of the results, the existing approaches do not offer the required functionality. Hence, in this paper we strive for a GUI as a convenient way for such domain experts to check the suitability of algorithms while keeping a developer with understanding of the simulation platform in the loop for implementation.



(a) choice of the subsystem **(b) simulation configuration panel** **(c) simulation runs and analysis panel**

Figure 1: Screenshots of the GUI of the simulation tool.

3 PLATOONING COORDINATION SYSTEM

The *Platooning Coordination System (PCS)* coordinates the formation of platoons [6]. It receives information from drivers such as their destination, searches a suitable platoon, and navigates the vehicle to the platoon. After reaching the platoon, a vehicle uses vehicle-to-vehicle communication and sensors (e.g., distance sensors) for controlling the joining process. Further, if a platoon meets another platoon, the *PCS* decides whether they should merge or overtake. The *PCS* constantly receives updates about vehicles' positions and determines when to leave or dissolve a platoon.

In [3], we used the Java-based FESAS Framework [4] to build a demonstrator for the *PCS* for coordinating self-driving Mindstorms robots[2]. Following the MAPE-K approach [2], the *PCS* is structured into the four key functionalities of monitoring the vehicles, analysing which platooning actions are necessary (e.g., join requests of vehicles or inter-platoon actions), planning necessary actions, and controlling the execution of these adaptations. The monitor and the executor elements communicate with the vehicles (or the a platooning simulation) using a JSON-based protocol for collecting data and sending instructions, respectively. For analyzing and planning of the platooning behavior using the collected data, the *PCS* can integrate different coordination strategies to comply with individual objectives of drivers, e.g., travel as fuel efficient as possible versus travel as fast as possible while keeping the benefits of platooning. These functions are supported by a shared knowledge repository which represents a typical self-adaptive systems approach [5] and enables adaptations of platooning behavior of vehicles at any time.

[2]A video showing the platooning demonstrator can be found at: https://www.youtube.com/watch?v=Nnrbq-4Dn24

4 SIMULATION FRAMEWORK

To simplify simulations with the *PCS*, we build a simulation framework connecting the *PCS* with Plexe that includes a configuration tool and a web interface for the analysis of simulation runs. The *PCS* is well integrated into our simulation framework. Accordingly, users do not have to change the *PCS* itself to test new platooning coordination strategies. Users are rather able to just implement the algorithms of their strategies in a common Java class. We offer a development environment which supports an API for interacting with the *PCS*, such as accessing collected information or abstracting the commands of the JSON protocol. Accordingly, users can just implement their platooning coordination strategies, load them into the simulation tool and evaluate them. In the next section, we detail the components of the simulation framework.

4.1 Simulation Tool

We implemented the simulation tool using Python. A GUI permits the users to quickly setup a simulation, run it, and import the simulation outcome into the web interface for the visual analysis. Users can choose the Plexe subsystem to be used, which can either be the version of Plexe installed on the host machine or Instant-Plexe, i.e., a Linux-based Virtual Machine (VM) which comes with all the required software pre-installed (Fig. 1a). In addition, it permits the user to choose the location of the web analyzer (Section 4.2) for importing simulation results into the analysis tool.

Once the user chooses the subsystem to use, it presents to the user a window enabling the quick creation of a simulation by entering some basic information such as the duration (Fig. 1b). The user can then choose the *SUMO* map and a traffic flow configuration. Currently, the tool offers two sample maps and a couple of pre-configured flow files, but the user can integrate additional ones. Next, the user chooses the

coordination strategy. The different algorithms of the coordination strategies are loaded from a *jar* file and displayed as a choice to the user. This will tell the *PCS* which coordination logic to load and to employ during the simulation. Finally, the tool creates a new Plexe simulation folder including all the required configuration files. These files are standard OMNeT++ configuration files, as the ones included in any Veins or Plexe tutorial. The experienced user can thus also generate a basic simulation and then manually tune additional parameters (e.g., IEEE 802.11p network parameters). The final tab (Fig. 1c) permits the user to run a simulation and, at the end, to extract the data from the simulation and import it into the web analyzer tool.

4.2 Analysis Web Interface

The web interface for providing the graphical qualitative analysis of platooning coordination simulations was implemented using the Symfony Framework for PHP and JavaScript. It is composed of two web pages. The first one lists the simulations that have been run and permits either to analyze one, or to choose two of them for comparison. The list of simulations is retrieved from a database which, in turn, is populated by the GUI interface described in Section 4.1. Once a simulation (or a pair) is chosen, the second page of the interface displays the *SUMO* map associated with the simulation and permits to re-play it. Each vehicle is displayed as a rectangle, and the color can either identify the vehicle type or the association to a platoon. Hence, vehicles belonging to the same platoon can be displayed using the same color. In addition, by clicking on a vehicle, the interface shows additional information such as *current speed* and its time evolution, *platoon id*, *position*, *distance* or *relative speed* to the front vehicle. Currently, we are developing a dashboard that shows the aggregated results of simulation runs w.r.t. platooning compositions, velocity, environmental pollution, energy consumption, and time spent in platoons.

5 CASE STUDY

This section describes how to define coordination strategies and the analysis of their outcome. In particular, we define three toy coordination strategies:

- All-In-One: all vehicles are assigned to a single platoon;
- Max-3-Cars: the system assigns a vehicle to the closest platoon with less than 3 vehicles. If there is no such platoon, the system creates a new one; and
- Max-Distance: a vehicle is assigned to the closest platoon, provided that this is closer than 400 m.

The coordination strategies are defined as Java classes for the *PCS*. The *generateStrategy* method takes one parameter, i.e., an object (of class *Vehicle*) representing the vehicle for which the coordination strategy should be computed and must return an object (of class *DrivingStrategy*) representing the action. Currently we have three categories of strategies, i.e., *BasicDrivingStrategy*, *CreatePlatoonStrategy*, and *JoinPlatoonStrategy*. The first one simply indicates that the vehicle should drive on its own. The second one creates a new platoon with certain characteristics, e.g., a certain speed and driving on a certain lane. The last one controls the join of a platoon. In this paper we consider this small set of actions as a proof-of-concept. In future we will implement new ones, e.g., to support leaving or changing platoons.

Once the user implements the algorithms, they are compiled to a single *jar* file, which is loaded by the *PCS* at runtime. Then, the user can choose the coordination strategy that should be employed using the configuration tool (Section 4.1). In the following we show the pseudo-code of the three aforementioned coordination strategies.

```
function generateStrategy(Vehicle vehicle)
  if (using BasicDrivingStrategy)
    platoon = findBestPlatoon(vehicle);
    if (platoon == null) return CreatePlatoonStrategy();
    else return JoinPlatoonStrategy(platoon);
  else return null;
function findBestPlatoon(Vehicle vehicle)
  platoons = getNearbyPlatoons(vehicle);
  if (platoons is empty) return null;
  else return platoons[0];
```

Listing 1: All-In-One strategy.

```
function generateStrategy(Vehicle vehicle)
  if (using BasicDrivingStrategy)
    Platoon platoon = findBestPlatoon(vehicle);
    if (platoon == null || platoon.getVehicles().size() == 3)
      return CreatePlatoonStrategy();
    else return JoinPlatoonStrategy(platoon);
  else return null;
function findBestPlatoon(Vehicle vehicle)
  platoons = getNearbyPlatoons(vehicle);
  suitable = {p ∈ platoons | p is ahead and has less than 3 cars}
  if (suitable is empty) return null;
  else return argmin_{p∈platoons} distance(vehicle, p);
```

Listing 2: Max-3-Cars strategy.

```
function generateStrategy(Vehicle vehicle)
  if (using BasicDrivingStrategy)
    platoon = findBestPlatoon(vehicle);
    if (platoon == null) return CreatePlatoonStrategy();
    else return JoinPlatoonStrategy(platoon);
  return null;
function findBestPlatoon(Vehicle vehicle)
  platoons = getNearbyPlatoons(vehicle);
  suitable = {p ∈ platoons | p is ahead and distance is smaller than 400 meters}
  if (suitable is empty) return null;
  else return argmin_{p∈platoons} distance(vehicle, p);
```

Listing 3: Max-Distance strategy.

Listings 1 to 3 list the three implemented coordination strategies. Each of the three coordination strategies, within the *generateStrategy* function, first check whether the vehicle is still driving on its own. If that is the case, the coordination strategy invokes the *findBestPlatoon* method, which actually finds the platoon given the constraints of the strategy. If no platoon is found, the vehicle becomes a new platoon;

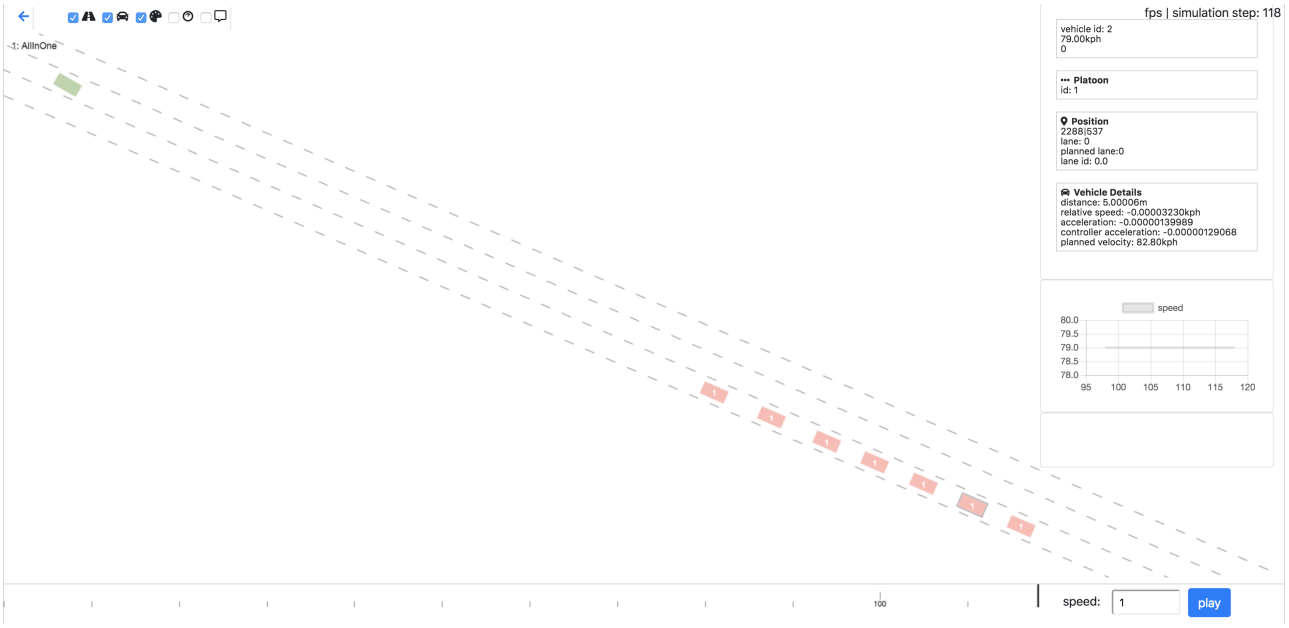


Figure 2: Screenshot of the web analyzer showing the result of the All-In-One strategy.

otherwise the coordination strategy commands the vehicle to join the best one.

Inside the *findBestPlatoon* method, the coordination strategy exploits the functionalities provided by the *PCS*, e.g., *getNearbyPlatoons*. As shown in the code snippets, the *findBestPlatoon* method is a straightforward implementation of the coordination strategy.

For testing the behavior of the coordination strategies and to show the analysis tool described in Section 4.2 we create three simple 8-car simulations, each of which uses one of the coordination strategies. We run the simulation using the tool described in Section 4.1, extract the data, and import it into the database of the web analyzer. With respect to simulation parameters, the desired platoon speed is set to 80 km/h, while the *PCS* commands the joiners to speed up to 130 km/h to catch-up with the platoon. This speed delta is clearly unrealistic and it is used here only to make the join process quicker. As the communication parameters are not relevant in this paper, we omit them. We are just using the IEEE 802.11p PHY and MAC models provided by Veins.

Figure 2 shows a screenshot of the web analyzer for the All-In-One coordination strategy simulation. In particular, the first seven vehicles have already formed a platoon, and the tool shows this by drawing them all with the same color. The eight vehicle is still approaching the platoon, so it displayed with a different color. The user can use the time line at the bottom to move back and forth in time, or start and stop the replay. Finally, by clicking on a vehicle, in the top-right corner the tool shows information about the selected car, including identifier, current speed, position, platoon identifier, etc. In addition, it is possible to show time series of certain quantities. Currently we only show the speed as an example, but we currently add information such as fuel consumption.

Figure 3 shows a screenshot of the analyzer in comparison mode, after choosing the Max-3-Cars and the Max-Distance simulations for comparison. The two views in the browser page are linked together, so they display the same portion of the road at the same zoom level. The Max-3-Cars coordination strategy (top of Fig. 3) results in the creation of three platoons, the first two with three vehicles and the last with the remaining two cars (not displayed in the figure due to the zoom level). Conversely, the lower part of Fig. 3, shows the outcome of the Max-Distance strategy. The first platoon is composed of four vehicles because the three joiners were closer than the chosen 400 m at the time of joining.

6 CONCLUSION AND FUTURE WORK

In this paper, we presented a framework that eases the implementation of platooning coordination strategies as well as their evaluation. We show the applicability with the Plexe simulator in combination with the *PCS* for coordinating platooning. Due to modularity of the simulation framework, the simulation itself can be substituted.

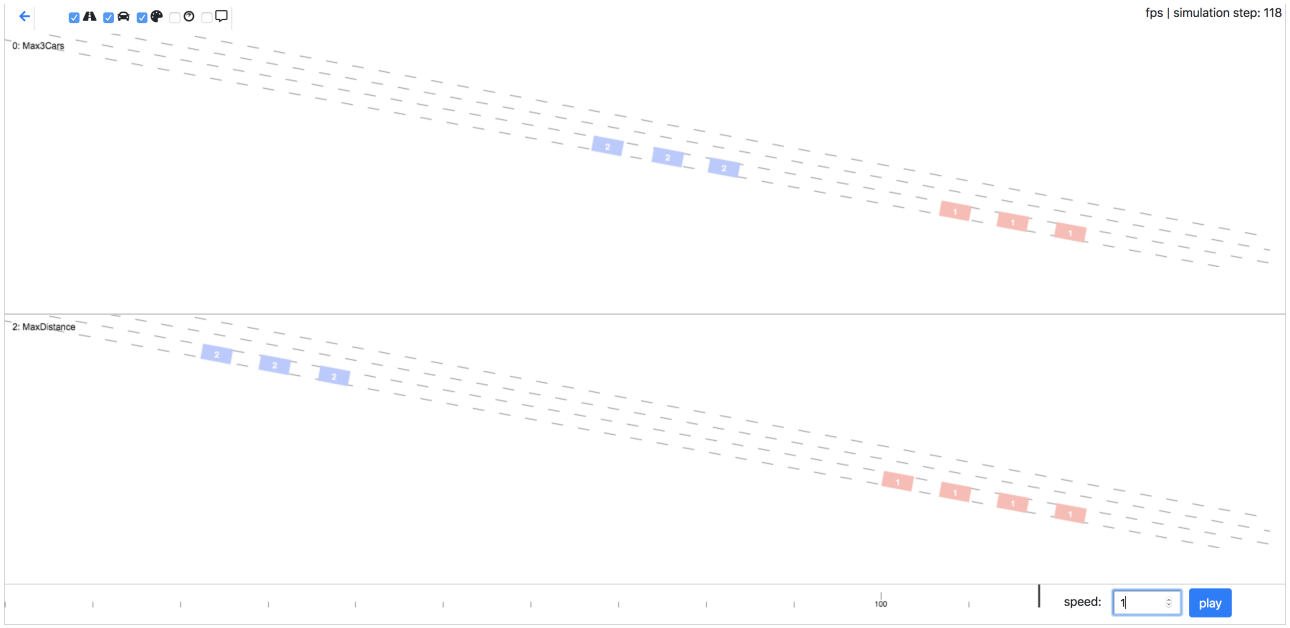


Figure 3: Screenshot of the web analyzer used in comparison mode, showing the results of the Max-3-Cars (top) and the Max-Distance strategies.

We are currently extending the graphical analyzer with a dashboard to include fuel consumption and efficiency analysis. Fuel consumption data is already collected but not yet displayed. Further, the *PCS* can now manage non-platooning interfering vehicles if they are communicating, so that the *PCS* is aware of their presence. The detection of non-communicating interfering vehicles using local sensors of autonomic vehicles and communicating this to *PCS* is part of out future work. So far, we consider a join at the rear of a platoon. For future work, we plan to integrate situations in which a vehicle joins in another position.

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