2015 IEEE 18th International Conference on Intelligent Transportation Systems

COMPANION - Towards Co-Operative Platoon Management of Heavy-Duty Vehicles

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***Abstract*—The objective of the EU project COMPANION is to develop co-operative mobility technologies for supervised vehicle platooning, in order to improve fuel efficiency and safety for goods transport. The potential social and environmental benefits inducted by heavy-duty vehicle platoons have been largely proven. However, until now, the creation, coordination, and operation of such platoons have been mostly neglected. In addition, the regulation and standardization of coordinated platooning, together with its acceptance by the end-users and the society need further attention and research.**

In this paper we give an overview over the project and present the architecture of the off-board and onboard platforms of the COMPANION cooperative platoon management system. Furthermore, the consortium reports on the first results of the human factors for platooning, legislative analysis of platooning aspects, clustering and optimization of platooning plans and prediction of congestion due to planned special events. Finally, we present the method of validation of the system via simulation and trials.

I. INTRODUCTION

Platooning of heavy duty vehicles (HDV) provides the opportunity to save fuel, increase safety and add road capacity. The COMPANION (Cooperative dynamic formation of Platoons for safe and energy-optimized goods transportation) project [1] aims to develop and validate a system for creation, coordination and operation of platoons (see fig. 1). Furthermore, it addresses the user acceptance of such a system and analyzes the current legal and standardization issues, the envisioned system poses.

The COMPANION project has five main objectives. The first three objectives are the development and validation of:

- an off-board platform for the coordination of platoons
- an on-board system for coordinated platooning
- multimodal on-board and off-board user interfaces

The off-board platform is a collection of services in the backend that communicate with the vehicles via the mobile network. The on-board system is an on-board unit on the vehicles, that is responsible for the control of the vehicle, control of the platoon and communication between the vehicles and the off-board platform.

The fourth objective of the COMPANION project concerns the legislative and standardization aspects of platooning. To this end, the current state of the legislation in the EU for platooning has been analyzed and legal gaps have been identified for the operation of platoons [1]. Within the COMPANION project a proposal for legal solutions will be made for the adoption of platooning technologies. Furthermore, it will be analyzed how V2V-communication standards have to be amended for platooning.

The fifth objective is to demonstrate the COMPANION system on European roads in multiple countries and show the capabilities of the off-board platform in a large scale simulation.

In this paper the consortium reports on the overall concept of coordinated platooning, the architecture of the system and first results of the project.

II. RELATED WORK

In recent years the topic of platooning has been researched under different aspects, for example fuel saving potential, road capacity analysis, control and automation in several research projects. Among them are California PATH [2], Chauffeur [3], KONVOI [4], SARTRE [5] and Energy ITS [6]. Bergenhem et al. [7] provide a concise overview of several of the above mentioned platooning systems.

Regarding the estimated fuel savings from platooning, results vary between 5 to 15 percent [8], [9], [10]. Influencing factors for the fuel saving effect of platooning due to the slipstream are distance between vehicles, velocity of the vehicles and weather conditions.

With respect to the increase of road capacity due to platooning it was shown within the California PATH project, that the capacity can be doubled, when considering only heavy duty vehicles [7].

Due to the beneficiary effects of platooning, the company Peloton [11] is aiming at commercializing the concept of platooning in the US.

In all recent approaches to platooning the aspect of coordinating platoons has not been addressed and were working under the assumption that a platoon will be created ad-hoc on the highway or that the vehicles in the platoon already have a common start and destination. The COMPANION system aims at closing this gap with an off-board platform to plan

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[1] http://www.companion-project.eu/

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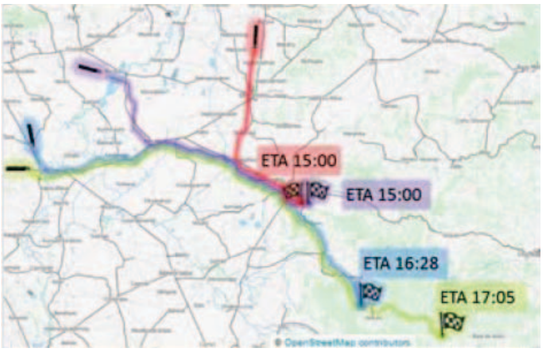
978-1-4673-6596-3/15 $31.00 © 2015 IEEE
DOI 10.1109/ITSC.2015.208

(a) Four different HDVs from different companies need to be coordinated for platooning.



(b) The COMPANION system calculates fuel-optimal routes for each vehicle and optimizes the speed profiles of the HDVs in such a way that the vehicles are able to meet on the road and platoon together.

Fig. 1: Strategic coordination of several HDVs to a platoon.

platoons for a large set of HDVs before an actual transport takes place.

III. SCENARIO DESCRIPTION

This section describes the nominal use case of the COMPANION system, without going into the specifics of the technical components in order to convey the overall concept.

Prior to a transport, the dispatcher at a carrier company enters a transport assignment into the system. The transport assignment consists of a start, destination and desired time of delivery. The off-board system calculates the optimal route for this transport. In a subsequent optimization phase, the off-board platform tries to find other vehicles to platoon with and calculates the according speed profiles, merge and split points for these vehicles. Route, nominal speed profile, merge and split points together represent a platooning plan. This platooning plan is sent to the vehicle before the transport starts.

When driving on a highway, the driver has to activate the automatic longitudinal control. The speed of the vehicle is controlled according to the nominal speed profile of the platooning plan and the vehicle in front of it. When reaching a merging point and in vicinity of vehicles to platoon with, the driver is informed that he can activate the merging process. The merging process begins by closing the gap to the other vehicles of the platoon. When the gap has been closed, the driver has to activate the platooning mode of the control system. The level of automation aimed at in COMPANION is considering the automatic longitudinal control of the vehicle. The driver is responsible for the lateral control of the vehicle.

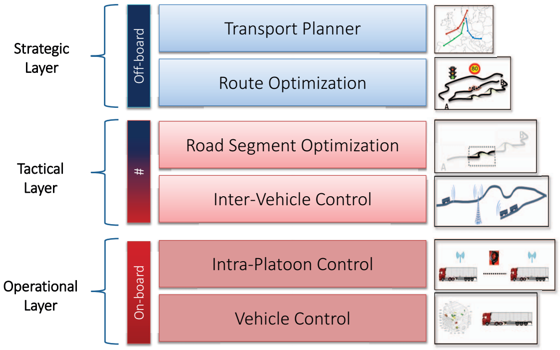


Fig. 2: Planning and control hierarchy

As the vehicles are in contact via vehicle to vehicle communication, they exchange state variables as current position, velocity and further needed information. In case of an emergency braking of one of the vehicles in the platoon, the following vehicles of the platoon are notified of this event and decelerate automatically in order to ensure a safe operation of the platoon.

When a vehicle reaches its split point, the driver has to perform a split by taking over the longitudinal control of the vehicle and continue the trip as an individual vehicle.

The off-board platform monitors the vehicles of the system. In case a vehicle or platoon is not able to follow its plan, due to events like traffic-jams or adverse weather conditions, a recalculation of the speed profile and/or route of the vehicle can be triggered.

IV. ARCHITECTURE

Fig. 2 shows the three layers of the planning and control hierarchy in the COMPANION system. The three layers of this hierarchy can be subdivided again. The topmost layer represents the strategic planning, which concept was introduced in the scenario description.

Once the vehicle received a platooning plan, which incorporates a coarse speed profile, the tactical layer is responsible for refining this coarse speed profile. This happens according to the specific vehicles dynamical capabilities. The communication between the vehicles and the off-board platform is established via the cellular network (3G).

The operational layer comprises the control of the platoon and the vehicle itself. The platoon controller is a distributed controller that is responsible for keeping the right distance between vehicles, performing merging maneuvers and ensuring string stability of the platoon. The vehicles use an extended version of the ITS-G5 V2V communication at this layer. The vehicle controller, which is the inner control loop of the operational control, controls the vehicle's speed according to

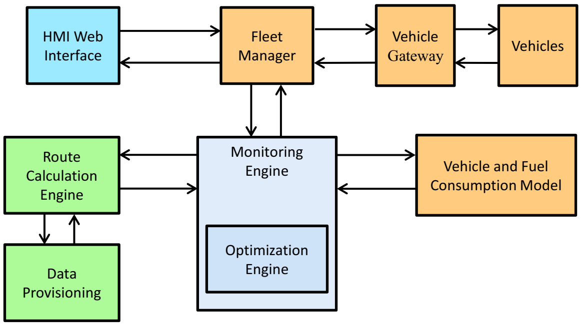


Fig. 3: COMPANION overall component architecture

the input of the platoon controller other ADAS systems and driver input.

In the following three sections these three layers will be described in more detail.

V. STRATEGIC: OFF-BOARD PLATFORM

Fig. 3 depicts the overall component architecture of the COMPANION system. In this section the main components of the system are described.

A. HMI Web Interface

The off-board HMI is a human-machine interface which provides input and output functionality for the dispatcher. Dispatchers can create and manage transport assignments. The calculated route, truck status, tracking data and the benefits of the platooning is displayed. The interface is accessible via a web-browser.

B. Route Calculation Engine

The Route Calculation Engine (RCE) calculates a single route for a single vehicle at a time. It takes into account the traffic situation (live and forecast), vehicle parameters (weight) and road attributes (slope, truck attributes). The route result contains velocity windows (v_{min}, v_{max}) which the Optimization Engine uses to optimize the overall system platooning potential.

One example for a forecast is the prediction of congestion due to planned special events, which has been developed within the COMPANION project and was presented in [12].

C. Monitoring and Optimization Engine

The Monitoring and Optimization Engine (MOE) calculates optimal and feasible velocity profiles and merging/splitting points for platoons, given a set of individual routes, velocity constraints, timing constraints and fuel consumption models. For each individual transport assignment there has been a truck appointed and that truck has been given an optimal eco-route from the RCE. The assumption is that there is some freedom in choosing the velocity along this route, so that, by jointly optimizing the velocity of several vehicles, one can find a *platooning plan* that delivers the goods in time at minimal fuel cost. The *routes* from the RCE are given as sequences of *links*, see Fig. 4, but the MOE will not work on link level, but on larger *segments*, consisting of several links. The connection nodes between segments are called *waypoints*.

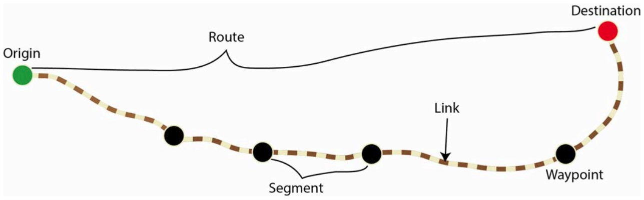


Fig. 4: Definitions of *route*, *segment*, *link* and *waypoint*

The route holds information about the nominal velocity range, as described in Section V-B. This range is further refined and aggregated on segment level by the Vehicle and Fuel Consumption Model Service. A fuel consumption model per segment is also delivered by the same service. The collection of routes are modeled as a directed graph where the nodes represent the waypoints and edges represent the road segments. Conceptually, the graph is built in the following way. Consider the example of three assignments with partially overlapping routes R1–R3 (going from left to right) as depicted in Fig. 5. Start with route R1 and define a graph with a single edge representing the entire route, with one node at the origin and one at the destination, corresponding to the red nodes in Fig. 5. When the second route R2 is added, there is a segment that overlaps route R1. The beginning and end of the overlapping segment define two new nodes in the graph, and so do the origin and destination of route R2. This new graph corresponds to the red *and* green nodes in the figure. Appending also route R3 adds the additional four blue nodes and corresponding edges.

The MOE jointly optimizes each vehicle's average segment velocity over the graph with the objective to minimize the total fuel consumption. Merging or splitting of a platoon is only permitted at the nodes meaning that two vehicles either drive solo or drive as a platoon over the whole segment. To allow for merging (soon) after the junction of two routes, or for splitting prior to the junction, additional nodes could be

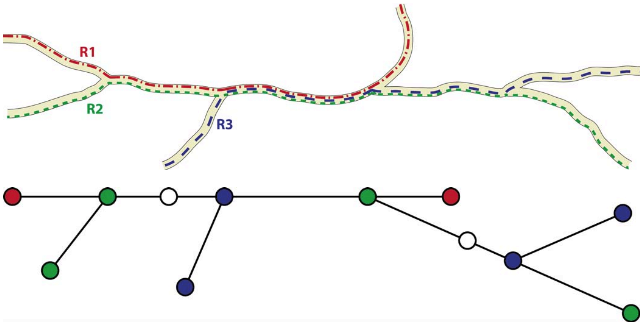


Fig. 5: Upper plot: Three assignments with partially overlapping routes. Lower plot: The corresponding network representation

added to the network during the optimization. Two such nodes are depicted in white in Fig. 5.

The output of the optimization is a platooning plan that specifies, for each truck, the required average velocity on each segment of the route, and for each segment also a list of other trucks with which to platoon. Route R1, for example, consists of five segments. On the first segment truck 1 will drive solo, on the second it will platoon with truck 2, on the fourth it will platoon with truck 2 and 3, and on the fifth segment it will drive solo again. The velocities are chosen such that truck 1 and 2 arrive at the second node at the same time, and when trucks platoon they have the same velocity. The details of the optimization algorithms are beyond the scope of this presentation, but first results within the COMPANION project can be found in [13] and [14].

D. *Fleet Manager*

Having coarse-grained platooning plans from the Monitoring and Optimization Engine and route, weather and traffic information from the Route Calculation Engine, the Fleet Manager generates fine-grained assignment plans for each vehicle. It also gathers information about fleet state and sends it to the Monitoring and Optimization Engine and off-board HMI.

E. *Vehicle and Fuel Consumption Model Service*

The Vehicle and Fuel Consumption Model Service calculates possible speed sets for road segments depending on a vehicle's dynamic characteristics. Furthermore, it calculates the according fuel consumption for the possible speed sets.

F. *Vehicle Gateway*

The Vehicle Gateway handles the communication between the off-board components and the on-board components for each vehicle connected to the COMPANION system. This service makes sure all data is buffered (queued) if a vehicle is offline at that moment.

Fig. 6 depicts the sequence diagram of the nominal use case of the COMPANION system with the according components of the system. All components except the Monitoring and Optimization Engine are state-less.

VI. TACTICAL

The tactical layer consists of two main components; the Road Segment Optimizer and the Platoon Orchestrator (see fig. 7a). The Road Segment Optimizer defines the detailed speed profile and spacing policy for the vehicle according to the constraints given by the assignment plan. Hence, in it simplest form the speed profile equals the mean speed required to meet the given velocity and timing constraints. However, utilizing a detailed digital map (eHorizen) including road attributes such as road incline, speed limits, etc, more fuel optimal speed profiles and spacing policies can be derived. Examples of such control policies is presented in Alam [15] for HDV platoons and in Hellström [16] for a single HDV. The Platoon Orchestrator synchronizes vehicles and platoons that have to start to interact at a given point, e.g. a merging point. This is done before the point is reached and before direct contact via V2V-communication is established between the vehicles.

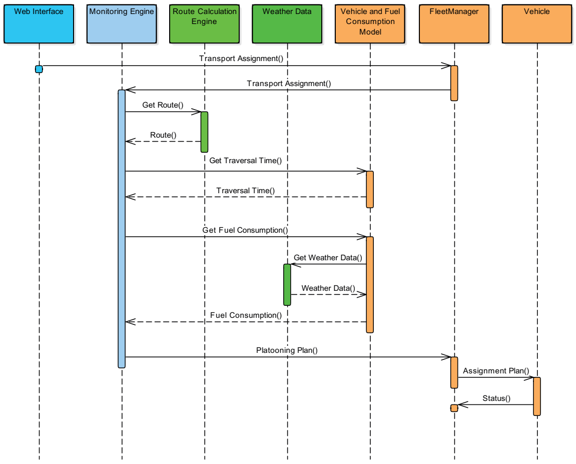
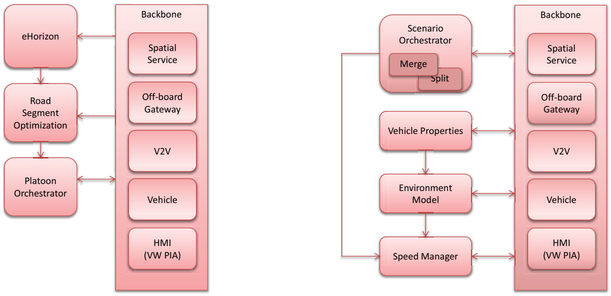


Fig. 6: Sequence diagram of the nominal use case



(a) Tactical layer

(b) Operational layer

Fig. 7: Operational and tactical layer

VII. OPERATIONAL: PLATOON AND VEHICLE CONTROL

The operational layer is where the control signals to the trucks engine management system and brake management system are defined. The main components of the operational layer are the Scenario Orchestrator, the Speed Control, the Environmental Model and the Vehicle Properties (see fig.7b).

The Scenario Orchestrator defines the control state of vehicle based on the assignment plan and it also handles sequential events such as merging and splitting of platoons. The main control states used are driving in a platoon, driving as platoon leader, driving alone, merge into a platoon and split from a platoon.

The Speed Control can be described as an adaptive cruise control that controls the vehicles speed based on the speed profile and spacing policy defined in the tactical layer and the current control state defined by the Scenario Orchestrator. Information about other vehicles that the Speed Control has to adapt to is obtained from the Environment Model and information about the ego vehicle is obtained from the Vehicle Properties component.

The Environment Model is a component where data about the surrounding of the vehicle is fused based on sensor data from onboard sensors such as radar and data received from other vehicles and platoon members via V2V-communication.

VIII. BACKBONE

The backbone is a set of services that is utilized by a number of components in the tactical and operational layer. The most important ones to make the system work are described here.

The Spatial Service is a service handling the assignment plan. It also keeps track where the vehicle are related to the plan.

The Off-board Gateway is the communication link between the on- and off-board systems. Stable connection and good access is for the off-board communication of higher importance then latency and transmission speed. Hence, 3G is used.

The communication link between the ego and other vehicles is based on the IEEE 802.11p and ITS-G5 standard to ensure a communication link with low latency. However since ITS-G5 is not adapted for Platooning the information to be broadcasted according to ITS-G5 is not adequate. Therefore additional information have been added, information such as intended speed and retardation, platoon status corresponding to the control state of the Scenario Orchestrator and a platoon ID.

The trucks used in the COMPANION project are standard production trucks with the COMPANION on-board system added. On-board sensors, such as radar, tachograph, and accelerometers utilized are standard production units. The COMPANION onboard system is connected to other ECUs of the truck via the CAN bus.

IX. HUMAN FACTOR ASPECTS AND HMI DEVELOPMENT

Drivers in a platoon experience a new driving situation which differs to a large extend from the usual driving. Due to the small inter-vehicle distances, drivers miss visual information from the environment. This might result in a lack of Situation Awareness (SA), which can lead to human-out-of-the-loop problems. In this semi-autonomous driving context, lateral movement is controlled by the driver while the longitudinal movement is controlled by the system. Moreover, the predefined assignments and maneuvers narrow the ground for decision making for routes, maneuvers, breaking times, and speed control.

The goal of the HMI development is a) keep drivers in the loop by increasing SA, and b) assist drivers with platooning operations. To keep drivers in the loop and increase SA, information is shown to the driver. Novel interaction concepts are developed that will not violate the drivers' experience and expectations. However, it is important that drivers are not distracted from driving by directing too much attention to the HMI. Because of this, drivers should comprehend the information shown on the HMI quickly. For this, Ecological Interface Design (EID) can be a solution. It incorporates the skill, rules and knowledge (SRK) taxonomy of Rasmussen, which states that the perception of information should rely on visual low-level processes which are naturally fast, effortless and can proceed in parallel [17]. Low-level perception features and a focus on supporting skill-based and rule-based behavior will be used to reduce interpretation effort. Thus, the driver is not forced to direct his attention away from driving more than needed. For the HMI development, user-centered design approach is applied. Requirements are collected based on questionnaires, interviews, and observations from real drivers. These requirements are then applied in designing interaction concepts which are developed as low-fidelity prototypes. In an iterative process, different designs are evaluated with drivers, so that the HMI will gain large acceptance among drivers.

A state-of-the-art analysis of current driver assistant systems was performed along with initial interviews with drivers and stakeholders. Questionnaires on technology readiness and overall perception of platooning were distributed among drivers and the feedback was collected. Then, an observation study with two truck drivers was run. In essence, drivers want to make sure that their personal safety is ensured. Thus, the focus lies in making imminent information visible to increase trust and acceptance of the system. Based on these findings, a first paper prototype on merging and platooning was created and discussed with truck drivers. In the next step, the paper prototype will be transformed into a working prototype, which will be evaluated in a driving simulator. In these tests, several factors such as users' satisfaction and decision making errors are measured. In another step, an evaluation method is developed which enables design-time evaluation of HMI impact on driving performance using a cognitive modeling approach [18], which is a first result in the COMPANION project.

The future steps include evaluations on proving grounds to assess the usability of the HMI. The HMI will be assessed under real-world conditions in a qualitative study. System usability is evaluated in merging and platooning use cases.

X. LEGAL AND STANDARDS

One of the obstacles towards a current exploitation of heavy-duty vehicle platooning on public roads is given by the absence of EU legislation on this topic. In fact, the manual operation of heavy-duty vehicles at the small inter vehicle distances proposed by platooning is generally not allowed in the European Union member states and regulations covering such close collaborative automatic control driving are currently lacking. Moreover, relevant regulations differ worldwide, but also among the EU member states.

An extensive analysis has been performed on the current state of EU and local rules regarding automated driving, driving time regulations, traffic regulations and aspects of safety within the COMPANION project [1]. In order to properly analyze the COMPANION project, the use of the platoons and the vehicles that are part of them, the analysis done has been divided in three different subjects: vehicles as individual elements regarding the semi-autonomous driving, the use of vehicles and platoons as a system and the use of the infrastructures where the COMPANION system will run.

Therefore, the COMPANION project intends to contribute on several levels, starting with the Vienna Convention on Road Traffic (1968) who forms the international laws framework for the embodiment of traffic law in the legal systems of the contracting parties. Besides the analysis of the current state of EU legislation, the activities of the United Nations Economic Commission for Europe (UNECE) in their World Forum for Harmonization of Vehicle Regulations (WP.29) have an important role inside the COMPANION project. This World Forum decides minimum requirements of new and innovative solutions to be applied to vehicle technologies while continuously improving global vehicle safety. The ITC, the subsidiary body World Forum for Harmonization of Vehicle Regulations (WP.29) has established six permanent Working Parties (GRs), with the aim to incorporate into its regulatory framework the technological innovations of vehicles to make them safer and more environmentally sound.

Among them, the Working Party on Braking and Running Gear (GRRF) is the body in charge of evaluating proposals under WP.29 for matters concerning vehicle handling and chassis systems considering longitudinal safety dynamics, such as AEBS (UNECE Regulation N 131) and lateral safety dynamics, such as LKAS (UNECE Regulation N 79) and LDWS (UNECE Regulation N 130). GRRF reviews all significant proposals in this area and decides whether to forward them to the World Forum for final decisions on their adoption.

The COMPANION architecture and technical specifications are being developed according to the current published standards by the European Telecommunications Standards Institute (ETSI). Long range communications use consolidated cellular access technologies i.e. 3G or LTE. In the case of short range communications, the requirements are different. ITS-G5 technology for ad hoc network at the 5,9 GHz frequency is used since it provides low latency, robust and royalty free interaction. Communication protocols and interfaces are compliant to standardized interfaces defined by ETSI for the ITS station reference architecture.

The responsible Standardization Development Organizations (SDOs) published the release 1 of standards where no platoon use case was considered. Therefore it is necessary to set up the standardization proposals related to the technical specifications and requirements the involved vehicles and operations should fulfill. Due to the fact that some initiatives at European level are also addressing the platoon use case (Autonet2030, i-Game), COMPANION will try to find synergies between the different activities. These proposals will be compiled and made available to the European Commission and the different standardization bodies as recommendations for future regulatory and self-compliance initiatives from public and private parties.

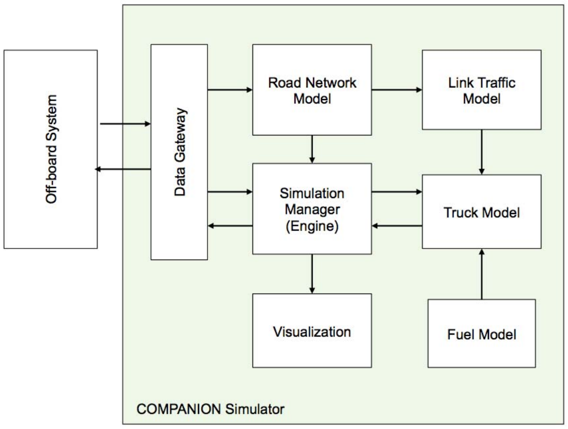


Fig. 8: General framework and components of the COMPANION simulator.

XI. DEMONSTRATION

A. Simulation

The heavy-duty vehicle (HDV) platooning technology, developed in COMPANION, will be demonstrated and validated through computer simulation due to its abilities to evaluate the whole system and major components at a large network level and with flexibility to configure various test scenarios. In general, the COMPANION simulator is designed as a discrete event simulation tool with two main capabilities:

- mimic fleet planning and management, and describe online states of COMPANION HDV trucks and platoons under dynamic traffic and weather conditions;
- demonstrate the off-board decision making and information guidance to individual HDVs while updating online assignment plans according to scheduling and platooning requirements.

The first aspect indicates that the simulator should demonstrate the assignment of an off-board decision and initial itinerary to each COMPANION truck. When a simulation starts, the engine should describe the online movements of all COMPANION trucks on the road network while presenting live traffic and weather information received from the route calculation engine of the off-board system. A simple traffic model will be applied to estimate travel delay of each individual truck on road links and for the whole journey. Fuel consumption will be estimated according to the real driving cycle of each COMPANION truck. The second capability requires the simulator to demonstrate the assignment plan updates for each truck after the Monitoring and Optimization Engine of the off-board system provides updated assignment and platooning plans.

Fig. 8 shows the general framework and essential model components of the simulator. The road network is represented as nodes and links using information from the map database. The speed of an individual truck on road link is predicted by the traffic model. The departure time and initial route, speed and platooning plans are assigned to each truck through the simulation engine. When the off-board system runs optimization and updates the plans due to incidents such as delay, each truck will be informed with a new plan. The truck model provides the detailed states of a truck including position, speed, delay, instantaneous and total fuel consumption etc.

B. Trials

The full COMPANION system capabilities will be demonstrated in a real environment. A driving trial on public highways will show the platooning technology integrated in heavy-duty vehicles working together with the off-board fault-tolerant real-time platoon coordination. This will not only demonstrate the formation, merging and dissolving of platoons, but will also show the benefits on infrastructure usage, safety improvement, fuel consumption reduction and provide a valuable assessment of driver acceptance of the system. For safety reasons, non-critical maneuvers will be requested during the trial, therefore the full performance of the platooning operations will be performed on Applus IDIADA's proving ground.

XII. CONCLUSION

In this paper we presented the concept behind the COMPANION platoon management system. The COMPANION architecture with the main components for the off-board platform and the onboard system was described. Within the COMPANION project a legislative analysis [1] regarding platooning aspects has been performed and first results in the fields of human factors [18], optimization of platoon coordination [13], [14] and traffic prediction [12] were shown. Furthermore, the method of validation of the system via simulation and trials was presented.

ACKNOWLEDGMENT

The COMPANION project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under the ICT.2013.6.5 Co-operative mobility Grant No. 610990.

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