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Study of the Platooning Fuel Efficiency under ETSI ITS-G5 Communications

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***Abstract*—In this paper we evaluate the performance of platoon enabled by contemporary ITS-G5 vehicular communications through the number of simulation experiments. We assess platooning fuel consumption performance under two communication setups and estimate the potential influence of the communication system on the efficiency of the platooning. We also make an attempt to transform our results on platoon fuel efficiency into potential cost reduction gain. Our study shows that platooning fuel-efficiency may vary depending on the communication setup.**

I. INTRODUCTION

Vehicle platooning means a group of vehicle driving closely after each other and being controlled as one unit. It allows many vehicles to accelerate or brake simultaneously, while decreasing the distances between vehicles using vehicle-to-vehicle (V2V) communication. Grouping vehicles into platoons saves space on the highway so that the highway section can accommodate more vehicles. On the other hand, platoon followers experience reduced aerodynamic resistance due to small inter-vehicle distances, which results in fuel saving.

Fuel saving in vehicle platooning, especially for heavy-duty vehicles (HDVs), has been studied extensively by researchers and automotive manufacturers. Vehicle platooning introduces a split-stream effect for the follower vehicle and decreases corresponding air-drag, thus reduces overall restrictive forces. In fact, air-drag constitutes 23% of the total forces acting upon a vehicle at highway speed [1], even modest decrease can have noticeable impact on fuel saving. Previous studies showed that the fuel consumption of HDV platoon follower can achieve 20% saving [2] when it was operating in small inter-vehicle distance. However, this requires robust controller and appropriate communication scheme to guarantee stability and safety. For example, in the case of KONVOI project, it showed no saving during test on public highway since the platoon follower needed to vary its speed to maintain a desired distance to the preceding vehicle [3], which incurred additional fuel consumption.

V2V communications, stability and fuel efficiency in platoon are closely coupled. Proper communication setup can make a platoon follower maintain a desired distance to its predecessor while reducing acceleration and braking frequencies. To enable inter-vehicle communications European Telecommunication Standard Institute (ETSI) delivered the first ITS-G5 release of set of C-ITS standards under European Commission Mandate M/453 [4]. ITS-G5 defines the overall vehicular communication protocol stack [5]. So far there has been no dedicated message type standardized for platooning. However, there is currently pre-standardization activity (ETSI TR 103 301) studying how to apply currently available standards for platooning application [6]. In conformity with aforementioned in this study we implement and apply recently standardized Cooperative Awareness Messages [7] to enable platooning operation. Also according to [8]: Decentralized congestion control (DCC) is a mandatory component of ITS-G5 stations operating in ITS-G5A and ITS-G5B frequency bands to maintain network stability, throughput efficiency and fair resource allocation to ITS-G5 stations.

To the best of our knowledge there are no studies available, that test the fuel efficiency of the platooning under the detailed implementation of the ETSI ITS-G5 communication protocol stack. We compare the potential fuel consumption reduction, when platooning is enabled by two different DCC setups available in ITS-G5. The contribution of the paper is twofold:

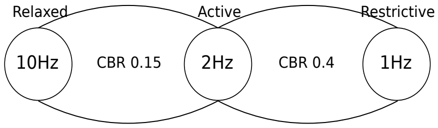
- performance of the platoon enabled by the V2V communications in accordance with a complete ETSI ITS-G5 protocol stack is studied;
- case study of fuel savings for ITS-G5 enabled HDV platooning on E4 highway is provided.

The manuscript is organized as follows. In Section II the description of CAM and DCC is summarized. Section III presents the reference platooning fuel consumption models, while Section IV gives specification of the tested reference scenarios. Performance evaluation results are provided in Section V. Finally, Section VI concludes the paper.

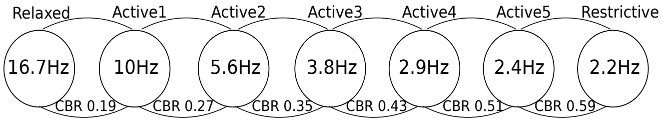
II. ITS-G5 COMMUNICATIONS

The coordination between vehicles in the platoon relies on the frequent exchange of broadcast communication messages containing information about vehicle's position, speed, acceleration and other attributes. The process of broadcast messages' exchange is usually referred to as beaconing [9]. To support beaconing in the platoon, following [6], we implemented Cooperative Awareness Messages (CAM), which are part of ETSI ITS-G5 stack [7]. For the sake of simplicity we skip the description of CAM, interested reader may to refer to [10] for detailed explanation.

In order to comply with ITS-G5 requirements we also implemented DCC functionality. DCC operates as gate-keeper at the medium access layer (MAC). The operation of DCC relies on the DCC state-machine 1. In each of the states DCC specifies the restrictions on the vehicle's transmission behavior. In particular, DCC defines 5 mechanisms to control the access to the communication channel: ”Transmit Power Control” (TPC), ”Transmit Rate Control” (TRC), ”Transmit Datarate Control” (TDC), ”DCC Sensitivity Control” (DSC), ”Transmit Access Control” (TAC). In this study we are focusing on the TRC. TRC defines for each DCC state the minimum allowed time between two consecutive message transmission. In Figure 1 this time is represented in generation frequency of the messages, i.e. 10 Hz means, that vehicle can not generate more than 10 messages per second or in other words, time between two consecutive transmissions is not allowed to be less than $1/10 = 0.1$ s. The transitions between DCC states are performed based on the Channel Busy Ratio (CBR), measured by each vehicles. The detailed DCC operation explanation could be found in [8], [11], [12].



a) ETSI TS 102 687 Configuration, "DCC 2+1"



b) ETSI TR 101 612 Configuration, "DCC 2+5"

Fig. 1: DCC configurations.

To study the influence of the communication setup on the platooning fuel efficiency we implement two different DCC configurations:

- Basic 3-state DCC state-machine, Figure 1.a, described in [8]. Throughout this paper we will refer to this configuration as Communication Setup 1.
- DCC state-machine configuration with set of sub-states in ”Active state”, Figure 1.b, described in [12]. Throughout this paper we will refer to this configuration as Communication Setup 2.

To enable the beaconing in the platoon each vehicle follows the approach below:

- Generates CAM message according to [7];
- The DCC controls the access to the communication channel, according to [8], [12];
- Transmits message on the dedicated ITS-G5 channel according to IEEE 802.11p.

TABLE I: Simulation Parameters

Parameter	Value
Communication parameters	
CAM size	2000 $bytes$
T_x power	23 dBm
Bitrate	6 $Mbit/s$
Path-loss exponent	2
Common parameters	
Size of the platoon (N)	15 vehicles
Number of disturbing vehicles	4 vehicles
Inter-vehicle gap	5 m
Scenario 1	
Platoon's leader speed	100 km/h
Vehicle acceleration capability	2.5 m/s^2
Vehicle deceleration capability	6 m/s^2
Vehicle length	4 m
Number of simulation runs	10
Scenario 2	
Platoon's leader speed	90 km/h
Vehicle acceleration capability	0.4 m/s^2
Vehicle deceleration capability	6 m/s^2
Vehicle length	15 m
Number of simulation runs	10

Signal attenuation is modeled using Log-distance path loss model. We also set the sampling rate CAM parameter the value in a way that effect described in [10] is not observed. Other communication parameters are summarized in the Table I.

III. FUEL CONSUMPTION IN PLATOONING

In order to better understand how communication setup affects the performance of platoon followers, a simplified fuel consumption model is applied to estimate instantaneous fuel usage [13]:

$$f = \frac{\int_{t_0}^{t_f} \delta \left[(\mu\cos\theta + \sin\theta)Mgv + \kappa v^3 + Mav \right] \mathrm{d}t}{H\eta} \tag{1}$$

where t_0 and t_f are the initial and final time instances; H and η are energy density and efficiency respectively; v and a are vehicle speed and acceleration; M is the mass of vehicle; δ indicates if the engine is active:

$$\delta(t) = \begin{cases} 1 & \text{if } (\mu\cos\theta + \sin\theta)Mgv + \kappa v^3 + Mav > 0 \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

the air-drag coefficient κ is computed from:

$$\kappa = \frac{1}{2}\rho_a A_a c_D (1 - \phi) \tag{3}$$

The air-drag reduction ϕ is illustrated in Figure 2 or Figure 3, depending on inter-vehicle distance, vehicle type and vehicle position in platoon. The n^{th} $(n \geq 4)$ vehicle in car platoon has the same air-drag reduction as 4th vehicle, and the n^{th} $(n \geq 3)$ vehicle in HDV platoon has the same air-drag reduction as 3rd vehicle. The detail of parameters for fuel consumption model is presented in Table II.

TABLE II: Parameters of Fuel Consumption Models [13].

Vehicle Parameters	Description	Value	Unit
M_{HDV}	Vehicle Mass of HDV	40000	kg
M_{car}	Vehicle Mass of Car	3000	kg
c_D	Air-Drag Coefficient	0.6	—
$A_{a-\text{HDV}}$	Front Area of HDV	10.26	m^2
$A_{a-\text{car}}$	Front Area of car	2.1	m^2
μ_{HDV}	Rolling Resistant Coefficient for HDV	7×10^{-3}	—
μ_{car}	Rolling Resistant Coefficient for car	0.02	—
ρ_a	Air Density	1.29	kg/m^3
g	Standard Gravity	9.8	—
H	Energy Density	36	MJ/L
η	Energy Efficiency	0.4	—

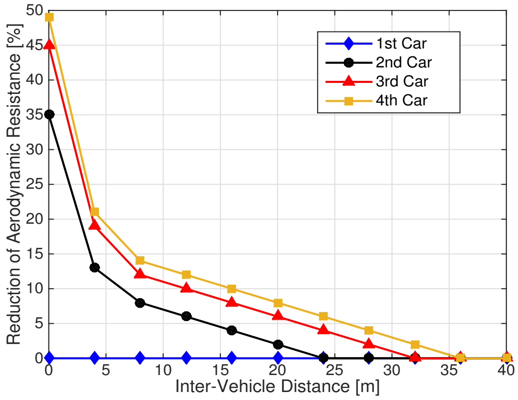


Fig. 2: Air-Drag Reduction of Passenger Cars [14]

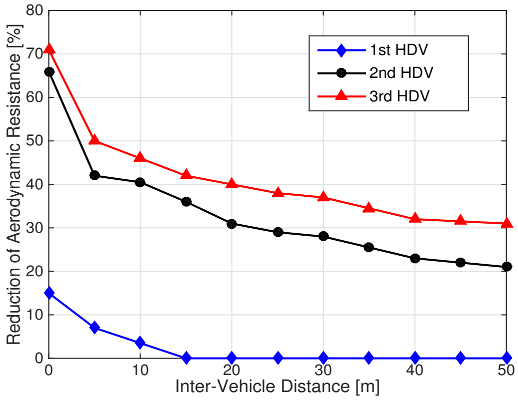


Fig. 3: Air-Drag Reduction of HDVs [15]

IV. SIMULATION SETUP

A. Reference scenarios

In this paper we consider two following reference scenarios:

1) Platooning consisting of N passenger cars moving along the road.
2) Platooning consisting of N Heavy Duty Vehicles (HDVs) moving along the road.

For both scenarios we exploit ”disturbance scenario” as speed pattern [6], [16]. Moving along the highway platoon repeatedly meets slower vehicles in front of it and performs appropriate acceleration/deceleration maneuver, see Figure 4. Four additional vehicles are repeatedly added and then removed in front of the platoon during each simulation run. The scenario is equivalent to the road situation when slower vehicle comes to the right-most lane from metering ramp or after the lane changing.

B. Simulation platform

To emulate realistically the operation of the platoon we use novel Plexe simulation platform [17]. Plexe incorporates Omnet++ for the real-time V2V communications simulation together with SUMO as a realistic traffic simulator. Simulator also contains platoon controller part, which allows to control platoon members based on the input obtained from the communication exchange.

To comply with the ITS-G5 protocol stack [5] we additionally implemented ETSI CAM messages on facilities layer [7] and ETSI DCC functionality [8], [11]. The detailed description of the communication setup is given in Section II. Each vehicle in the platoon utilizes as a control input messages containing kinematic data received from the preceding vehicle and platoon leader, following controller algorithm presented in [18]. Controller implements fixed-spacing policy, which means that inter-vehicle gap between the platoon members is fixed and does not depend on the vehicle’s speed.

The detailed simulation parameters are summarized in Table I.

V. PERFORMANCE EVALUATION

In this section, the performance of different communication setups is evaluated in terms of fuel economy, which is the relationship between the amount of fuel consumed and the distances traveled by the vehicle. Fuel economy of an automobile is generally expressed as liters per 100 kilometers (L/100km) and used in most European countries. In order to estimate the fuel economy of each vehicle in platoon, experiments are conducted in microscopic simulation environment.

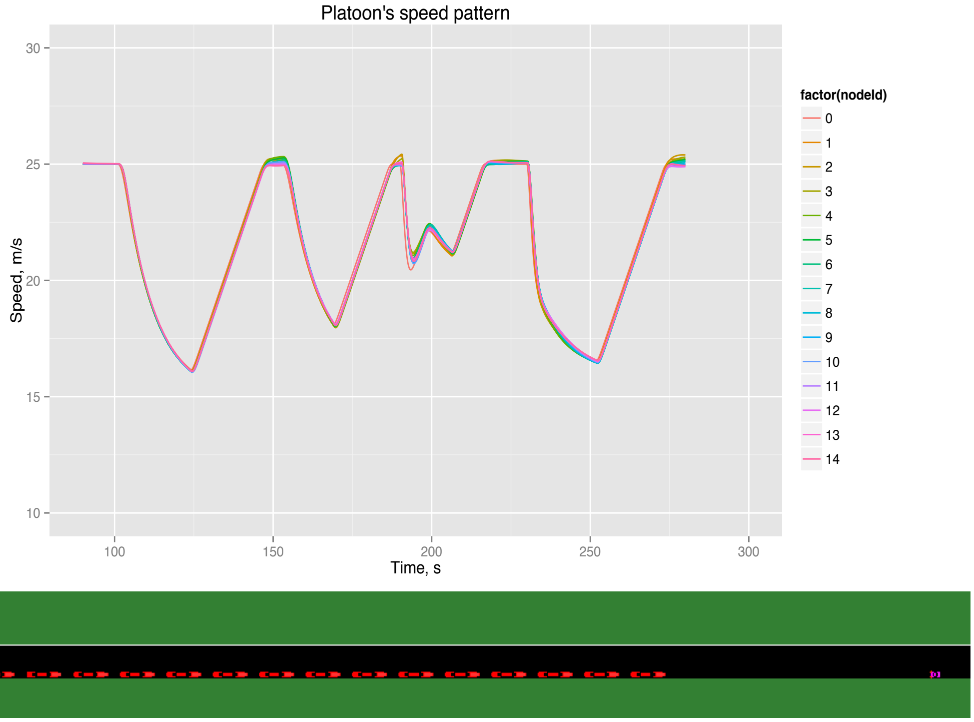


Fig. 4: Reference scenario.

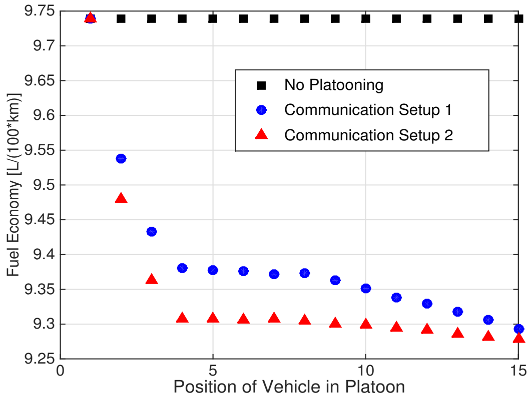


Fig. 5: Fuel efficiency. Passenger vehicles

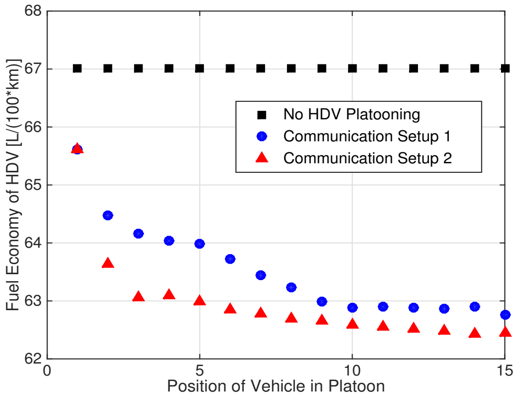


Fig. 6: Fuel efficiency. HDV

A. Fuel Economy of Platoon in Each Communication Setup

Figure 5 corresponds to the fuel economy of the 15-car platoon. Evidently the platoon leader in two different communication setups has identical fuel economy, due to the same settings and reaction to disturbances. It can be seen that there is only minor difference between the no platooning and platooning cases (for passenger car) in fuel economy, about 0.2–0.44L/100km. And the difference between two platoon communication setup is almost negligible, only 0.01–0.07L/100km. This to some extent indicates that passenger cars usually do not have fuel saving incentive to form platoons, and platooning of cars might probably happen for driving comfort in traffic congestion.

Figure 6 corresponds to the fuel economy of 15-HDV platoon. In the HDV platooning cases, all platoon members, including leader and followers can achieve fuel saving compared with the no platooning case. Communication Setup 1 results in 2.1%– 6.4% improvement in fuel economy, and Communication Setup 2 further enhances the improvement to 2.1%– 6.8%, indicating that platoon communication setup also plays an important role in fuel consumption. An appropriate communication setup will be able to further improve fuel economy and reduce fuel cost.

The enhanced fuel efficiency in Communication Setup 2 is a result of platoon's ability to maintain required inter-vehicle gap with higher precision under this scenario comparing

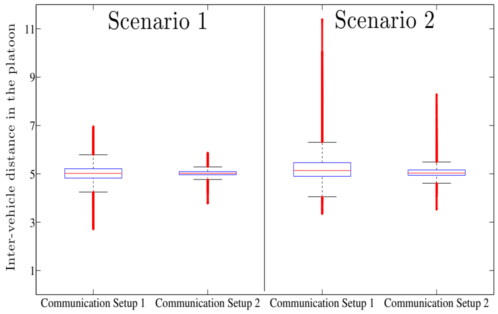


Fig. 7: Platoon Inter-vehicle distance

to Setup 1, see Figure 7. This could be explained by the fact that DCC setup with a larger number of ”Active” sub-states allows better granularity in controlling CBR while still keeping congestion level at required low level. Hereby, even though both Communication Setups are defined in ETSI standards and allowed to exploit they may demonstrate sufficiently different performance in the platooning scenario and influence noticeably on the performance of application in terms of stability and fuel efficiency.

B. Numerical Experiment on European route E4

The European route E4 is the highway backbone of Sweden and used by most of freight transport. It starts from the border between Sweden and Finland, and passes through 22 cities of Sweden with a total length of 1590km. An overview of E4 can be seen in Figure 8.

Fig. 8: European Route E4

In this subsection, two communication setups are applied on a 15-HDV platoon which starts from Tornio and travels to Helsingborg. It is assumed that there are two on-ramps and off-ramps from/to each of the 22 cities, the speed limit for on-/off-ramp is 60km/h [19]. Since HDV is restricted to drive on the truck lane at the rightmost, the platoon has to decelerate to 60km/h in the ramp area and accelerate to desired speed 90km/h afterwards. Fuel economy can be estimated from the ratio of total fuel consumption to length of E4.

TABLE III: Estimated Overall Fuel Economy and Yearly Total Cost of 15-HDV Platoon

Communication Setup	No HDV Platooning	Communi. Setup 1	Communi. Setup 2
Fuel Economy (L/100km)	36.79	30.54	30.31
Yearly Total Cost (MSEK)	15.89	13.11	13.09

HDV platooning improves fuel economy, which can be seen in Table III. HDVs consume significantly less fuel when traveling the same distance. The platoon saves 6.44L, or equivalently 17.5% in Communication Setup 1 and 6.48L (17.6%) in Communication Setup 2 respectively for every 100km. In general, an HDV travels over 200,000km per year [20], with average diesel cost 14.4SEK/L. Both HDV platooning in Communication Setup 1 and Communication Setup 2 lead to remarkable amount of saving compared with the no HDV platooning scenario. Table III shows that HDV platooning in Communication Setup 1 and Communication Setup 2 can potentially save 2.78MSEK and 2.8MSEK respectively. According to simulation outcomes presented in Figure 9, 3^{rd}–15^{th} HDV contribute the most significant saving, which is inline with the dramatic air-drag reduction for HDV platoon followers. It is also worth mentioning that HDV platooning in Communication Setup 2 has slightly more saving than Communication Setup 1, which can be explained by the fact that Communication Setup 1 results in smaller fluctuation in the speeds of HDV platoon follower (See Figure 10 and Figure 11) and more stable inter-vehicle distances (See Scenario 2 in Figure 7), therefore reduce acceleration and braking efforts and frequencies.

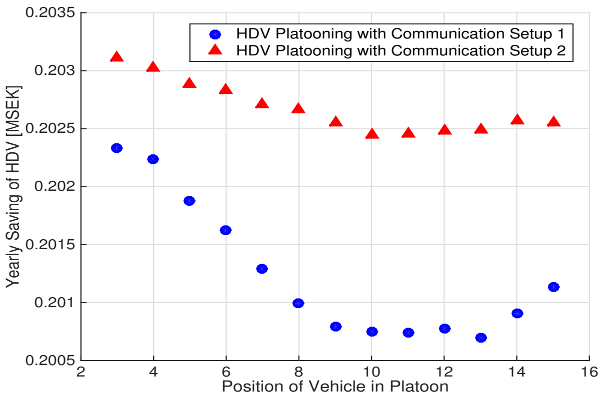


Fig. 9: Estimated Yearly Saving of HDV Compared with No HDV Platooning Scenario

Note that the numerical experiment is presented for illustrative purpose only. In fact, the results from numerical experiment largely depend on the number of disturbances occurred in front of the platoon leader during operation. More disturbance could result in more significant difference in speed profiles, acceleration behaviors, inter-vehicle distances and fuel efficiency of platoon among scenarios. In this manuscript we show, that parameters of communication setup have direct impact on the platoon's air-drag reduction under disturbance scenario, regardless of the frequency they appear.

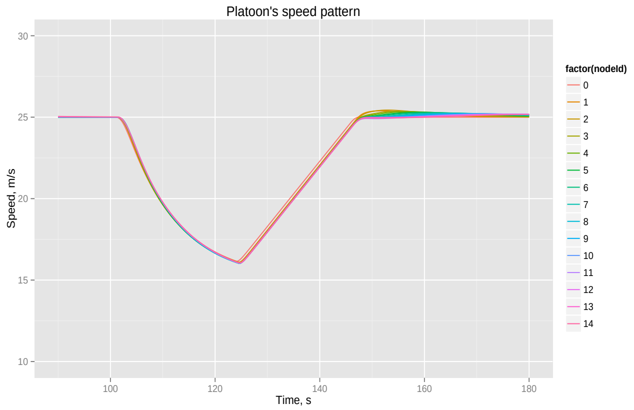


Fig. 10: Speed Profile of HDV Platoon at Ramp Area in Communication Setup 1

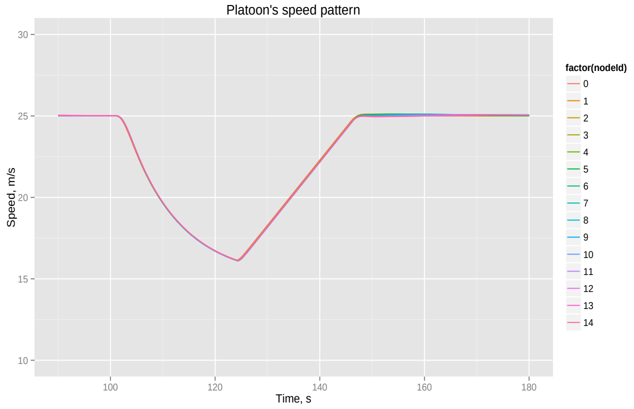


Fig. 11: Speed Profile of HDV Platoon at Ramp Area in Communication Setup 2

VI. CONCLUSION

In this manuscript we make a first attempt to assess platooning fuel efficiency performance under realistic ITS-G5 communication setups. Two types of platoons consisting of passenger cars and HDVs have been tested. Our simulation study shows that fuel savings for HDV platooning scenario are much more significant. Moreover the parameters of communication setup may influence notably on platooning fuel efficiency as it influences directly the performance of the vehicle's control system.

Our ongoing work is focusing on the testing the platoon under both realistic communication setups and road traffic patterns. We are also aiming to test the influence of different platooning control algorithms on the potential fuel efficiency performance of application.

ACKNOWLEDGMENT

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REFERENCES

[1] T. Sandberg, *Heavy Truck Modeling for Fuel Consumption Simulations and Measurements*. Linköping University, 2001, Licentiate Thesis.

[2] T. Robinson, E. Chan, and E. Coelingh, “Operating Platoons On Public Motorways: An Introduction To The SARTRE Platooning Programme,” in *the 17th ITS World Congress*, 2010.

[3] S. Shladover, “Recent International Activity in Cooperative Vehicle - Highway Automation Systems,” Tech. Rep. FHWA-HRT-12-033, 2012.

[4] “Directive 2010/40/eu of the european parliament and of the council on the framework for the deployment of intelligent transport systems in the field of road transport and for interfaces with other modes of transport,” *Official Journal of the European Union*, 2010.

[5] “Intelligent transport systems (ITS); access layer specification for intelligent transport systems operating in the 5 ghz frequency band.” *ETSI TS 102 687 V1.1.1*, 2013.

[6] A. Vinel, L. Lin, and N. Lyamin, “Vehicle-to-vehicle communication in c-acc/platooning scenarios,” *IEEE Communications Magazine*, vol. 53, no. 8, pp. 192–197, 2015.

[7] “Intelligent transport systems (ITS); vehicular communications; basic set of applications; part 2: Specification of cooperative awareness basic service,” *ETSI EN 302 637-2 V1.3.2*, 2014.

[8] “Intelligent transport systems (ITS); decentralized congestion control mechanisms for intelligent transport systems operating in the 5 GHz range; access layer part,” *ETSI TS 102 687 V1.1.1*, 2011.

[9] C. Campolo and A. Molinaro, “Multichannel communications in vehicular ad hoc networks: a survey,” *Communications Magazine, IEEE*, vol. 51, no. 5, pp. 158–169, 2013.

[10] N. Lyamin, A. Vinel, and M. Jonsson, “Does ETSI beaconing frequency control provide cooperative awareness?” in *2015 IEEE International Conference on Communications (ICC), IEEE International Conference on*, London, UK, June 2015, pp. 10 459–10 464.

[11] “Intelligent transport systems (ITS); cross layer dcc management entity for operation in the its g5a and its g5b medium.” *ETSI TS 103 175 V1.1.1*, 2015.

[12] “Intelligent transport systems (ITS); cross layer dcc management entity for operation in the its g5a and its g5b medium; report on cross layer dcc algorithms and performance evaluation,” *ETSI TS 101 612 V1.1.1*, 2014.

[13] Q. Deng, “A General Simulation Framework for Modeling and Analysis of Heavy-Duty Vehicle Platooning,” *IEEE Transactions on Intelligent Transportation Systems*, 2016, accepted for publication.

[14] M. Zabat, N. Stabile, S. Farascaroli, and F. Browand, “The aerodynamic performance of platoons: A final report,” Tech. Rep. UCB-ITS-PRR-95-35, 1995.

[15] H. Wolf-Heinrich and S. Ahmed, “Aerodynamics of road vehicles,” *Society of Automotive Engineers*, 1998.

[16] D. Jia, K. Lu, and J. Wang, “A disturbance-adaptive design for vanet-enabled vehicle platoon,” *Vehicular Technology, IEEE Transactions on*, vol. 63, no. 2, pp. 527–539, 2014.

[17] M. Segata, S. Joerer, B. Bloessl, C. Sommer, F. Dressler, and R. Lo Cigno, “PLEXE: A Platooning Extension for Veins,” in *6th IEEE Vehicular Networking Conference (VNC 2014)*. Paderborn, Germany: IEEE, December 2014, pp. 53–60.

[18] R. Rajamani, *Vehicle dynamics and control*. Springer Science & Business Media, 2011.

[19] Møde for Forbedret Vejudstyr (NMF), http://nmfv.dk/wp-content/uploads/2014/04/Entry-ramp-designs-in-tunnels-Sweden.pdf.

[20] K.-Y. Liang, *Coordination and Routing for Fuel-Efficient Heavy-Duty Vehicle Platoon Formation*. KTH Royal Institute of Technology, 2014, Licentiate Thesis.