PlatoonSIM - Coordination of Heavy-duty Vehicle Platoons in Real Traffic

Public Report

Author   Xiaoliang Ma and Henrik Pettersson
Date   March 2018

Content

1 Summary

The previous research has shown big potentials of saving energy by implementation of autonomous heavy-duty vehicle (HDV) platoons on highway. The approaches and technologies were however developed without consideration of the interference from other traffic. This project contributes to the extension of the research front to include real traffic interference in platooning decision-makings and implementation. Platoon coordination and control strategies are developed with consideration of traffic impacts and tested in real experiment. To facilitate the study on coordination strategies in mixed traffic, a traffic simulation platform has been developed and includes the interaction models between HDV platoons and normal traffic. On the other hand, the project has applied simulation in designed scenarios and answered questions on how platoon may affect traffic system concerning energy efficiency, road capacity and even environmental impacts.

The work is done in collaboration between KTH and Scania CV. The research results have been presented for planers and researchers in different seminars, workshops, meetings and national and international conferences. The scientific publication includes 3 doctoral or licentiate theses, 7 journal publications, 10 presentations at international peer-reviewed conferences and 5 presentations at national conferences.

2 Sammanfattning på svenska

Tidigare forskning kring tunga fordons platooner har visat på stora bränslebesparingspotentialer. Dock har dessa arbeten huvudsakligen fokuserat på de platoonade fordonen och hur dessa skall styras, liten eller ingen hänsyn har tagits till omgivande trafik och dess eventuella påverkan. Resultaten från detta projekt bidrar till att utvidga forsknings fronten genom att inkludera övrig trafik. Projektet har studerat hur övrig trafik påverkar styrningen och bildandet av platooner. Koordineringsstrategier och besluts arkitekturer som tar hänsyn till trafiken har utvecklats och utvärderats i experiment. En trafiksimuleringsplattform har utvecklat för att möjliggöra studier kring koordineringsstrategier i blandad trafik. Simuleringsplattformen som inkluderar modeller för att beskriva interaktionen mellan personbilar och platooner användas också för att studera hur tunga fordons platooner påverkar trafiksystemet som helhet med avseende på energi effektivitet, vägkapacitet och även miljö aspekter. Resultaten kan användas av beslutsfattare för att förstå och utveckla strategier med syfte att implementera automatiska tunga fordons platooner i Sverige.

Projektet är ett samarbetsprojekt mellan KTH och Scania CV och merparten av arbetet utföras av fyra doktoranden. Forskningsresultat har presenterats för planerare och forskare i olika seminarier, workshops, möten, nationella och internationella vetenskapliga konferenser. Vetenskaplig produktion omfattar 3 doktors- eller licentiat avhandlingar, 9 tidskriftsbidrag, 10 presentationer i internationella peer-granskade

konferenser och 5 presentationer i nationella konferenser.

3 Background

Transport is responsible for the main part of the increase in oil consumption during the last three decades and the growth is expected to continue. Nowadays, the environmental footprint of transport in EU corresponds to 23.8% of greenhouse gases and 27.9% of CO_2. The latest goal of the EU commission is to improve the efficiency of road transport by 50% by 2030. In the 2006 mid-term review of the White Paper 2001 of the European Commission, goods transport in Europe is however projected to increase by 50% between 2000 and 2020. Therefore, the entire transport sector, and particularly road freight transport by trucks and lorries, has been targeted as a main policy area where further environmental and overall efficiency improvements are critical for a sustainable future of European transport.

To ensure sustainability and global acceptance of commercial transport, new systems reducing the dependence on oil and minimizing emission of greenhouse gases need to be developed. While the transportation system faces the big challenges in congestion, energy and environmental impacts, the rapid development in information and communication technology (ICT) presents an excellent opportunity to tackle these problems through novel integrated intelligent transport system (ITS) solutions. Advanced ITS technologies will play a key role to address the transport challenges outlined above. An example is given by the so called green corridors, which will require the development of a new type of intelligent and cooperative vehicles and supporting ICT infrastructure and systems. The vehicles in these corridors need to communicate to each other (V2V) and to the infrastructure (V2I). This opens up opportunities for concepts like *autonomous platooning*, that is, synchronized convoy driving aimed at reducing inter-vehicle headways, which is expected to reduce the environmental impacts significantly as well as decrease congestion in real traffic effectively.

Platooning concept has gained international attention over the years as a way to save energy and reduce CO2 emission produced in road transport, as well as a way to increase transport capacity in current road network. Platooning here means a number of vehicles driving after each other and being controlled as one unit, i.e., all vehicles in the platoon mimicking the lead vehicle.

Studies have shown that a fuel reduction of 15 to 20 % [23] can be obtained for a vehicle in the platoon relative to driving solo. This estimation assumes a distance of 8-16 m between the platooning vehicles and a speed of 80 km/h. Similar results can be found in projects such as SARTRE [24], Energy ITS [25] Chauffeur [26] and Distribuerad Reglering av Fordonståg [27]. These projects have shown the potential of conducting platoon, and how a safe control of the platoon and the vehicle driving can be obtained utilizing on-board sensors such as radar, cameras, LIDAR, in combination with v2v communication.

4 Purpose, research questions and method

4.1 Research questions and purpose

The previous iQfleet project has focused on developing advanced cruise control (ACC) for platooning with support of V2V communication, platooning initialization strategies and generation of traffic information for real-time guidance and planning of heavy duty vehicle (HDV) fleets. Some important research questions were identified and hence need to be further addressed. In particular, the latest HDV platoon research has raised concerns on the following questions:

- When and where should HDV form platoons?

- How will the forming of platoons be affected by real traffic?

- What are the performance of platoon control and coordination strategies in real traffic?

- How will the traffic be impacted by such HDV platoons?

- How can we evaluate the total effects of platooning?

Therefore, this project intends to answer those questions by:

- Developing control and coordination strategies for when and how HDV can form platoons with respect to the paths properties such as road topography, speed limits, traffic and weather conditions;

- Developing simulation models incorporating the interactions between platoon and other road users;

- Evaluating the performance of platoon control and coordination strategies using simulation-based evaluation;

- Evaluating the impacts of the platoons on other traffic.

4.2 Methods

In order to answer the question raised for control and coordination strategies, research efforts have been put on how and when HDVs should form platoons given their states or plans if they are not started yet. The work of Liang [20] initially investigates how and when a pair of HDVs should form platoons given their positions, speeds, and destinations. An optimization problem is formulated, and a break-even ratio that describes how far a vehicle should check for possible vehicles to platoon with is derived [3]. Then, the merging maneuver for forming a platoon is studied. Traffic condition may disturb and delay when the two HDVs will form a platoon and such delay leads to less fuel saved than initially planned. Based on shockwave and moving bottleneck theories, a merge distance predictor is analytically derived to calculate where the HDVs will merge depending on traffic condition. This is first validated in a microscopic traffic simulation tool developed in the project [5]. Then, extensive physical experimental studies were also

conducted during one month on a public highway between Stockholm and Södertälje to evaluate the merging maneuver with different traffic densities.

The platoon coordination is also studied together with departure time scheduling considering travel time uncertainty [6]. Theoretical investigation was carried out by formulating a minimization framework of the expected cost taking into account of travel time cost, schedule miss penalties and fuel cost.

In order to evaluate the platooning control and coordination strategies and explore the effects on overall transport systems, simulation platforms have been proposed in this project. Starting from iQFleet, initial work was conducted on modeling and simulating detailed platoon maneuvers using a commercial traffic simulator, VISSIM [5]. The interaction between HDV platoons and other traffic is described in traffic simulation using the same frameworks of car-following and lane changing models. Based on the development work, the platform was further applied to validate the platoon coordination strategy developed in [20].

This project also developed another micro-simulation-based traffic model to analyze platooning controls and strategies for larger network. The open-source simulator, SUMO, is used as the simulation engine. The software framework is similar but platooning operation is simplified in order to enhance computational efficiency. Meanwhile, the new SUMO-based model is technically easier to extend, compared to the VISSIM based platform. Real traffic data is introduced to calibrate the traffic model, which makes the simulation more realistic than the previous study.

Another major extension in this project is the addition of different platoon control strategies. For example, a proportional-integral-derivative (PID) controller for the longitudinal behavior of HDV has been implemented and evaluated in [19]. A case study was carried out to evaluate the potential fuel reduction and other effects by adopting HDV platooning on a simulated highway stretch between Stockholm and Södertälje. In addition, we have also implemented more advanced CACC controls for HDV platooning. In addition to HDV platooning controls, this project also considers taking advantage of vehicle to infrastructure (V2I) communication to improve fuel saving potential of HDV platoons. This is studied in [7], where local traffic information is assumed available in advance for HDV platoons when they approach motorway gantries on which speed limits are posted.

Finally, the project has also assessed the effects of HDV platoons on other traffic using the developed simulation platform. This has been done for a motorway scenario that light traffic congestion is formulated. It is known that formulating HDV platoons is not a beneficial strategy when the traffic is congested. But there is barely detailed analysis. This project quantifies the effects of HDV platoons on other traffic concerning mobility performance, safety, as well as fuel and emission impacts [9].

5 Objectives

The overall objective of this project is to take into account the interference of other traffic in the development of heavy-duty vehicle platoon coordination and control strategies. A decision support framework has been developed for platoon coordination including strategies and algorithms for rerouting vehicles, adapting departure times and adjusting speed profiles. To evaluate some coordination and control strategies, a traffic simulation model is developed to include interaction between HDV platoons and normal traffic. The impacts from platoon on traffic have also been evaluated concerning energy efficiency, mobility and environmental impacts, which contribute to devise strategies towards the implementation of the HDV platoons in Sweden.

The project has fulfilled the overall objective that was set at the start of the project. The platoon coordination strategies have also been evaluated in experiment by Scania on E4 motorway in Stockholm. The decision support framework, coordination and control strategies and simulation tool have laid foundation for investigating the potential of further field trial.

6 Results and deliverables

6.1 Results

In general, the results from the project contribute to the development of coordination and control strategies for HDV platoons in traffic. The project has developed and tested a number of strategies for platoon formation, scheduling and control. A traffic simulation model has also been developed for evaluation of some strategies in real conditions. They are also tested in experiment on E4 motorway. The simulation model has also been used to evaluate the impacts of platoons on normal traffic.

In the work concerning control and coordination strategies for heavy-duty vehicle, methods and algorithms for determining if a number of vehicle should form a platoon has been developed [20]. The decision is done based on the criteria of fuel saving potential over the vehicles whole assignment.

Method and algorithm are also developed for calculating the distance and time that take for two trucks to merge into a platoon dependent on the initial distance between them and the expected speed of the vehicles during the merging and the traffic situation [3]. The result shows that it is possible to make a fair estimation of the merging time, but also that there is an upper limit on the traffic density, over which merging is impossible.

For platoon scheduling, it is shown that platooning is beneficial only when the planned arrival times differ less than a certain threshold [6]. Travel time uncertainty typically reduces the threshold schedule difference for platooning to be beneficial. Platooning in networks is less beneficial on converging routes than diverging routes, due to delay at the

merging point. Hence there are lots to consider regarding platooning benefits for freight transport planning in advance.

The HDV platoon simulation tools developed based on microscopic traffic models are, by themselves, important results of this project [5][9]. They provide a practically effective means to evaluate control and coordination strategies of HDV platoons, but also to assess the effects of HDV platoons on other vehicles. Detailed HDV platoon control such as PID controller has been implemented in the simulation. The stability and sensitivity of the applied PID controller with different parameter settings are investigated, and the effects on the HDV platoons themselves and on the other vehicles in the network have been evaluated for the motorway scenarios through multiple simulation runs [19]. As a result, it is found that a fuel reduction of at least 6% can be achieved for HDVs by introducing HDV platooning in the evaluation case. The analysis on other traffic shows no strong indication of negative impacts due to HDV platooning.

The introduction of V2I information is beneficial for HDV platoons. This is confirmed in the simulation study of a simple motorway scenario in [7]. In the scenario, traffic speed information, normally posted on Motorway Control Systems, is assumed available for HDV platoons and so the platoon leaders can adapt their speed optimally according to the speed limit information. The simulation results show great fuel saving potential for HDV platoon if such information can be incorporated into the HDV platoon control.

Lastly, vehicle probe data obtained from fleet management system has been used to support HDV platoon studies. In [18], freight GPS probe data is used to derive traffic conditions in terms of link travel time. The study of Liang [20] also investigated the potential fuel savings from HDV coordination in a larger road network. The number of vehicles platooning can be increased significantly through coordination compared to today.

Finally, all scientific results have been presented at seminars, workshops, meetings and conferences. The goals have been met by the studies carried out within the project.

6.2 Other Deliverables

The work in the project has mainly been done by three doctoral students with support from supervisors and academic staffs at KTH and by supervisors and technical staffs at Scania CV. The result from their work has been presented in scientific publication includes 3 doctoral or licentiate theses, 9 journal publications, 10 presentations at international peer-reviewed conferences and 5 presentations at national conferences. (see section 7)

From an overall picture of the project the main contribution from the project has been an enhanced understanding on the interaction between heavy-duty vehicles that are platooning and the interaction with other road users. This, together with the simulation

tool developed within the project, has the potential to greatly contribute to the implementation cooperative-control functionalities, like platooning, in real traffic.

The result from the work concerning control and coordination strategies has been used and further developed in other Scania CV platooning projects where coordinated formation of platoons has been used. Robust and accurate coordination strategies will be a key component if one aims for a global coordination strategies optimizing the operation of a fleet of vehicles.

7 Dissemination and publications

7.1 Dissemination

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	
Be passed on to other advanced technological development projects	X	
Be passed on to product development projects		
Introduced on the market		
Used in investigations / regulatory / licensing / political decisions	X	

7.2 Publications

Peer Reviewed International Journals

[1] J. Larsson K.-Y. Liang, K. H. Johansson. A distributed framework for coordinated heavy-duty vehicle platooning. IEEE Transactions on Intelligent Transportation Systems, 16(1), 2015

[2] B. Besselink, V. Turri, S. Van De Hoef, K.-Y. Liang, A. Alam, J. Mårtensson, K. H. Johansson. Cyber-Physical Control of Road Freight Transport. Proceedings of the IEEE, Vol. 104, nr 5, 2016

[3] K.-Y. Liang, J. Mårtensson, K. H. Johansson. Heavy-Duty Vehicle Platoon Formation for Fuel Efficiency. IEEE Transactions on Intelligent Transportation Systems. Vol. 17, nr 4, 2016

[4] K.-Y. Liang, S. Van De Hoef, B. Besselink, H. Terelius, V. Turri, , J. Mårtensson, K. H. Johansson. Network control challenges in

collaborative road freight transport. European Journal of Control, 2016

[5] Q. Deng, A general simulation framework for modeling and analysis of heavy-duty vehicle platooning, IEEE Transactions on Intelligent Transportation Systems. Vol. 17, nr 11, 2016

[6] W. Zhang, E. Jenelius, X. Ma, Freight transport platoon coordination and departure time scheduling under travel time uncertainty, Transportation Research Part E: Logistics and Transportation Review, Elsevier, Vol.98, 2017

[7] Johansson, J. Jin, X. Ma, H. Pettersson, Look-ahead speed planning for heavy-duty vehicle platoons using traffic information, Transportation Research Procedia, vol. 22, pp. 561-569, 2017.

[8] X. Ma, F. Al-Khoury and J. Jin, Prediction of arterial travel time considering delay in vehicle re-identification, Transportation Research Procedia, vol. 22, pp. 625-634, 2017.

[9] J. Jin, X. Ma, I. Johansson, Simulating heavy duty vehicle platooning control strategies in real traffic, 2017, submitted and under review.

Peer Reviewed International Conferences

[10] F. Farokhi , K.-Y. Liang, K. H. Johansson. Cooperation patterns between fleet owners for transport assignments. IEEE Conference on Control Applications. Sydney, Australia, 2015

[11] K.-Y. Liang, Q. Deng, J. Mårtensson, X.Ma, K. H. Johansson. The influence of traffic on heavy-duty vehicle platoon formation. IEEE Intelligent Vehicles Symposium. Seoul South Korea, 2015

[12] Q. Deng, X. Ma, A simulation platform for autonomous heavy-duty vehicle platooning in mixed traffic, Transportation Research Board 94th Annual Meeting, 2015

[13] Johansson, J. Jin, X. Ma, Look-ahead speed planning for heavy-duty vehicle platoons based on traffic information, The 19th EURO Working Group on Transportation Meeting, 2016.

[14] X. Ma, F. Al-Khoury and J. Jin, Prediction of arterial travel time considering delay in vehicle re-identification, The 19th EURO Working Group on Transportation Meeting, 2016.

[15] K.-Y. Liang, J. Mårtensson, K. H. Johansson. Experiments on Platoon Formation of Heavy Trucks in Traffic. IEEE 19TH International Conference on Intelligent Transportation Systems (ITSC), 2016.

[16] N. Lyamin, Q. Deng and A. Vinel, Study of the platooning fuel efficiency under ETSI ITS-G5 communications, IEEE 19TH International Conference on Intelligent Transportation Systems (ITSC), 2016.

[17] W. Zhang, X. Ma, E. Jenelius, Planning of heavy-duty vehicle platoon formulation: basic scheduleing problem considering travel time variance, Transportation Research Board 95the Annual Meeting, 2016

[18] C. Yang, X. Ma, Y. Ban, Demonstration of intelligent transport applications using freight transport GPS data, Transportation Research Board 95th Annual Meeting, 2016.

[19] J. Jin, X. Ma and I. Johansson, Modelling and analysis of PID-controlled heavy-duty vehicle platoons in real traffic, Transportation Research Board 86th Annual Meeting, 2017.

Theses (fully funded by this project)

[20] K.-Y. Liang, Fuel-Efficient Heavy-Duty Vehicle Platoon Formation. Ph.D. thesis, KTH Royal Institute of Technology, 2016

[21] Q. Deng, Heavy-Duty Vehicle Platooning: Modelling and Analysis. Licentiate thesis, KTH Royal Institute of Technology, 2016

[22] I. Johansson, Simulation Studies of Heavy-Duty Vehicle Platooning in Real Traffic, Licentiate thesis, KTH Royal Institute of Technology, 2018 (to defend in June 2018)

Students

fully funded by this project

Kuo-Yun Liang (Industrial PhD student, 2015-2016, PhD defended)
Qichen Deng (PhD student, 2014-2016, Licentiate defended)
Ingrid Johansson (PhD student, 2016-2018, Licentiate to defend in June 2018)

partially funded by this project

Junchen Jin (PhD student, Research assistant 2016-2017)
Wei Zhang (PhD. Student, Research assistant in 2015)
Fadi Al-Khoury (MSc. Student, Research assistant in 2016)

8 Conclusions and future research

HDV platooning is known as an effective means to save fuel consumption of freight transport on road. This project extends the previous research with consideration of interference of real traffic. The results lead to the strengthening of HDV platoon control and coordination strategies when real traffic disturbance is involved. Meanwhile, the essential impacts of HDV platoons on other traffic have been quantified using the simulation models developed in the project. In conclusion, this project has basically fulfilled the goals that have been set in the beginning. But there is one limitation that the project has done a comprehensive cost benefit analysis using the simulation results.

HDV platooning technologies tend to be more and more mature. There is need for standardization and business model innovation for its application in reality. Extensive field trials are promoted in several countries. Sweden has unique contribution due to the early research investment. Currently, a new project, Sweden 4 Platoon, is a pilot study funded by Vinnova FFI.

Concerning HDV platooning research, the recent advance in communication provides new opportunities to enhance vehicle to vehicle communication and therefore advanced controls. In addition, there is also need to coordinate HDVs to form platoons in a large scale network. This is important for business operation. The methodologies developed in this project have to be further advanced to handle the challenges.

External References

[23] C. Bonnet and H. Fritz, "Fuel Consumption Reduction in a Platoon: Experimental Results with Two Electronically Coupled Trucks at Closed Spacing", in 2000 Futer Transportation Technology Conference, Costa Mesa, Califonia, USA August 21-23, 2000.

[24] http://www.sartre-project.eu Accessed: November 10th, 2014

[25] Sadayuki Tsugawa,"An Overview on an Automated Truck Platoon within the Energy ITS Project", reprints of the 7th IFAC Symposium on Advances in Automotive Control, National Olympics Memorial Youth Center, Tokyo, Japan, September 4-7, 2013

[26] http://cordis.europa.eu/telematics/tap_transport/research/projectsum/chauffeur.html Accessed: November 9th, 2014.

[27] A. Alam Fuel-Efficient Heavy-Duty Vehicle Platooning, Doctoral Thesis, KTH Royal Institute of Technology, 2014.

9 Participating parties and contact persons

Transport System, KTH   Xiaoliang Ma (liang@kth.se)
Scania CV   Henrik Pettersson (henrik.x.pettersson@scania.com)