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### HEAVY-DUTY TRUCK PLATOONING: A REVIEW

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**Abstract.** *This paper presents a review of theoretical and experimental works related to heavy-duty truck platooning. The platoon formation is characterized by the string of vehicles traveling with small separation distances. Only the first vehicle is driven by a human driver while the followers are assisted by the control system. The main goal of this approach is to reduce fuel consumption and greenhouse gas emissions. This is achieved because the proximity of the vehicles in this configuration provides a more efficient airflow around the set of trucks reducing the overall energy consumption. In addition, the platoon configuration allows the increase of road safety, transport capacity, driver comfort and reduce congestion and personnel cost due to the lack of human intervention in the following vehicles. The academic studies related to heavy-duty truck platooning are reviewed according to three research areas: fuel consumption in truck platoons, maintenance of platoon formation and truck coordination. In this paper, the state of the art in each of these areas is presented, the related publications are categorized according to their focus of contribution and potential future research directions are discussed.*

**Keywords:** *Platoon, Heavy-duty vehicle, Fuel consumption, Control, Coordination*

#### 1. INTRODUCTION

The demand for freight transportation is increasing all over the world, the expansion of the road infrastructure is severely limited and the road sector shows high levels of greenhouse gases emission (IPCC, 2014). In order to overcome this problems some vehicular improvements are considered: engine and driveline optimization, electric and hybrid vehicles, kinetic energy recovery systems, weight reduction, and platoon formation (Liang *et al.*, 2015). Particularly, vehicle platooning has the potential to reduce transportation cost and emissions while increasing traffic flow and safety (Tsugawa *et al.*, 2016). In recent years, it is receiving relevant attention due to the market penetration of sensing and communication technologies that make this solution affordable. Heavy-duty vehicle platooning are likely to be the first application of vehicle automation to be commercially viable (Lammert *et al.*, 2014).

The main objective of the platoon formation is to reduce fuel consumption and greenhouse gas emissions (Tsugawa *et al.*, 2016). The decrease in fuel consumption is achieved due to the proximity between the vehicles that makes the airflow more efficient decreasing the aerodynamic drag of the set of trucks (Hucho and Ahmed, 1998). In platoons, the safe condition is feasible only with controllers since its reaction time is smaller than that of the human drivers. However, safety conditions are still subject of investigation due to possible risks involving communication failures (Dey *et al.*, 2016). Dey *et al.* (2016) also warn about the necessity to increase the reliability of the systems involved in this type of task.

The first system developed to control longitudinal dynamics is the cruise control (CC) (Teetor, 1950). It controls the engine torque to maintain a constant velocity rejecting disturbances as drag and road slope variations. Radar sensor measuring the obstacles ahead allowed the development of the adaptive cruise control (ACC) (Rajamani, 2015). It is capable of adjusting the cruising velocity according to the preceding vehicle. Both, CC and ACC, were developed primarily for safety and comfort but already provide higher energy efficiency through the smooth out of the acceleration profile (Moser *et al.*, 2017). With the increasing maturity of vehicle-to-vehicle (V2V) communication systems the cooperative adaptive cruise control (CACC) was presented and represent the keystone of truck platooning (van Arem *et al.*, 2006). However, to benefit from platooning, it is required that multiple vehicles are equipped with the CACC traveling next to each other. In practice, this condition still rarely occurs (Zhang *et al.*, 2017a).

Studies about heavy-duty truck platooning have been conducted by several research groups formed through partnerships between government, industry and academy. The first ones were within the European project *Chauffeur I* and investigated the fuel savings potential of truck platooning (Bonnet and Fritz, 2000). In the second phase of this project, under the *Chauffeur II*, the authors improved the control system to reduce the inter-vehicle distance (Fritz *et al.*, 2004). In 1986, the Partners for Advanced Transportation Technology (PATH) started at the University of California the development of intelligent transportation systems. In the early 1990, the group demonstrated for the first time a four-car platoon in a San Diego highway (Shladover, 2007). Recent studies focus on heavy-duty trucks and explore the reliability and control strategies of this type of configuration (Lu and Shladover, 2014). The German KONVOI from RWTH Aachen University (Kunze *et al.*, 2011) and the Safe Road Trains for the Environment (SARTRE) (Chan, 2016) were also research groups that addressed mainly automated truck technology, commercial viability and driver-platoon interaction. Moreover, Energy ITS was a five-year Japanese project started in 2008 focusing on emission reduction through truck platooning (Tsugawa, 2014). Finally, the Cooperative Dynamic Formation of Platoons for Safe and Energy-optimized Goods Transportation (COMPANION) project was an EU funded group that focused in truck coordination and operation (Eilers *et al.*, 2015). These and several other research groups and institutions contributed to platoon-related topics and their most relevant works are presented in the following sections.

Research related to heavy-duty truck platooning can be separated into three main areas of study: fuel consumption in truck platoons, maintenance of platoon formation and truck coordination. The first one consists of the aerodynamic studies that verify the reduction of fuel consumption when vehicles travel closely to each other. The second area of study deals with the control design, communication methods and interaction between driver and vehicle. Finally, the last area of study provides coordination strategies that take into consideration the platoon benefits to achieve energy efficient maneuvers and speed profiles. As the COMPANION project came to an end in 2016, the development of truck platoon systems reached another milestone providing a convenient timing for a literature review summing up the main contributions done so far. Thus, the goal of this paper is to review theoretical and experimental works related to heavy-duty truck platooning, present the state of the art, categorize the related publications according to their focus of contribution and point out future research directions.

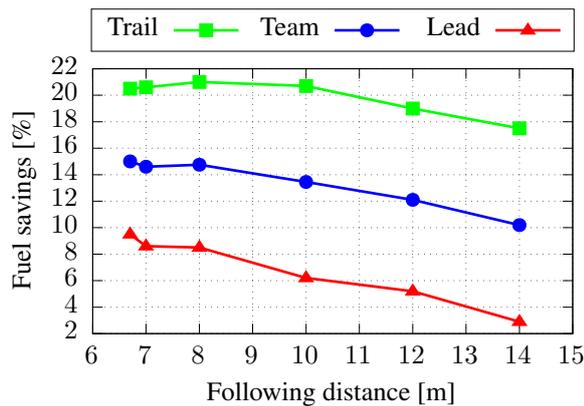
## 2. FUEL CONSUMPTION IN TRUCK PLATOONS

To investigate the fuel savings potential of on-highway platooning, experimental tests and/or computational fluid dynamics (CFD) simulations are usually performed. In both cases, the fuel consumption of the standalone (Following distance  $\rightarrow \infty$ ) vehicle is compared to the fuel consumption of the close-following configuration in order to quantify the benefits of platoon formation.

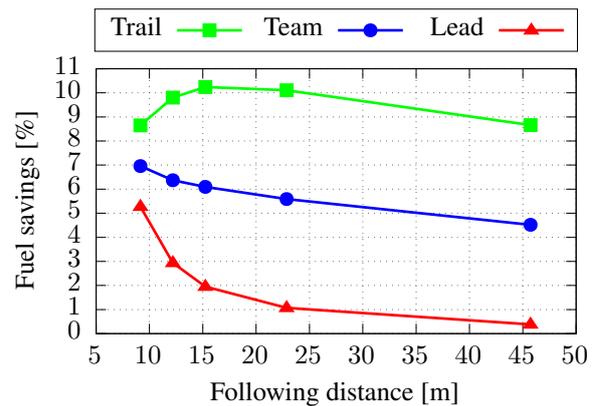
One of the first experimental studies about the fuel savings during truck platooning was presented by the *Chauffeur I* program (Bonnet and Fritz, 2000). The tests were conducted on the DaimlerChrysler test track at Papenburg with two Actros 1853 LS trucks equipped with the so called Electronic Tow Bar system developed by the group. In this experiment, the authors reported the fuel consumption reduction of the platoon for several following distances and two different velocities. In Fig. 1(a) is the reported savings for each truck of the platoon traveling at 80 km/h and spacings from 6.7 to 14 m. In this particular experiment and for the trailing truck, the authors found  $\approx 17.5\%$  fuel savings at 14 m. From that point, as the separation distance decreases, the fuel savings of the following vehicle increases until it reaches a peak value of 21% at 8 m of spacing. If the separation distance is further decreased the fuel savings of the following vehicle starts to decrease. However, the overall benefit of platooning increases due to the increase of the fuel savings of the leading vehicle.

In Fig. 1(b) the fuel savings results from Bishop *et al.* (2017) is presented. The experimental test was performed using Peterbilt 579 trucks traveling at 105 km/h. The peak value of fuel savings was 7% and occurred approximately at 9 m of spacing. The authors suggest that the reduction of fuel savings of the following vehicle for close inter-vehicle distances comes from the lateral offset between the two trucks. In a single lane configuration, when the vehicles are not perfectly aligned, the benefit of platooning is partially lost because of the increased exposure of the following truck to high pressure flow (Browand *et al.*, 2004). Differences from both experimental tests (Fig. 1(a) and (b)) are evident and can be explained mainly by the differences in test velocity, truck models and weather conditions. However, the general trend prevails.

As part of the PATH program, Browand *et al.* (2004) investigated the benefits of truck platooning on an unused airfield runway. Several runs were performed to measure the reduction of fuel consumption during platooning. Traveling at 89 km/h and a separation distance of 10 m, the average fuel consumption was about 8%. The authors also report the degrading effects of misalignment of the trucks. Within the SARTRE project, experimental tests were also performed at the Idiada High Speed Track. The studied platoon configuration was composed by two Volvo FH12 and three Volvo passenger cars traveling at 85 km/h and spacing from 8 to 15 m (Davila, 2013). The reduction in fuel consumption for each vehicle ranged from 7% to 16%. Similar test can also be seen in the experimental stages promoted by the Japanese Energy ITS project (Tsugawa, 2014). The researchers measured the fuel consumption of a four-truck platoon traveling at 80 km/h with inter-vehicle distances of 4.7 and 10 m. The total fuel consumption is reduced by an average of 13% when the separation is 10 m and can reach up to 18% when the separation is 4.7 m.



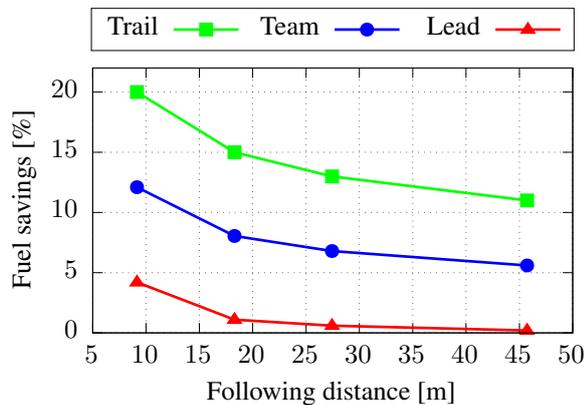
(a) Platoon at 80 km/h. Results from Bonnet and Fritz (2000).



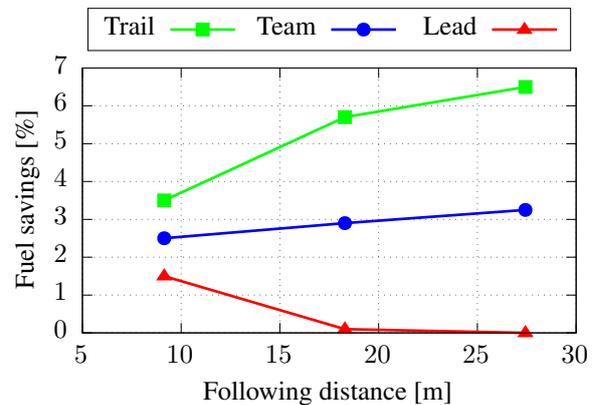
(b) Platoon at 105 km/h. Results from Bishop *et al.* (2017).

Figure 1. Experimental results of fuel savings as a function of the inter-vehicle distance.

Vegendla *et al.* (2015) studied the fuel consumption of the platoon formation in single and multiple lanes using a commercial CFD tool. A single lane platoon with 2 medium-duty trucks showed a 12% fuel savings at 89 km/h and 9.1 m following distance. A multi-lane configuration was also explored, for instance, with two trucks in different adjacent lanes of the highway keeping a longitudinal distance between them. This condition characterizes a lateral offset between the vehicles. The fuel savings for both cases are presented in Fig. 2. The fuel savings for perfectly aligned trucks (Fig. 2(a)) show that as the separation distance decreases the fuel savings for both trucks increases. In the two lane platoon (Fig. 2(b)), the resulting fuel consumption is also reduced in comparison to the standalone vehicle, but, contrary to the single lane platoon, this benefit increases with the increase of distance separation because of the vortex shredding by the leading vehicle. Indeed, the platoon benefit degradation is noticeable even with small offset distances between trucks (Bishop *et al.*, 2017). Since in practical conditions the trailing truck can not follow the preceding vehicle with perfect lateral alignment, some degree of offset will always be present. Thus, these curves corroborate the results and explanations of the experimental tests discussed above.



(a) Perfect alignment between trucks.



(b) One lane offset between trucks.

Figure 2. CFD results for fuel savings as a function of the separation distance. Results from Vegendla *et al.* (2015).

Legislation and highway infrastructure impact directly the setup of platoon studies. Mihelic *et al.* (2015) focused on platoons formed by different vehicle types, for instance, the tractor-semitrailer and the A-Train Double trailer configuration. The main finding of that paper is that the drag reduction normalized by the respective volume of cargo hauled favored the longer vehicles instead of truck platooning. However, the length and mechanical coupling of several trailers is limited by road infrastructure. However, the platooning of the longest allowed configuration could provide further savings. Regarding safe inter-vehicle distances, Nuskowski *et al.* (2017) reported an 8% fuel reduction for the trailing vehicle with the platoon traveling at 100 km/h and a separation distance of 67.4 m. The authors deliberately choose such big distance to meet highway guidelines provided by the United States Fire Administration.

The adverse impact of platooning on the engine cooling system of the following vehicles was investigated by Lammert *et al.* (2014) and Ellis *et al.* (2015). This undesired effect occurs because of the wake generated by the preceding truck.

The front vehicle shields the trailing vehicle from free stream when traveling at close distances. When no properly natural cooling is achieved, the fan has to engage oftener to meet the cooling demand, putting at risk the overall energy consumption. Lammert *et al.* (2014) tested two truck platoons in an oval track recording fan-on time. Based on the results, the authors suggest a correlation between fan engagement and the reduced efficiency at small inter-vehicle distances. For instance, traveling at 105 km/h and 9.1 m the team fuel savings was around 6%. Reducing only the spacing distance the fan-on time increases and the overall fuel savings drops to 4%.

Ellis *et al.* (2015) used a Lattice Boltzmann based CFD solver to estimate the drag reduction of a three vehicle platoon. With a 9 m distance between trucks the cooling performance is acceptable. However, at 5 m the engagement of the fan is expected for all but the leading vehicle. This is, reducing the gap from 9 m to 5 m gives an additional drag reduction but at the cost of lower cooling potential. The authors show that another approach to reduce the drag force is the use of aerodynamic packages. For a stand-alone truck, 26% drag reduction can be achieved only with additional fairings, advanced trailer skirts and boat tail. Besides, the aerodynamic packages show even better results in platoons.

To compare the several studies about the savings in platoons, details and results from the above mentioned tests are listed in Tab. 1.

Table 1. Details and results from experimental and simulation tests focusing on aerodynamic effects of truck platoons.

Lead author	Year	Vehicles	Analysis type	Peak savings (Team)
Bishop	2017	2 Peterbilt 579	Experimental - Track	Fuel: 7% @ (105 km/h & 9.1 m)
Bonnet	2000	2 Actros 1853 LS	Experimental - Track	Fuel: 15% @ (80 km/h & 6.7 m)
Browand	2004	2 Freightliners	Experimental - Runway	Fuel: 11% @ (89 km/h & 4 m)
Davila	2013	2 Volvo FH12	Experimental - Track	Fuel: 10% @ (85 km/h & 5 m)
Ellis	2015	3 Volvo VNL 670	CFD - PowerFLOW	Drag: 21% <sup>(1)</sup> @ (105 km/h & 5m)
Lammert	2014	2 Peterbilt 386	Experimental - Track	Fuel: 6% @ (89 km/h & 9.1 m)
Mihelic	2015	2 Peterbilt 579	CFD - PowerFLOW	Drag: 12.8% @ (105 km/h & 9.1 m)
Nuszkowski	2017	2 Freightliners	Experimental - Highway	Fuel: 8% <sup>(2)</sup> @ (100 km/h & 67.4 m)
Tsugawa	2014	3 heavy + 1 light trucks	Experimental - Track	Fuel: 18% @ (80 km/h & 4.7 m)
Vegendla	2015	2 Medium-duty truck	CFD - STAR-CCM	Fuel: 12% @ (89 km/h & 9.1 m)

<sup>(1)</sup> Truck with no aerodynamic package

<sup>(2)</sup> Following truck only

### 3. MAINTENANCE OF PLATOON FORMATION

The studies about the dynamics of truck platoons started in the fifties (Pipes, 1953) focusing on string stability analysis. It refers to the attenuation effect of spacing error along platoon after longitudinal perturbation of the leading vehicle. Today, the platoon maintenance can be separated in four components: vehicle dynamics, information flow topology, decentralized control and formation geometry (Zheng *et al.*, 2016b). Figure 3 illustrates this four-component framework in a  $N + 1$  vehicle platoon. Truck 0 is the leading vehicle,  $C$  is the controller and  $u$  is the control input. The first component describes the dynamic behavior of the vehicles, also called nodes. The information exchange among nodes is described in the information topology. In possession of the available information, control laws are implemented through distributed controllers. Finally, the desired distance between vehicles using different spacing policies provides a formation geometry (Li *et al.*, 2017).

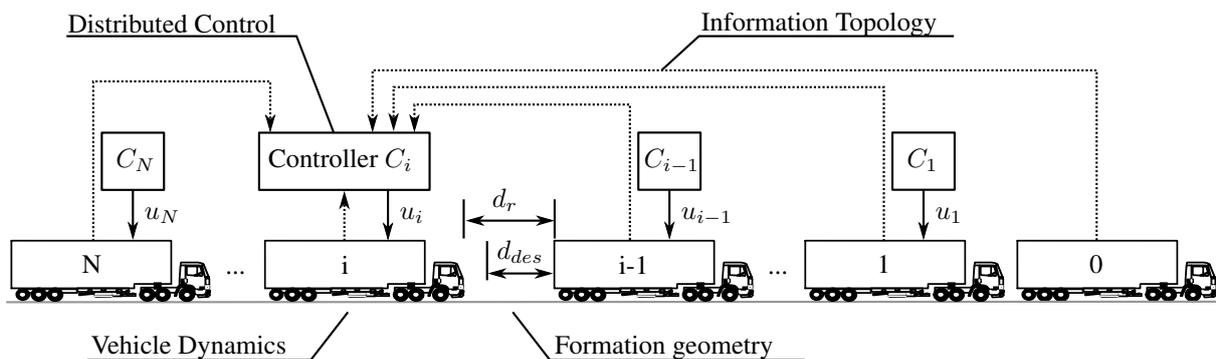


Figure 3. The four-component framework. Adapted from Li *et al.* (2017).

The vehicle dynamics can be separated into model and platoon types. Here, we focus on longitudinal models that

describe the coupled dynamics of the set of vehicles. The model types can be single integrator (Lin *et al.*, 2012), second-order (Peters *et al.*, 2014), third-order (Zheng *et al.*, 2016b), SISO (Herman *et al.*, 2015) and nonlinear (Zheng *et al.*, 2017a) models. Moreover, platoon types are generally classified according to its homogeneity, for instance, platoons composed by vehicles with the same dynamical capabilities are called homogeneous (HO) (Herman *et al.*, 2015). In that case, the control design is greatly simplified. In contrast, when vehicles that do not share identical dynamics form platoons, the set is called heterogeneous (HE) (Zheng *et al.*, 2017a).

The information flow topology can be understood as how information is spread throughout the members of a platoon. Such connectivity allows the real-time exchange of the vehicle position, velocity, and acceleration data. There are six commonly used topologies (Zheng *et al.*, 2016b). The first one is the, so called, *predecessor-following* (PF) which is achieved when the following vehicle receives information from the preceding one (Ploeg *et al.*, 2014). When a vehicle receives information from the following and preceding vehicle the topology is called *bidirectional* (BD) (Zheng *et al.*, 2016a). Both cases can be implemented using only radar sensing. However, with the development of V2V communications, those topologies can receive an additional information about the leader resulting in the *predecessor-leader following* (PLF) (Peters *et al.*, 2014) and *bidirectional-leader* (BDL) (Zheng *et al.*, 2016a) topologies. An extended version of the above mentioned topologies are the *two-predecessors following* (TPF) (Ploeg *et al.*, 2014) and *two-predecessor-leader following* (TPLF) (Gao *et al.*, 2016) where the information of two vehicles ahead is considered. A topology that does not fit in the above mentioned ones is considered a *generic topology* (GT). Each mentioned topology has its advantages and limitations to achieve string stability. For instance, under *predecessor following* topology string stability cannot be guaranteed for several conventional control strategies (Seiler *et al.*, 2004). A more detailed discussion about the impacts of flow topology can be found in Zheng *et al.* (2016b). Details about the communication framework are out of the scope of this paper. However, the interested reader should see the work of Dey *et al.* (2016). The authors present a review about the communication methods, their protocols and suitability for platoon applications.

Decentralized control schemes were developed to reduce delay problems due to wireless communication (Verginis *et al.*, 2017). Across the literature authors developed mainly linear (Milanés *et al.*, 2014), optimal (Alam *et al.*, 2014),  $H_\infty$  (Xia *et al.*, 2017), sliding mode (SMC) (Kwon and Chwa, 2014), model predictive (MPC) (Dunbar and Caveney, 2012; Zheng *et al.*, 2017b), backstepping (Yue *et al.*, 2015) and LMI-based (Salvi *et al.*, 2017) controllers. The performance metrics that those controllers have to fulfill are string stability, stability margin, and coherence behavior (Li *et al.*, 2017). As mentioned above, string stability is achieved when the disturbances are attenuated along the platoon. Stability margin refers to the convergence speed of the system and coherence behavior is calculated using the  $H_2$  norm of the closed loop system.

One of the control objectives of the following trucks is to maintain a desired formation geometry. This geometry is specified according to three main policies: *constant distance* (CD), *constant time headway* (CTH) and *nonlinear distance* (ND). In the first one, the longitudinal controllers try to maintain a constant distance between two adjacent vehicles and is independent of the platoon velocity (Peters *et al.*, 2014). In contrast, the desired distance in the *constant time headway* varies according to the velocity of the vehicles (di Bernardo *et al.*, 2015; Marzbanrad and Moghaddam, 2016). Finally, when the desired vehicle range is described as a nonlinear function of the platoon velocity, the geometry is achieved through the, so called, *nonlinear distance* (ND) policy (Zhang *et al.*, 2017a). Flow stability and traffic capacity constitute the main trade-off between these three range policies.

In Tab. 2, several control applications to vehicle platooning are briefly detailed. Please note that we included experimental passenger car platoons interpreting them as validation platforms for controllers that could be used in truck platoons.

#### 4. TRUCK COORDINATION

Vehicle coordination is intended to increase traffic flow and reduce fuel consumption. Addressing the former, studies was performed using a driving simulator (Sarvi *et al.*, 2004) and real vehicle experiments (Milanés *et al.*, 2011) in a ramp merge scenario. In this situation, the vehicles already in the highway have to adjust their speed in response to the incoming merging vehicle. Coordination of vehicles in a highway was then proposed by Khan and Boloni (2005) using a *Convoy Driving Device* that assist the driver on whether he should change his speed to join or leave a platoon. An automated system that can coordinate vehicles to enter and leave platoons was proposed by Hallé and Chaib-draa (2005) using a hierarchical architecture for collaborative driving. Those studies focused mainly on increasing the throughput of highways. In contrast, recent studies about ramp merge scenario (Rios-Torres and Malikopoulos, 2017b) and merge-in maneuvers (Goli and Eskandarian, 2014) consider additional benefits. For instance, Rios-Torres and Malikopoulos (2017a) propose a centralized optimal controller to coordinate up to 30 vehicles in a ramp merge scenario reducing both fuel consumption and travel time.

Another appealing application are the coordination strategies intended to guide scattered vehicles in a energy efficient way. In recent years, such approach became feasible due to the development of communication and positioning technologies. Previously, most of the studies focused on vehicles already in a platoon, while such coordination has been almost neglected (Liang *et al.*, 2016a; Saeednia and Menendez, 2017). As discussed above, trucks could benefit from close fol-

Table 2. Details of platoon maintenance studies. Fonte: Autor

Lead author	Year	Control	Type	Geometry	Topology	Analysis	Platoon
Alam	2014	Optimal	HE	CTH	PF	Experimental	2 Scania HDVs
Bernardo	2015	Linear	HE	CTH	GT	Simulation	5 vehicles
Dunbar	2012	MPC	HE	CD	PLF	Simulation	7 vehicles
Fritz	2004	Nonlinear	HE	CTH	PLF	Experimental	2 Actros 1853 LS
Gao	2016	$H_\infty$	HE	CD	TPLF	Simulation	11 vehicles
Herman	2015	Linear	HO	CD	BD	Simulation	>11 vehicles
Kwon	2014	SMC	HE	CD	BD	Simulation	6 vehicles
Lin	2012	Optimal	HO	CD	BD	Simulation	>11 vehicles
Marzbanrad	2016	SMC	HE	CTH	PF	Simulation	2 vehicles
Milanés	2014	Linear	HO	CTH	PF	Experimental	4 Infiniti M56s
Moser	2017	MPC	HE	CTH	TPF	Simulation	BMW 3 series
Peters	2014	Linear	HO	CD	PLF	Simulation	10 vehicles
Ploeg	2014	$H_\infty$	HO	CTH	PF & TPF	Experimental	3 Toyota Prii
Salvi	2017	LMI-based	HE	CTH	PLF, TPF & GT	Simulation	8 vehicles
Verginis	2017	GAPPC <sup>(1)</sup>	HE	CD	PF & BD	Experimental	5 small robots
Xia	2017	$H_\infty$	HE	CD	PF, BD & BDL	Experimental	11 vehicles <sup>(2)</sup>
Yue	2015	Backstepping	HE	CD	PLF	Experimental	4 Arduino cars
Zhang	2017a	SMC	HE	ND	GT	Simulation	4 vehicles
Zheng	2017a	MPC	HE	CD	Several <sup>(3)</sup>	Simulation	8 vehicles
Zheng	2017b	$H_\infty$	HO	CD	GT	Simulation	11 vehicles
Zheng	2016a	Linear	HO	CD	BD & GT	Experimental	5 small robots
Zheng	2016b	Linear	HO	CD	Several <sup>(4)</sup>	Simulation	11 vehicles

<sup>(1)</sup> Global approximation-free prescribed performance control (GAPPC) (Bechlioulis and Rovithakis, 2014).

<sup>(2)</sup> Hardware in the loop.

<sup>(3)</sup> PF, PLF, TPF & TPLF.

<sup>(4)</sup> PF, PLF, BD, BDL, TPF & TPLF.

lowing distances due to the reduced aerodynamic drag in this configuration. For that reason, this research domain aims to create collaborative frameworks and develop trucks capable of forming platoons along the highway.

The first coordination strategy considering the approximation guidance was presented by Meisen *et al.* (2008) using a data-mining algorithm to plan and organize platoons in order to reduce fuel consumption. In general, coordination of two separated trucks in a highway has two main strategies, the catch up and the slow-down approaches (Saeednia and Menendez, 2017). The former is characterized by the increased speed of the follower truck to catch up the leader. In contrast, the latter requires the slow down of the leading vehicle to allow the following truck to catch up. Both strategies are valid but the energy efficient speed profile is not evident. In the catch up strategy, the speed increase of the following truck causes an additional energy consumption that has to be compensated while traveling in the platoon. In the slow-down strategy, as the platoon is formed the set of trucks have to speed up to meet the schedule restrictions. Liang *et al.* (2013) show that a 7% fuel savings can be achieved in a 350 km highway stretch in a catch up scenario starting from a 10 km separation distance. Based on the initial separation and total traveling distance, the authors provide a break-even ratio above which the catching up strategy is beneficial.

The fuel savings potential is explored by Liang *et al.* (2014) using GPS probes provided by the Scania's fleet management system (FMS). The position log of more than seven thousand heavy-duty trucks during one entire day is used to verify platoon opportunities over a specific road network in Europe. Several coordination schemes were used, including the one developed by Liang *et al.* (2013). The authors reported a fuel savings of up to 0.22% under the catch-up coordination strategy. Although this number seems low, we point out that only Scania trucks equipped with the FMS were considered. The same data probe is used to verify the fuel savings potential of a distributed framework designed to coordinate trucks through controllers placed at highway intersections (Larson *et al.*, 2015). These controllers can adjust the speed and change route of the approaching trucks in order to form fuel-efficient platoons. The authors suggest that the fuel savings can exceed 5% with more than two thousand trucks considered in the system. Similar infrastructure can be used to coordinate the ramp merge scenario described above.

Liang *et al.* (2016a) propose an optimal algorithm to form platoons through the adjustment of the speed profiles. The optimization coordinates neighboring vehicles pairwise and aims to minimize the overall fuel consumption. A more sophisticated cost function is used by Zhang *et al.* (2017b). The authors investigate the platoon coordination and departure

time scheduling problem considering not only the fuel cost, but also labor cost and schedule miss penalty. Both approaches give particular useful insights to fleet owners about platooning decision and execution. Moreover, the influence of traffic density in collaboration opportunities and coordination efficiency can be found in Liang *et al.* (2016b). The authors report a delayed merging time in higher traffic conditions compared to the predicted time of uninterrupted maneuvers. Besides, some of the platoons cannot even be formed, for instance, because of vehicles persistently staying between the following and leading trucks. Saeednia and Menendez (2016) emphasize that platoons are moving bottlenecks influencing the overall flow of the highway. For that reason, the authors propose a traffic evaluation method to help guide trucks to form, maintain, modify and separate platoons to improve highway traffic operations. The formation and maintaining phases are addressed in Saeednia and Menendez (2017) through the development of an iterative consensus-based algorithm.

## 5. CONCLUSION

The platoon benefits and the aerodynamic phenomena are evident and well understood. However, the optimal distance and the mathematical modeling of fuel/drag reduction as a function of the following distance (Tadakuma *et al.*, 2016) are still under investigation and can provide significant insight to control design and coordination strategies. Thus, future research should focus on those topics considering the effects of the lateral offset, engine cooling performance, atmospheric conditions, differences in aerodynamic profiles (different models of trucks) and multi-lane analysis with other passing vehicles.

The unanimous topics for future research in the area of platoon maintenance are the improvement of the control systems under disturbances, model uncertainty and communication failures, such as packet dropouts and time delay, specially considering its time-varying characteristic in real applications. Moreover, studies should develop advanced vehicle models considering longitudinal and lateral dynamics, nonlinear braking and gear change. Several authors also suggest that a systematic methodology for the design of the controllers is needed and the resulting system should provide safety, transient performance and string stability in a probabilistic way. Additionally, heterogeneous platoons with non-identical controllers and the influence of different information flow topologies should be investigated. Finally, experimental validation of the current theoretical works is needed.

Until now, the studies about coordination strategies focused mainly on three tasks: ramp merge scenario, merge-in maneuver and approximation guidance. This is, truck exit maneuver and platoon splitting were less explored, but are still relevant topics for future investigation. Nevertheless, the above mentioned coordination strategies still need significant improvements for a large scale application. Thus, authors should focus on the overall traffic consequences of platooning and optimal strategies considering different origins, destinations, delivery time restrictions, road topography and traffic conditions. Moreover, to be truly appealing, the collaborative systems have to be able to coordinate trucks from different manufacturers and fleet owners. The main challenge in this situation is to fairly distribute the fuel savings benefit among the platoon participants, since different vehicles experience different air drag reduction according to its position along the platoon. Finally, traffic and transportation data should be acquired to help improve and validate the coordination frameworks.

## 6. ACKNOWLEDGEMENTS

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