Hindawi
Journal of Advanced Transportation
Volume 2020, Article ID 2604012, 10 pages
https://doi.org/10.1155/2020/2604012

Review Article

Fuel Economy in Truck Platooning: A Literature Overview and Directions for Future Research

Linlin Zhang, Feng Chen, Xiaoxiang Ma, and Xiaodong Pan

Key Laboratory of Road & Traffic Engineering of Ministry of Education, Tongji University, Shanghai 201804, China

Correspondence should be addressed to Feng Chen; fengchen@tongji.edu.cn

Received 13 March 2019; Revised 1 May 2019; Accepted 18 December 2019; Published 3 January 2020

Academic Editor: Shamsunnahar Yasmin

A truck platoon is a set of virtually linked trucks that travel in tandem with small intervehicle distances. Several studies have proved that traveling in platoons can significantly improve fuel economy due to the reduced aerodynamic drag. However, most literature only provides scattered pieces of information regarding fuel economy in truck platoons. Therefore, a literature survey is needed to understand what has been studied and what problems remain to be further addressed. This paper presents an overview of existing studies to illustrate the state of the art about fuel savings for truck platooning. Specifically, it summarized the methodologies, the contributing factors of fuel consumption, the coordination methods to improve the platooning rate, and the look-ahead control strategies to generate fuel-efficient speed profiles for each vehicle driving in a platoon over different road grades. After that, the autonomous truck platooning was introduced, and we raised and discussed a couple of outstanding questions to be addressed in future work.

1. Introduction

Transportation is crucial to society and economy, and road freight transportation accounts for nearly 60% of all surface freight transportation [2]. The demand for road freight transport is expected to increase in the coming years. As shown in the American Trucking Association's 2015 report [3], the trucking industry comprises nearly 80% of a $1.33 trillion-dollar shipping and logistics industry in the US. However, plenty of fuel consumption and greenhouse gas emission have been generated. For example, road transport represents approximately 27% of the energy consumption of the European Union [4]. Furthermore, Schroten et al. [5] indicated that vehicles account for 20% of the total carbon emission of which a quarter comes from heavy duty vehicles (HDVs). Therefore, the environmental impacts during the process of transport need to be reduced urgently. In addition, the cost of fuel possesses a large share of total transportation costs. Fuel cost represented nearly 30% of the life cycle cost of owning and operating a truck [6]. Similarly, according to the American Transportation Research Institute's (ATRI) recent report [7], fuel is regarded as the second largest cost, where the highest is personnel cost. With a large amount of HDVs and the increasing demand for road freight, it can be predicted that even small advances in fuel efficiency can translate into considerable cost reductions. And it is also beneficial to achieve the goal of environmental protection due to less exhaust gas. As a consequence, it is of great benefit to improve fuel economy, and how to reduce fuel consumption during traveling has turned into a popular topic in recent years.

Fortunately, the developments of intelligent transportation systems (ITSs) have enabled methods to enhance the energy efficiency of transportation networks. A promising approach to dealing with that problem is to reduce the gap between vehicles on the road, which is usually called truck platoons. Truck platoons, also known as convoys, are a set of vehicles forming a road train by traveling closely in single file to experience reduced air drag. This can significantly reduce fuel consumption because about one-fourth of the fuel consumption is relevant to aerodynamic drag [8]. As a result, fuel economy can be improved and environmental friendliness can be achieved due to less greenhouse gas emission in a platoon. Apart from fuel savings, truck platoons can also contribute to an increase of road capacity and can ease traffic congestion by a smaller gap between vehicles.

In recent years, with the development of autonomous driving technology, vehicles are equipped with several sensors that enable them to observe their surroundings and decide in real time what action should be taken, which are called "autonomous vehicles" or "driverless vehicles." Driverless vehicles are able to coordinate their way when driving, and they can travel in a platoon with smaller intervals to reduce fuel consumption. Furthermore, when driving automatically in a platoon, it is possible to reduce the risk of rear-end collisions and to improve traffic safety.

With great advantages mentioned above, vehicle platoons have attracted the attention from many governments and research institutions. As a result, several projects related to platoons were proposed. The first studies on truck automation were "Chauffeur" within the EU project T-TAP from the mid-1990s to the beginning of 2000 [9]. During the project, Bonnet and Fritz [10] conducted an experiment with two trucks coupled by an "Electronic Tow Bar" to quantify the fuel savings. Afterward, the California PATH program started its research on heavy truck platooning. In the PATH program, all vehicles were fully automated, including the leader. For example, in 2004, the program performed a fuel consumption test with two tandem trucks linked by an electronic control system for different spaces [11]. The project "KONVOI" also devoted to truck platoons, where a team of German scientists developed a platoon of four heavy trucks in order to improve fuel economy and increase the road capacity [12]. SARTRE is a European Commission cofunded FP7 project [13]. The lead vehicles in SARTRE are HDVs driving manually and the following vehicles drive automatically both laterally and longitudinally without modification to the infrastructure, such as dedicated lanes. Besides, the 5-year project "Energy ITS" which started in 2008, aimed at energy saving and global warming prevention by truck platooning. In this project, a platoon of 3 fully automated trucks was developed and drove at 80 km/h with a 10 m gap along an expressway before public use [14]. Other relevant projects are also conducted, such as GCDC, SCANIA, and so on [13].

The literature on truck platoons with respect to fuel savings is mainly divided into five categories. One category focuses on the air drag reduction through wind tunnel tests or computational fluid dynamics (CFD). The second category primarily aims at confirming fuel savings under different conditions by track tests or road tests. The third category revolves around the coordination and optimization of truck platoons to increase platooning rates. And the fourth mainly focuses on the calculation of speed profile for vehicles to gain fuel economy when driving under varying road topography. Nowadays, autonomous technology has been widely applied in the field of autonomous trucking [15]. And to this end, driverless truck platoons have attracted much attention from the research community and industry.

Research methods, influencing factors, and coordination means have been summarized by literature categorization in this paper. Based on that, a few issues to be addressed in the following study are proposed. The remainder of this paper is structured as follows. In Section 2, we briefly introduce our strategies for searching relevant papers. And in Section 3, the main research methods are discussed. This is followed by the analysis of related factors in Section 4. Then in Sections 5 and 6, coordination and optimization as well as look-ahead control for truck platoons are introduced to further improve fuel economy. In addition, we explain the three levels of autonomous truck platooning in Section 7. After that, problems to be solved in future research are presented in Section 8.

2. Search Method

In this section, we show our methodologies for selecting relevant studies of fuel economy in truck platoons. Since the aim of this paper is to understand what has been studied in aspect of fuel consumption in truck platoons, it is vital to have an overall perspective of the main topics in this field.

The literature related to the topic was collected and selected from online electronic databases, such as Web of Science, IEEE, ScienceDirect, SAE Journals, and Springer Link. And several articles were retrieved by tracking cited references from e-catalogues by Google Scholar in order to minimize the chances of missing important references. By searching the keywords "truck platoons" combined with "fuel economy" or "fuel consumption," we found that the study of fuel economy in truck platoons got the attention of scientists since 1990s.

After that, the retrieved papers were exported to Mendeley for further screening. The selection process was mainly divided into two stages. Firstly, by reviewing the title and abstract, part of irrelevant publications was removed. After that, the full text of each article was browsed to identify whether it was actually related to the topic. By using the above screening strategy, 54 publications have been kept for further study in the review. Thereafter, each remaining article was carefully reviewed and we categorized the 54 studies with respect to their research methodology and research content.

Although our study may not be exhaustive, it sufficiently shows what has been studied so far in the aspect of fuel economy in truck platooning and may offer some worthy suggestions for future research.

3. Research Methods of Fuel Economy

Since the 1990s, the study of fuel economy on truck platoons has gained its momentum. Among those studies, there are three main methods being used including wind tunnel test, road/track test, and simulation methods (mainly CFD). In wind tunnel tests, experimental conditions such as wind speed, wind direction, and the distances between vehicles can be controlled more precisely, and therefore repeatable experiments can be conducted. Road or track test is more authentic than the other two methods. However, doing reliable measurements of fuel consumption in a real vehicle is complicated and time consuming. Besides, surrounding factors are not repeatable and safety is an essential factor to be considered. As for CFD simulation, the differences between vehicles in air drag reduction can be studied. In this section, the research methods mentioned above will be described. Table 1 shows the summary of primary studies.

In 1990s, most researchers paid close attention to wind tunnel tests for air drag reduction of platooning. Then, track tests and road tests were conducted to understand the fuel savings during platooning. As shown in Table 1, track tests are more common compared with road tests, due to security possibly. Because of the huge cost and insecurity within road/track tests, CFD or other simulation methods have been applied in recent years and often combined with other ways to test and verify the results.

Experiments in wind tunnels can measure the changes of aerodynamic drag in different separation distances. A set of sensors are fitted on truck models, and the models are placed in wind tunnels. For instance, one-eighth scale models of the 1991 GM Lumina APV were used to quantify the behaviour of vehicle drag as a function of vehicle spacing in a wind tunnel [16]. However, truck platoons are not always perfectly aligned. When platoons are forming, or when one member of closely spaced vehicles reach a destination and must exit the platoon, the alignment of the vehicles is broken. In order to understand the aerodynamic interaction between the unaligned vehicles, a wind tunnel experiment was conducted using 1/8 scale models of 1991 Chevy Lumina minivan [17]. In addition, the influence of crosswind upon the aerodynamic interactions in truck platoons was also studied. The crosswind was simulated by yawing the platoon ten degrees with respect to the axis of the wind tunnel. Results showed that drag savings did not disappear under crosswind conditions [19].

Although the air drag reduction can partly reveal the trend of fuel economy, more direct and definite ways are needed to quantify fuel savings in a platoon. Real trucks are used to accomplish experiments in track tests and road tests in order to measure fuel consumption. Track tests are completed in closed sites, without other traffic except the test vehicles. Track tests conform to the SAE Type II Fuel Economy standard in most instances. For example, a series of ten modified SAE Type II J1321 track tests were performed to document fuel consumption reduction [26]. Besides, an SAE Type II fuel economy test complying with the SAE J1321 standard was carried out to correlate the computational studies [31]. Mcauliffe et al. [33] also conducted a modified version of the SAE J1321 Type II fuel consumption test procedure to evaluate the fuel-saving benefits of platooning.

The road test is conducted on the highway, which is a more convincing method. However, according to previous studies, most road tests were performed in the expressway before public use or in the highway with a low daily traffic volume considering safety [14, 24, 28]. Therefore, although the test conditions are similar to real roads, those studies cannot represent the influence of other traffic on fuel consumption either. Exceptionally, one experiment was performed along two Texas highway routes to determine the impact of surrounding traffic conditions to oncoming air flow to a vehicle [27]. After that, Alam et al. [29] conducted experiments on public roads with varying road grades, in the presence of traffic, and under varying weather conditions. The result showed that platooning can significantly reduce fuel consumption and road grade has a large impact on fuel economy.

CFD simulation is a relatively novel method to be used in this field. Truck models and turbulence models are built, and the wind is simulated according to fluid dynamics. CFD is used to learn about the changes of aerodynamics in a platoon [21]. But in most cases, CFD is combined with other means such as road tests or track tests to verify the results [25, 27, 30, 31]. Apart from CFD, other simulation methods have also been applied in recent studies. For example, Alam et al. [23] constructed the truck model in a modeling tool called Dymola. In this method, the powertrain part of a truck such as engine, gearbox, clutch, etc., was modeled in detail according to the truck's real-life behaviour, which led to a model consisting of 3313 variables, 1058 equations, and 626 states. Within this model, adaptive cruise control (ACC) and cruise control (CC) logic was implemented to control the trucks. Although the advanced truck model with the CC/ACC software is more authentic than CFD simulation, this method cannot show the changes of aerodynamics for each vehicle in a platoon.

The experiments performed through wind tunnel tests, track tests, and CFD are all simulations of a real-world environment. The differences between simulation and real traffic may produce confusing results. Hence, truck models, wind environment, and road conditions should be simulated comparable to actual situations to eliminate adverse effects as much as possible. As for a road test, it can overcome the disadvantages mentioned above in simulation. However, safety is an essential factor to be considered. For the sake of security, the separation gaps between test trucks should not be too small. In conclusion, each method has its own advantages and disadvantages, so multiple means should be combined to balance the reliability and safety in future studies.

4. Influencing Factors of Fuel Economy

Fuel savings in a platoon are associated with many factors. In this section, several important factors are analysed according to primary studies. The reference number of main influencing factors is shown in Figure 1.

As shown in Figure 1, longitudinal spaces are discussed in almost all the articles. To explore the impact of distances between trucks on fuel consumption, Bonnet and Fritz[10] conducted a series of track tests and proposed that a spacing of 10 m between the trucks seemed to be a good one. In 2004, another track test was performed and the result showed that the average fuel consumption savings to be achieved varied from about 11% at 3-4 meters to about 8% at 8–10 meters [11]. In addition, Lammert et al. [26] found that the average fuel consumption reduction of the lead tractor improved when separation distances decreased, with results showing 2.7% to 5.3% fuel savings under the following distances ranging from 20 ft to 75 ft. Besides, a road test demonstrated that 13% energy savings when 10 m gap and 18% savings when 4.7 m gap were gained [28]. Furthermore, a driver-

Table. 1: Summary of primary studies.

Classification	Lead author	Year	Method	Reference
Air drag reduction	Zabat	1995	Wind tunnel test	[16]
	Marcu	1998	Wind tunnel test	[17]
	Hong	1998	Track test	[18]
	Marcu	1999	Wind tunnel test	[19]
	Hammache	2001	Wind tunnel test	[20]
	Ellis	2015	CFD	[21]
	Gheyssens	2016	Simulation	[22]
Fuel consumption reduction	Bonnet	2000	Track test + simulation	[10]
	Browand	2004	Track test + wind tunnel test	[11]
	Alam	2010	Simulation + road test	[23]
	Lu	2011	Road test	[24]
	Tsugawa	2011	Road test	[14]
	Davila	2013	CFD + track test	[25]
	Lammert	2014	Track test	[26]
	Smith	2014	Road test + CFD	[27]
	Tsugawa	2014	Road test	[28]
	Alam	2015	Road test	[29]
	Humphreys	2016	CFD + track test	[30]
	Humphreys	2016	CFD + track test	[31]
	McAuliffe	2017	Track test	[32]
	McAuliffe	2018	Track test	[33]

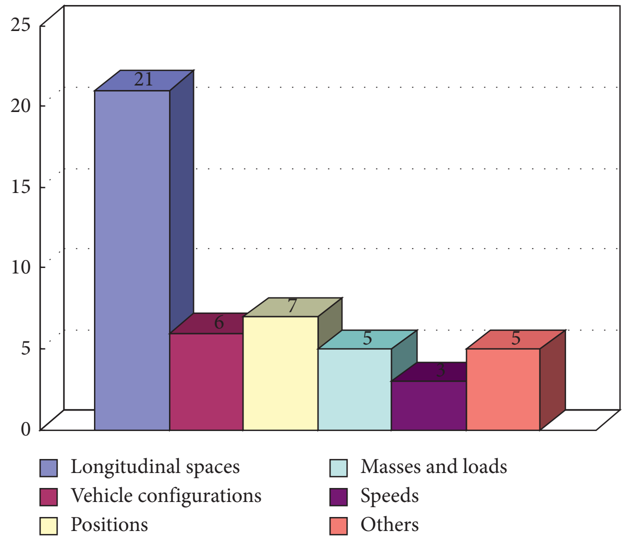

Figure 1: The reference number of different influencing factors.

assistive-truck-platooning (DATP) system was tested, where the overall fuel economy of vehicle platoon monotonically improved as intervehicular distances diminished [30, 31]. In Mcauliffe's study, the greatest net fuel saving was measured to be up to 14.2% at the shortest distance of 17.4 m [32]. All in all, a general conclusion has been drawn that the closer the longitudinal spacing, the better the overall performance of fuel consumption in a platoon.

Apart from following distances, the vehicle configurations also have an important impact on the fuel economy of truck platoons. Ellis et al. [21] explored the effect of platooning on four increasingly aerodynamic tractor-trailer configurations. It concluded that aerodynamic drag reduction increased when adding improved aerodynamic devices. In 2017 and 2018, trucks in different configurations were applied in track tests, and results showed that the aerodynamic-trailer configuration experienced a greater percentage fuel saving from platooning than the standard trailer [32, 33].

The vehicle's position in a platoon can also influence fuel consumption. In 2011, three Class 8 tractor-trailer trucks were tested on Nevada SR-722. The data showed that the lead truck reduced its fuel consumption by about 18%, while the second truck saved 24% and the third truck saved 23% [24]. Similarly, Davila et al. [25] found that the following tractor could achieve around a 16% fuel saving while the lead vehicle could obtain a noteworthy 8% fuel saving. Lammert et al [26] pointed out that trailing vehicle could enjoy more benefits than the lead tractor, with 2.8% to 9.7% fuel savings compared with 2.7% to 5.3%. In a three-vehicle platoon, the same result was achieved that the trailing vehicle experienced the optimal fuel economy of three vehicles [32].

Furthermore, masses and loads of trucks are also influential on energy consumption. Experiments were performed, and results indicated that the trail truck which had a total weight of 28 tons obtained about 21% fuel consumption reduction, while a fuel saving of 17% could be predicted for the trail truck with a mass of 40 tons [10]. As to loads, heavy loads will affect the percent savings from platooning but still result in significant fuel savings according to [26]. For example, when the truck was empty-loaded, 13% energy savings when 10 m gap and 18% savings when 4.7 m gap were gained. While the truck was ordinarily loaded, the fuel savings would be 8% and 15%, respectively [28]. In addition, an increasing fuel saving of 1.6% associated with the cooperative adaptive cruise control (CACC) platooning system was observed for the empty trailer, compared with the loaded trailer [32]. Furthermore, Alam et al. [23] studied the effects of the ACC strategy on fuel savings with different masses of vehicles.

As for the influence of speed on fuel economy, Mcauliffe et al. [32, 33] proposed that no significant effect of vehicle speed on the fuel savings was observed from the CACC platooning system.

To summarize, many factors have an impact on fuel consumption reduction in a platoon. Although tests conducted under different conditions may cause diverse results, the general trend is summed up as follows:

(1) The fuel economy will be improved when the intervehicle spaces decrease

(2) The aerodynamic-trailer configurations such as trailer skirts and trailer boat tails can experience a greater percentage fuel savings than standard trailers

(3) In a platoon, trailing vehicles usually experience the optimal fuel savings

(4) When masses or loads increase, fuel consumption reduction will decrease partly

(5) The speed of a platoon shows no appreciable effect on fuel savings

5. Coordination and Optimization of Truck Platooning

The majority of the current literature mentioned above has focused on vehicles already in a platoon. However, this is not always the case in practice. In other words, although fuel economy can be improved when driving in a platoon, vehicles are usually assigned with different transport missions (with different origins, destinations, and delivery times) and they are scattered on the road. As a result, platoons do not take shape spontaneously on a road network. Liang et al. [34] analysed sparse vehicle position data from a region in Europe during one day, and the result showed that the spontaneous platooning rate was found to be 1.2%, which brought about a total fuel saving of 0.07% compared to if none of the vehicles were platooning. Similar results were also obtained in 2015 [35]. A saving of 5% was observed in a large-scale simulation of the German Autobahn network. Besides, the authors analysed real-world HDV's data and found that potential platooning opportunities existed. Therefore, it is essential to coordinate the trucks to increase the platooning rate and fuel savings.

In this section, coordination and optimization of trucks are discussed to confirm when and how to form a platoon will improve fuel economy to the full extend. Table 2 summarizes several present optimizations of truck platooning.

Route planning and speed adjusting are two main methods to increase the platooning rate according to primary studies. Considering the origins, destinations, deadlines, road network, and other factors of fuel saving, fuel-efficient routes and speed profiles should be determined.

It is obvious that vehicles have to follow a common route to form platoons, while they are scattered over a road network in real life. As a consequence, researchers have put forward various methods to plan the routes for trucks to take. In 2013, Kammer [36] developed a comprehensive mathematical formulation of the route-planning problem and presented a global solution approach to the problem. Then, the author promoted a locally distributed approach to reduce the computational complexity. And the simulation showed that significant savings could be achieved on a model of the German autobahn road network which consisted of 647 nodes, 695 edges, and 12 possible destinations with a few hundred trucks. Larsson et al. [37] defined a routing problem called the platooning problem and proved that the problem was NP-hard, even when all trucks started at the same time and point. After that, two heuristics with a local search were applied to the problem. And their performance is compared with the optimal solutions on the German autobahn road network, which contained 647 nodes and 1390 edges. Then, Nourmohammadzadeh and Hartmann [38] presented a nonlinear mathematical model for the platooning problem. Moreover, a genetic algorithm was applied to solve the large instances in a relatively short time.

However, for HDVs today, drivers often drive a predefined route to reach the destination. Besides, taking longer detours to form platoons may yield no noticeably additional fuel savings compared to taking the vehicle's own optimal route [34]. As a consequence, adjusting the speed slightly to form a platoon is more applicable than rerouting.

The speed-adjusting coordination mode mainly consists of distributed coordination scheme and centralized coordination scheme. A distributed network of controllers was placed at major intersections in a road network to coordinate platoon formation [35, 42]. By knowing the vehicle's position, speed, and destination from GPS, the local controller could decide how to slightly adjust the speed of vehicles to make them synchronize travel in a platoon. Centralized coordination scheme is more popular in the platooning field in recent years. In 2008, data-mining techniques were used to identify the vehicles' common routes. In overlaps of the routes, a vehicle would wait at a certain meeting point to form a platoon if the waiting cost was lower than platooning benefit [39]. Liang et al. [40] proposed a method by letting the follower vehicle drive faster to catch up with the lead vehicle which maintained a constant speed till destination. The distance between the vehicles and the distance to the destination would depend whether it was beneficial to form a platoon than maintaining current speed. After that, a novel algorithm was put forward in 2016 [41] as a natural and significant extension of Liang et al. [40]. In this paper, all vehicles driving on the same route were allowed to adjust their speed to form a platoon rather than the following vehicles only. Besides, Liang et al. [34] analysed platooning potentials based on vehicle probe data and introduced several coordination schemes to increase the platooning possibilities. Then, Hoef et al. [43] proposed a centralized coordination scheme to form platoons at junctions of a network based on each vehicle's shortest path to its destination. Firstly, the shortest path for each truck was determined. Then, possible platoon configurations were identified. Finally, the optimal speed profile for a certain platoon configuration was calculated.

Table 2: Optimizations of truck platooning

Optimization method	Reference	Main contribution
Route planning	[36]	Developing a comprehensive mathematical formulation and promoting a locally distributed approach
	[37]	Proving that the platooning problem is NP-hard
	[38]	A nonlinear mathematical model was presented and a genetic algorithm was applied
Speed adjusting	[39]	A vehicle would wait at a certain meeting point
	[40]	Letting the follower vehicles drive faster
	[34]	Introducing several coordination schemes
	[41]	Both follower and lead vehicles were allowed to adjust the speed
	[42]	A distributed coordination scheme
	[35]	
	[43]	A centralized coordination scheme
	[44]	Proposing an iterative algorithm

However, the proposed methods mentioned above are not suitable for a large number of trucks, and therefore several researchers have concentrated on that problem to reduce the computational complexity. For example, Hoef et al. [43] formulated the coordination problem as a clustering problem based on pairwise fuel-optimal speed profiles. In this paper, the authors derived pairwise fuel-optimal plans based on a first-order fuel model and proposed a clustering algorithm to coordinate a large number of trucks. A similar centralized coordination system for truck platooning was proposed in 2016 [44]. The system returned routes and speed profiles for vehicles to form platoons. To handle realistically sized problem instances, the author proposed an iterative algorithm to quickly compute good but not necessarily optimal solutions for each truck.

6. Look-Ahead Control for Truck Platooning

The focus within platooning in current literature has mainly been on intervehicular control for maintaining a suitable distance between vehicles. However, due to the large mass and limited engine power of HDVs, the given spacing cannot be maintained when considering the road topography. Besides, fuel consumption may increase because maintaining a constant intervehicle distance on varying slopes will cause excessive acceleration and braking. An experiment was conducted to evaluate fuel-saving potential by platooning under realistic conditions with different slopes [29]. And the results indicated that the road grade had a significant impact on the fuel savings of a platoon. Therefore, preview information on the road slopes must be exploited when developing fuel-efficient driving strategies in truck platoons, and that is discussed in this section.

The initial studies on fuel-optimal control considering preview information of the road topography are mainly for a single HDV traveling alone. For instance, Schwarzkopf and Leipnik [45] presented a minimum-fuel problem for a nonlinear vehicle model, and vehicle speed control can be found in their study. More recent work based on preview information of the road topography referred to look-ahead cruise control (LAC), also called predictive cruise control (PCC) [46]. LAC used upcoming slope information and predicted traffic information in a finite receding horizon to optimize vehicle speed profile. The result indicated that fuel economy could be improved through LAC by adjusting the velocity prior to an uphill or a downhill segment [47, 48]. After that, the use of the model predictive control (MPC) framework which can generate optimal speed trajectory through online optimizations has improved PCC systems. In the MPC framework, dynamic programming (DP) has been used extensively to solve the optimization problem numerically at each iteration, thus generating an optimal speed trajectory for the vehicle to follow [49]. Another alternative approach called speed profile optimization (SPO) was proposed in 2017 [49]. In this method, an optimal speed profile is generated for a longer section of road and larger fuel savings can be achieved than MPC-based methods. In addition, SPO does not require any iterative online calculations and there is no need to update the optimal speed profile. Therefore, the computation is less expensive than MPC.

As mentioned above, fuel consumption can be reduced by traveling in a platoon. And eco-driving technologies such as LAC have the potential to further increase fuel efficiency by optimizing the speed trajectories of vehicles. Therefore, it is feasible to combine the benefits of platooning and LAC to fully exploit the potential for reducing fuel consumption. However, although several methods considering varying slopes have generated optimal speed trajectory for single HDV, the strategies might not be applicable when traveling in a platoon. Fortunately, researchers have realized the importance of this problem and have concentrated on utilizing preview road gradient information in control for HDV platooning.

Alam et al. [50] proposed an alternative cooperative look-ahead controller for platooning (LAP). LAP control strategy changed the speed of all the vehicles at a specific point in the road instead of simultaneously implementing each individual HDV's control action to maintain a fixed spacing. And the simulation result showed that the LAP could reduce the fuel consumption up to 14% over a downhill segment and a subtler benefit of 0.7% for an uphill climb, compared to the combination of the commercially available cruise controller and adaptive cruise controller. The similar controller was described in 2014, while the strategy was defined as a cooperative look-ahead controller for platooning (CLAC) [51]. In the same year, a two-layer control system architecture was introduced as an approach towards look-ahead control for HDV platooning [52]. Here, the two layers of architecture consisted of the platoon coordinator layer and the vehicle trajectory tracking layer. The platoon coordinator was responsible for generating a fuel-optimal speed profile for the entire platoon according to preview road topography information. The vehicle controller layer generated the real-time vehicle control according to the reference speed profile while ensuring safety. Based on the control architecture, a predictive control strategy was developed. The two-layer architecture was also explained in Turri et al. [52], and simulations of several realistic scenarios were performed to identify the effectiveness of the proposed controller. In addition, Alam et al. [29] presented a three-layer system architecture, consisting of a transport layer, a platoon layer, and a vehicle layer. The transport layer was responsible for transport planning and vehicle routing. The function of the platoon layer and the vehicle layer was similar to the two-layer control system architecture mentioned above. Torabi [49] was also concerned with fuel-efficient driving strategies for HDVs driving on highways with varying topography. He proposed the method named speed profile optimization for platooning (P-SPO), using a genetic algorithm to find fuel-efficient speed profiles. Additionally, a cooperative look-ahead control strategy was discussed in [53], and the results of the simulation showed that the proposed control strategy could significantly improve fuel efficiency compared with benchmarks. Here, the benchmarks were standard control methods of vehicle platoon, such as cruise control with a space gap policy (CC-SG) and cruise control with a headway gap policy (CC- HG).

7. Platooning of Autonomous Trucks

Until now, we have mainly covered the fuel economy of truck platoons involving human drivers. Nowadays, autonomous driving technology has been successfully applied in some closed environments such as logistics parks and harbour terminals [54, 55]. Considering the rapid development of automated driving technology, platooning of autonomous trucks would be a possible solution towards automated freight transportation in an open and uncontrolled environment [56]. Driverless truck platooning consists of vehicles which drive closely and communicate with each other through wireless communication technology. And this will be more beneficial to fuel economy due to a smaller distance between vehicles.

Bhoopalam et al. [56] proposed new classification to describe three levels of automated platooning according to the drivers' involvement degree. The first level is human-driven platooning with in-platoon resting. In this stage, the leading vehicles are handled by drivers and the following trucks can complete the driving tasks automatically. Therefore, the drivers in following vehicles can rest for a while when traveling in a platoon. To ensure that all drivers can have a chance to relax in a long trip, sequence, time of breaks, and travel times should be taken into consideration. The authors indicated that time-related costs will probably be more relevant than fuel related costs in that platooning form. The second level is the hybrid platooning. The main difference is that the following trucks can be driverless in this level. However, drivers are still required when the trucks drive alone in the first and last part of their trips. As a result, the pickup and delivery problem becomes a major question. The third level is the driverless platooning. This platooning form involves completely automated trucks without human drivers. Driverless platooning can be more flexible and more efficient since no rest time is required even in a long journey. And it can be beneficial to fuel economy because trucks could travel to different stops to form a platoon rather than returning to a fixed location to drop off the drivers.

8. Future Work

Truck platooning has been a popular topic to study for several decades. The previous sections present a literature review on truck platooning from the perspective of fuel economy. Although some theoretical and experimental results have been provided, there are still many open questions to be addressed in the future.

First of all, it is vital to discuss reasonable distances between vehicles considering safety, fuel economy, and passenger comfort. Here, the reasonable distances mean the longitudinal spaces between vehicles when driving on the flat road because the spaces should not be fixed on varying slopes in order to reduce fuel consumption. As shown in Section 4, it is favorable to minimize the relative distances between the vehicles to achieve a maximum reduction in air drag in theory. And Alam et al. [23] discovered that if the vehicles transmitted their control information through wireless communication, 2 meters would be allowed without endangering safety. However, when taking real conditions into consideration, issues such as feedback delay and communication delay for safety and passenger comfort arise. Besides, as for autonomous truck platooning, although ancillary ultrasonic rangefinder and other sensors are applied to autonomous vehicles for rang finding, operating at a short distance requires tight control, which may lead to an increased control effort and huge costs for communication between vehicles. Thus, further investigations are needed to find out the reasonable longitudinal spaces between vehicles in a platoon by balancing various aspects.

Another interesting direction for future research is to understand how traffic will affect coordination decisions. So far, most studies have been accomplished under nearly ideal conditions or in specific simulations and have assumed that the external traffic did not interfere with the motion of the trucks when following the speed profiles. However, in fact, traffic plays an important part in coordination decisions since the speeds and catch-up possibilities might decrease when the traffic is heavy, and this will affect the potential fuel savings. Hence, it is of great interest to study when and how to make a coordination decision in a dynamic network. For example, it might be uncertain to coordinate merge points after a region with heavy traffic, while a plan that merges the platoon before the region of heavy traffic should be preferred. Therefore, scenario-based model predictive control as well as stochastic and robust optimization can be appropriate sources of inspiration. In addition, due to the disturbances of traffic, vehicles might not be able to execute the speed plans suggested by the coordination system and new assignments could be added on the fly as the time goes. As a consequence, feedback is required to weaken the disturbances. For the truck platoon coordination problem, this means repeating the calculation of the plans based on updated information, similar to a model predictive controller [44]. Furthermore, the changes of speed profile and fuel consumption in a platoon also need to be investigated when the repeated planning is adopted. It might be a difficult problem to handle and will be subject to future work.

Apart from traffic, it will be meaningful to study how a platoon coordination system can work and be further improved in practice. Although some experiments have been made with real trucks or real traffic data, more tests need to be conducted and more studies have to be made to make large-scale deployment of platoon coordination systems come true. For instance, most coordination systems provide speed profiles without requiring information about the specific vehicle parameters such as masses or available engine powers, which may lead to several uncertainties in the system. The reason is that due to errors in mass estimation or maximum available engine torque, some HDVs in the platoon might not be able to track the recommended velocity profile. And as a result, platoons may not be formed in the most beneficial way. This problem was discussed in [50], which revealed the result that it is most fuel-efficient for a truck to reach the desired maximum or minimum speed before reaching an uphill or downhill segment, respectively, in such circumstances. However, it is still unclear for HDVs traveling in a platoon that how to take a fuel-efficient action with the uncertainties in coordination systems. Therefore, further investigation should focus on a more detailed analysis of the control architecture, including the system uncertainties and other related factors that need to be considered in reality.

It is necessary to decrease the complexity of the algorithm in future studies. In Sections 5 and 6, a variety of coordinating methods have been put forward while most of them may be inapplicable or too expensive to compute in scenarios where plenty of trucks can platoon. Besides, due to the high complexity of rerouting, a large number of literature made the assumption that routes were not altered. However, it might be more beneficial to slightly change the driving routes to form a platooning. Additionally, reducing the complexity of the algorithm can also decrease the delay in data processing. As a result, researchers should investigate how to reduce the complexity of the algorithm and put forward more practical methods to coordinate the vehicles in order to further increase the fuel efficiency in truck platoons.

Finally, the limitations on the number of trucks in a platoon and the potential effects of autonomous trucks on transportation infrastructure need further study and exploration. Although it can be predicted that the fuel economy will be improved with more vehicles in a platoon due to the air drag reduction, a platoon containing too many trucks may impose an adverse effect on traffic. For example, long platoons may disturb the traffic flow and make it difficult for other vehicles to merge. As for the influence on infrastructure, long platoons especially long automated truck platoons would contribute to increased wear and tear of roads due to channelized traffic and excessive concentration of wheel path regarding the lateral position [57, 58], which increases the life cycle costs. The impact of the truck platoon on road infrastructure has already attracted attention. Noorvand et al. [57] conducted a pavement performance simulation, and they suggested a dedicated lane for autonomous vehicles. Chen et al. [59] estimated rutting depth and fatigue damage by finite element analysis and proposed four lateral control modes for autonomous trucks. The result showed that the lateral distribution of autonomous trucks has a significant effect on pavement infrastructure, and autonomous trucks could be highly beneficial to asphalt pavements if controlled appropriately [60].

Conflicts of Interest

The authors declare that there are conflicts of interest regarding the publication of this paper.

Acknowledgments

Special thanks should be given to Prof. William H.K. Lam, Dr. Weihua Gu, and Dr. Shuaian Wang from Hong Kong Society for Transportation Studies for their copyright permission. This work was supported by the National Natural Science Foundation of China (grant nos. U1733113 and 71531011) and Shanghai Sailing Program (grant no. 18YF1424600).

References

[1] L. Zhang, F. Chen, and X. Ma, "A literature review of fuel economy in truck platoons," in *Proceedings of the 23rd International Conference of Hong Kong Society for Transportation Studies (HKSTS)*, pp. 39–46, Hong Kong, December 2018.

[2] Forum, OECD/International Transport, *International Transport Outlook 2013: Funding Transport*, OECD Publishing/ITF, Paris, France, 2013.

[3] American Trucking Association, *ATA American Trucking Trends 2015*, Richmond, VI, USA, 2016, http://www.trucking.org/article.aspx?uid=d62a253d-b830-4fa3-b069-f7f8ff5d40df.

[4] EC-European Commission, *EU Transport in Figures—Statistical Pocketbook*, Publications Office of the European Union, Brussels, Belgium, 2013.

[5] A. Schroten, G. E. A. Warringa, and M. Bles, "Marginal abatement cost curves for heavy duty vehicles: background report," CE Delft, Delft, Netherlands, 2012.

[6] M. Schittler, *State-of-the-Art and Emerging Truck Engine Technologies for Optimized Performance, Emission and Life Cycle Costs*, DaimlerChrysler AG (US), Stuttgart, Germany, 2003.

[7] I. V. Torrey, W. Ford, and D. Murray, *An Analysis of the Operational Costs of Trucking: A 2014 Update*, American Transportation Research Institute, Altanta, GA, USA, 2014, http://atri-online.org/2014/09/24/an-analysis-of-the-operational-costs-of-trucking-2014-update-report-request/.

[8] V. Turri, B. Besselink, and K. H. Johansson, "Cooperative look-ahead control for fuel-efficient and safe heavy-duty vehicle platooning," *IEEE Transactions on Control Systems Technology*, vol. 25, no. 1, pp. 12–28, 2017.

[9] S. Tsugawa, S. Jeschke, and S. E. Shladover, "A review of truck platooning projects for energy savings," *IEEE Transactions on Intelligent Vehicles*, vol. 1, no. 1, pp. 68–77, 2016.

[10] C. Bonnet and H. Fritz, "Fuel consumption reduction in a platoon: experimental results with two electronically coupled trucks at close spacing," in *Proceedings of the SAE Technical Paper Series*, USA, 2000.

[11] F. Browand, J. Mcarthur, and C. Radovich, *Fuel Saving Achieved in the Field Test of Two Tandem Trucks*, University of California, Berkeley, Berkeley, CA, USA, 2004.

[12] R. Bae, R. Ramakers, K. Henning, and S. Jeschke, "Organization and operation of electronically coupled truck platoons on german motorways," in *Proceedings of the Automation, Communication and Cybernetics in Science and Engineering 2009/2010*, pp. 427–439, Springer Berlin Heidelberg, Heidelberg, Germany, 2011.

[13] C. Bergenhem, H. Pettersson, E. Coelingh, C. Englund, S. Shladover, and S. Tsugawa, "Overview of platooning systems," in *Proceedings of the 19th ITS World Congress*, Vienna, Austria, 2012.

[14] S. Tsugawa, S. Kato, and K. Aoki, "An automated truck platoon for energy saving," in *Proceedings of the 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 4109–4114, IEEE, San Francisco, CA, USA, 2011.

[15] T. Litman, *Autonomous Vehicle Implementation Predictions: Implications for Transport Planning*, Victoria Transport Policy Institute, Victoria, Canada, 2019, https://www.vtpi.org/avip.pdf.

[16] M. Zabat, N. Stabile, S. Farascaroli, and F. Browand, "The aerodynamic performance of platoons: a final report," UC Berkeley: California Partners for Advanced Transportation Technology, Berkeley, CA, USA, 1995, http://escholarship.org/uc/item/8ph187fw#page-1.

[17] B. Marcu and F. Browand, "The aerodynamic forces on misaligned platoons," UC Berkeley: California Partners for Advanced Transportation Technology, Berkeley, CA, USA, 1998, https://escholarship.org/uc/item/0fg1j34q.

[18] P. Hong, B. Marcu, F. Browand, and A. Tucker, "Drag forces experienced by two , full-scale vehicles at Close spacing at close spacing," UC Berkeley: California Partners for Advanced Transportation Technology, Berkeley, CA, USA, 1998, https://escholarship.org/uc/item/50q2p3sn.

[19] B. Marcu and F. Browand, "Aerodynamic forces experienced by a 3-vehicle platoon in a crosswind," in *Proceedings of the SAE Technical Paper Series*, USA, 1999.

[20] M. Hammache, M. Michaelian, and F. Browand, "Aerodynamic forces on truck models, including two trucks in tandem," in *Proceedings of the SAE Technical Paper Series*, USA, 2002.

[21] M. Ellis, J. I. Gargoloff, and R. Sengupta, "Aerodynamic drag and engine cooling effects on Class 8 trucks in platooning configurations," *SAE International Journal of Commercial Vehicles*, vol. 8, no. 2, pp. 732–739, 2015.

[22] T. Gheyssens and G. Van Raemdonck, "Effect of the frontal edge radius in a platoon of bluff bodies," *SAE International Journal of Commercial Vehicles*, vol. 9, no. 2, pp. 371–380, 2016.

[23] A. Al Alam, A. Gattami, and K. H. Johansson, "An experimental study on the fuel reduction potential of heavy duty vehicle platooning," in *Proceedings of the 13th International IEEE Conference on Intelligent Transportation Systems*, IEEE, Funchal, Portugal, 2010.

[24] X.-Y. Lu and S. E. Shladover, "Automated truck platoon control," UCB-ITSPRR-2011-13, UC Berkeley: California Partners for Advanced Transportation Technology, Berkeley, CA, USA, 2011.

[25] A. Davila, E. Aramburu, and A. Freixas, "Making the best out of aerodynamics: platoons," in *Proceedings of the SAE Technical Paper Series*, USA, 2013.

[26] M. P. Lammert, A. Duran, J. Diez, K. Burton, and A. Nicholson, "Effect of platooning on fuel consumption of Class 8 vehicles over a range of speeds, following distances, and mass," *SAE International Journal of Commercial Vehicles*, vol. 7, no. 2, pp. 626–639, 2014.

[27] J. Smith, R. Mihelic, B. Gifford, and M. Ellis, "Aerodynamic impact of tractor-trailer in drafting configuration," *SAE International Journal of Commercial Vehicles*, vol. 7, no. 2, pp. 619–625, 2014.

[28] S. Tsugawa, "Results and issues of an automated truck platoon within the energy ITS project," in *Proceedings of the 2014 IEEE Intelligent Vehicles Symposium Proceedings*, pp. 642–647, IEEE, Dearborn, MI, USA, 2014.

[29] A. Alam, B. Besselink, V. Turri, M. Jonas, and K. H. Johansson, "Heavy-duty vehicle platooning for sustainable freight transportation:A cooperative method to enhance safety and efficiency," *IEEE Control Systems Magazine*, vol. 35, no. 6, pp. 34–56, 2015.

[30] H. Humphreys and D. Bevly, "Computational fluid dynamic analysis of a generic 2 truck platoon," in *Proceedings of the SAE Technical Paper Series*, USA, 2016.

[31] H. L. Humphreys, J. Batterson, D. Bevly, and R. Schubert, "An evaluation of the fuel economy benefits of a driver assistive truck platooning prototype using simulation," in *Proceedings of the SAE Technical Paper Series*, 2016.

[32] B. Mcauliffe, M. Croken, M. Ahmadi-Baloutaki, and A. Raeesi, "Fuel-economy testing of a three-vehicle truck platooning system," 2017, https://escholarship.org/uc/item/7g37w4fb.

[33] B. Mcauliffe, M. Lammert, X.-Y. Lu, S. Shladover, M.-D. Surcel, and A. Kailas, "Influences on energy savings of heavy trucks using cooperative adaptive cruise control," in *Proceedings of the SAE Technical Paper Series*, 2018.

[34] K. Y. Johansson, M. Jonas, and K. H. Johansson, "Fuel-saving potentials of platooning evaluated through sparse heavy-duty vehicle position data," in *Proceedings of the 2014 IEEE Intelligent Vehicles Symposium Proceedings*, pp. 1061–1068, Dearborn, MI, USA, June 2014.

[35] J. Larson, K.-Y. Liang, and K. H. Johansson, "A distributed framework for coordinated heavy-duty vehicle platooning," *IEEE Transactions on Intelligent Transportation Systems*, vol. 16, no. 1, pp. 419–429, 2015.

[36] C. Kammer, "Coordinated heavy truck platoon routing using global and locally distributed approaches," 2013.

[37] E. Larsson, G. Sennton, and J. Larson, "The vehicle platooning Problem : computational complexity and heuristics,"

Transportation Research Part C: Emerging Technologies, vol. 60, pp. 258–277, Elsevier Ltd., Amsterdam, Netherlands, 2015.

[38] A. Nourmohammadzadeh and S. Hartmann, "The fuel-efficient platooning of heavy duty vehicles by mathematical programming and genetic algorithm," *Theory and Practice of Natural Computing*, pp. 46–57, Springer, Cham, Switzerland, 2016.

[39] P. Meisen, T. Seidl, and K. Henning, "A data-mining technique for the planning and organization of truck platoons," in *Proceedings of the International Conference on Heavy Vehicles*, pp. 270–279, 2008, http://road-transport-technology.org/Proceedings/HVTT_10/Papers/Papers_HVTT/A_DATA-MINING.

[40] K.-Y. Liang, J. Mårtensson, and K. H. Johansson, "When is it fuel efficient for a heavy duty vehicle to catch up with a platoon?," *IFAC Proceedings Volumes*, vol. 46, no. 21, pp. 738–743, 2013.

[41] K.-Y. Liang, J. Martensson, and K. H. Johansson, "Heavy-duty vehicle platoon formation for fuel efficiency," *IEEE Transactions on Intelligent Transportation Systems*, vol. 17, no. 4, pp. 1051–1061, 2016.

[42] J. Larson, C. Kammer, K. Y. Liang, and K. H. Johansson, "Coordinated route optimization for heavy duty vehicle platoons," in *Proceedings of the 16th International IEEE Conference on Intelligent Transportation Systems (ITSC 2013)*, pp. 1196–1202, IEEE, The Hague, Netherlands, 2013.

[43] S. van de Hoef, K. H. Johansson, and D. V. Dimarogonas, "Fuel-optimal centralized coordination of truck platooning based on shortest paths," in *Proeedings of the 2015 American Control Conference (ACC)*, pp. 3740–3745, IEEE, Chicago, IL, USA, 2015.

[44] S. V. D. Hoef, *Fuel-Efficient Centralized Coordination of Truck Platooning*, KTH Royal Institute of Technology, Stockholm, Sweden, 2016.

[45] A. B. Schwarzkopf and R. B. Leipnik, "Control of highway vehicles for minimum fuel consumption over varying terrain," *Transportation Research*, vol. 11, no. 4, pp. 279–286, 1977.

[46] T. Ohtsuka, "A continuation/GMRES method for fast computation of nonlinear receding horizon control," *Automatica*, vol. 40, no. 4, pp. 563–574, 2004.

[47] A. Fröberg, "Efficient simulation and optimal control for vehicle propulsion," *Institutionen För Systemteknik*, 2008.

[48] E. Hellström, *Look-Ahead Control of Heavy Vehicles*, Linköping University, Linköping, Sweden, 2010.

[49] S. Torabi, *Fuel-Efficient Truck Platooning Using Speed Profile Optimization*, Department of Mechanics and Maritime Sciences, Chalmers University of Technology, Gothenburg, Sweden, 2017.

[50] A. Alam, M. Jonas, and K. H. Johansson, "Look-ahead cruise control for heavy duty vehicle platooning," in *Proceedings of the 16th International IEEE Conference on Intelligent Transportation Systems (ITSC 2013)*, pp. 928–935, IEEE, The Hague, Netherlands, 2013.

[51] A. Alam, *Fuel-Efficient Heavy-Duty Vehicle Platooning*, KTH Royal Institute of Technology, Stockholm, Sweden, 2014.

[52] V. Turri, B. Besselink, M. Jonas, H. Karl, and Johansson, "Fuel-efficient heavy-duty vehicle platooning by look-ahead control," in *Proceedings of the 53rd IEEE Conference on Decision and Control*, pp. 654–660, IEEE, Los Angeles, CA, USA, 2014.

[53] C. Zhai, F. Luo, and Y. Liu, "Cooperative look-ahead control of vehicle platoon for maximizing fuel efficiency under system constraints," *IEEE Access*, vol. 6, pp. 37700–37714, 2018.

[54] K. H. Kim and J. W. Bae, "A look-ahead dispatching method for automated guided vehicles in automated port container terminals," *Transportation Science*, vol. 38, no. 2, pp. 224–234, 2004.

[55] K. J. Roodbergen and I. F. A. Vis, "A survey of literature on automated storage and retrieval systems," *European Journal of Operational Research*, vol. 194, no. 2, pp. 343–362, 2009.

[56] A. K. Bhoopalam, N. Agatz, and R. Zuidwijk, "Planning of truck platoons: a literature review and directions for future research," *Transportation Research Part B: Methodological*, vol. 107, pp. 212–228, 2018.

[57] H. Noorvand, G. Karnati, and B. S. Underwood, "Autonomous vehicles," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2640, no. 1, pp. 21–28, 2017.

[58] X. Zhu, Z. Dai, F. Chen, X. Pan, and M. Xu, "Using the visual intervention influence of pavement marking for rutting mitigation— part II: visual intervention timing based on the finite element simulation," *International Journal of Pavement Engineering*, vol. 20, no. 5, pp. 573–584, 2019.

[59] F. Chen, M. Song, X. Ma, and X. Zhu, "Assess the impacts of different autonomous trucks' lateral control modes on asphalt pavement performance," *Transportation Research Part C: Emerging Technologies*, vol. 103, pp. 17–29, 2019.

[60] A. Gattami, A. Al Alam, K. H. Johansson, and C. J. Tomlin, "Establishing safety for heavy duty vehicle platooning: a game theoretical approach," *IFAC Proceedings Volumes*, vol. 44, no. 1, pp. 3818–3823, 2011.