A Review of Truck Platooning Projects for Energy Savings

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***Abstract*—Technical studies on automated driving of passenger cars were started in the 1950s, but those on heavy trucks were started in the mid-1990s, and only a few projects have dealt with truck automation, which include "Chauffeur" within the EU project T-TAP from the mid-1990s, truck automation by California PATH from around 2000, "KONVOI" in Germany from 2005, and "Energy ITS" by Japan from 2008. The objectives of truck automation are energy saving and enhanced transportation capacity by platooning, and eventually possible reduction of personnel cost by unmanned operation of following vehicles. The sensing technologies for automated vehicle control are computer vision, radar, lidar, laser scanners, localization by GNSS, and vehicle to vehicle communications. Experiments of platooning of three or four heavy trucks have shown the effectiveness of platooning in achieving energy saving due to short gaps between vehicles.**

***Index Terms*—Automated driving, lateral control, longitudinal control, platooning.**

I. Introduction

Although technical studies on automated driving for passenger cars have a long history starting from the 1950s and much work has been done since then, those for heavy trucks were only started in the mid-1990s and are relatively few. The objectives of truck automation by platooning—whereby a string of vehicles drive along the same trajectory with only a short gap in between—are energy saving and highway capacity increase, with an eventual possibility of personnel cost reduction by unmanned operation of the following trucks.

The emphasis here is on cooperative longitudinal control of trucks, combining information from forward-looking remote sensors measuring the distance and speed difference to the immediately preceding truck with additional information communicated from that truck and other trucks ahead of it.

The first studies on truck automation were "Chauffeur" within the EU project T-TAP from the mid-1990s to the beginning of 2000 [1], [2], where driving experiments were conducted with three heavy trucks along the Brenner Pass through the Alps between Austria and Italy. In the beginning of the 2000s, the California PATH Program started its research on heavy truck platooning, conducting experiments with trucks that have only an automated longitudinal control function to assess the effectiveness of platooning on energy saving and highway capacity [3]. In 2011, they conducted experiments with three heavy trucks at a gap of 6 m, resulting in the improvement of fuel consumption by about 10% on the average [4]. From 2005 to 2009 a team of German scientists from the RWTH Aachen University developed a platoon of four heavy trucks in their project "KONVOI" [5] with the objectives of increasing transportation capacity as well as reduction of fuel consumption. In their platoon, which was tested also on German highways, the lead truck was driven by a human driver followed by three automated trucks with a gap of 10 m. In 2008 Japan started a 5-year project "Energy ITS" aiming for energy saving and consequent CO_2 emission reduction by truck platooning [6]. Within the project a platoon of three automated heavy trucks was developed and drove on a test track with a gap of 4.7 m at 80 km/h. Recently a team of researchers from Auburn University published their results on "driver-assistive truck platooning"—a form of cooperative adaptive cruise control (CACC) using radar, vehicle to vehicle (V2V) communications, localization, and human-machine interface (HMI) [7]. In this paper we describe background, technologies, effectiveness, and issues of automated truck platooning based on the work from California PATH, RWTH Aachen University, and Energy ITS of Japan. This topic is important because truck platooning is likely to be one of the earliest applications of road vehicle automation to be commercially viable.

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II. Objectives of Automated Truck Platooning

General objectives of automated driving of vehicles are, from a social perspective, increase in safety, reduction in congestion, energy consumption and emissions, and from a driver's perspective, increase in comfort and convenience. The objectives of truck automation are not only the above-mentioned general objectives but also, in the long term, when drivers are no longer needed in the following trucks, a potential reduction in personnel costs.

A. Energy Consumption and CO_2 Emission

Energy conservation is essential, and CO_2 emission reduction is also important to reduce global warming effects. In Japan in 2011 the energy consumption by trucks was about 8% of that of the whole country [8]. Also in Japan in 2011 the CO_2 emission from trucks was 6.2% of the emissions from the whole country [9].

The source of CO_2 emission in trucks is the burning of petroleum as energy source in their internal combustion engines.

Countermeasures for reducing CO_2 emission in trucks are therefore equivalent to efforts to save energy. There are several ways for achieving energy saving in road transportation [10] including automation. When a platoon of vehicles drives with a small gap, the aerodynamic drag coefficient of each vehicle decreases depending on its position in the platoon, and since the aerodynamic drag is proportional to square of the vehicle speed, platooning is more effective concerning energy saving at higher speed. Automatic speed control can also smooth out acceleration and deceleration maneuvers, and cooperative vehicle following control can attenuate speed variations in traffic, both of which save energy and reduce emissions of criteria pollutants as well as CO_2.

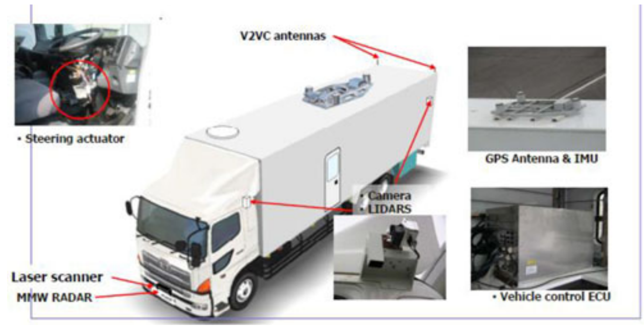

Fig. 1. Configuration of the Energy ITS automated truck.

B. Characteristics of the Trucking Industry

Particular concerns for the trucking industry in Japan are minimizing operating costs and the aging of drivers. Personnel and fuel costs accounted for 36% and 18% respectively of the total expenses in the trucking industry in 2010. In addition, while the number of elderly drivers of heavy trucks is increasing the number of younger drivers is decreasing: in 1993 only 22.9% of truck drivers were over 50, but in 2010 the percentage increased to 35.1%. The reason for this is the decrease of the Japanese population, with a concurrent increase in the percentage of elderly citizens. Thus, introduction of truck automation can be a way of counteracting the shortage of heavy truck drivers. The trends are similar in Europe and North America, even if the specific numerical values are different.

C. Transportation Capacity

In the EU the largest portion of freight is transported via road (44%) followed by short distance maritime (41%), rail (8%), and inland waterways transportation (4%). The importance of road traffic is even more pronounced in the area of passenger transportation, with a market share of 79% compared to rail with only 5%.

This is a critical situation because further growth in all transport sectors is estimated: For the period between 2000 and 2020 a growth in freight transport of approx. 2% per year is anticipated (50% for the whole period) [11]. The most important structural trends are:

1) The roads still bear the biggest portion of the freight traffic within the EU.
2) Freight traffic on rail is gaining a stronger importance in some EU member states, though in percentage it will contribute the least to the whole transport volume in the medium long term.

Therefore one should be aware that the European economy is seriously endangered by an overload of the trans-European roadway network. The chronic overload is attributed to the non-transparent price structure of infrastructure costs, congestion costs, environmental impact costs and accident costs. Among other things the suboptimally organized European traffic system and use of the freight carriers as well as new technologies are mentioned as reasons. To provide means to face the mentioned challenges and to increase road safety and optimize road traffic, scientists of the project "KONVOI" developed and analyzed electronically coupled truck platoons [12].

The road networks in all industrialized countries, including Japan and the USA, face similar problems of capacity and congestion, without the ability to significantly expand their physical infrastructure. Therefore they need to depend on new technologies such as vehicle automation to increase the effective capacity of the existing infrastructure.

Improving safety was identified as one of the general objectives of automated driving, based on the hope that automation system will be able to avoid some of the crashes that are currently caused by human drivers' limitations. Truck platooning is not explicitly aimed at crash avoidance, but its reliance on frequent vehicle-to-vehicle communication provides an opportunity for the following trucks to react to problems with the leading trucks faster than a driver would be able to perceive the problems.

III. TECHNOLOGIES OF TRUCK PLATOONING

The technologies used to implement automated truck platooning in each system are introduced.

A. Automated Trucks in Energy ITS

The automated truck platoon developed in the project "Energy ITS" consists of three heavy (25 tons) trucks and one light truck, both laterally and longitudinally automated. The platoon drove at 80 km/h with gaps of 10 m and 4 m on a test track (The trucks have a bumper at the rear for passive safety, with a length of 0.7 m. Thus, the aerodynamic gap is 4.7 m). The functions of the platoon are lane keeping, speed control, collision avoidance, and gap keeping. Among these functions, the gap keeping function contributes to energy saving, and the other functions contribute to increase the safety and reduce the workload of drivers. Fig. 1 shows the configuration of a truck for the automated platoon. The automated platoon does not require any infrastructure equipment.

1) Sensing for Lateral Control: Each truck is equipped with two downward-facing machine vision units for lateral control, which have the same configuration and function, one attached to the front and one to the rear (see Fig. 1). The vision units not only detect the deviation of a truck from a lane marker but

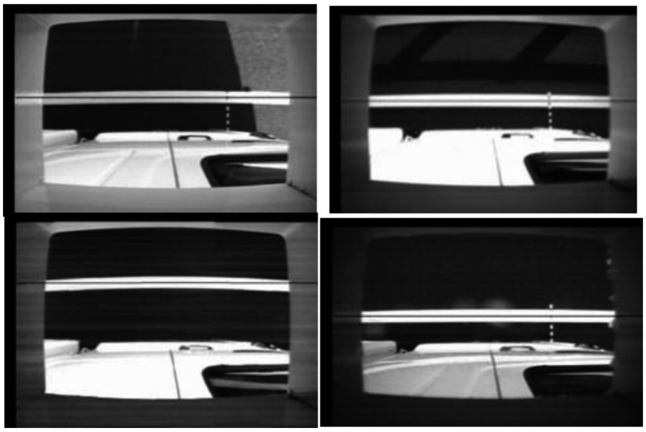

Fig. 2. Lane marker detection by the CCD camera: (top-left) shadow of the ego vehicle; (top-right) shadow of the roadside construction; (bottom-left) in a tunnel; (bottom-right) in rainy weather.

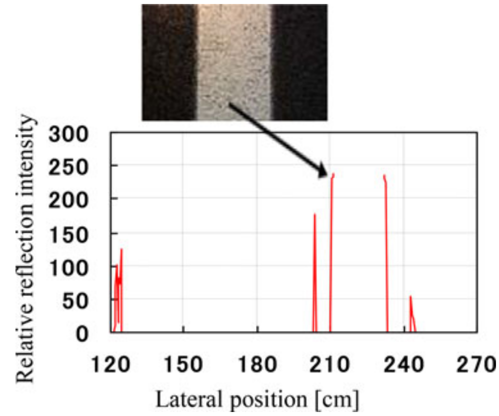

Fig. 3. Detection of a lane marker with the active vision.

also detect the yaw angle of a truck relative to the lane markers, which plays an important role in the lateral control.

One of the features of the vision system is that it looks downward and detects a lane marker immediately at the left hand side of the truck. The configuration and the direction of the optical axis of the machine vision unit can prevent optical noise, but the lateral control becomes difficult because of the lack of preview of upcoming road curvature changes. The other feature is that the vision system consists of two kinds of sensors for robustness: one is a conventional CCD camera, and the other is active vision consisting of a laser scanner and an opto-electronic receiver.

In most cases the lane marker is detected by the CCD camera as shown in Fig. 2. The size of the image is 640 × 480 pixels, and the accuracy of the detection is 1 cm for lateral deviation, and 0.1° of heading.

In some cases, including under an overpass or at a junction of a bridge, the lane marker cannot be detected by the CCD camera. The active vision can work under such conditions, and detect a lane marker covered with water from rainfall, when the CCD camera cannot detect it due to the reflections from the water surface. The principle of the detection is the use of the reflection ratio difference between the asphalt pavement and the lane marker. The laser scanner laterally scans the lane marker. The reflection from the marker is stronger, and the marker is easily identified. Fig. 3 shows the reflection from the pavement and the lane marker [13].

2) Sensing for Longitudinal Control: Each truck is equipped with a 76 GHz radar and a 2-dimensional lidar (Light Detection and Ranging) used for obstacle detection on the first truck, and for gap measurement on the following trucks. The use of two different sensors is for robustness. Since the sensing system is not sufficient for precise control of the gap keeping and provides no feedforward information about the state of the trucks before the immediate predecessor, the platoon employs V2V communications.

3) V2V Communications: The communications employ two media, 5.8 GHz DSRC and infrared, for robustness. The DSRC is primary, and Table I shows the specifications of the V2V communications at 5.8 GHz DSRC and infrared.

TABLE I
V2V COMMUNICATION SPECIFICATIONS FOR ENERGY-ITS TRUCKS

Media	Microwave	Infrared
Frequency/wave length	5.820 GHz	850 nm
Modulation	$\pi/4$ shift QPSK	On-off-keying
Transmission		Full duplex
Error detection		CRC-CCITT
Band width	< 4.4 MHz	
Rate	4.096 Mbps	100 kbps
Power	10 dBm	
Antenna	Omnidirectional	
Access control	CSMA/CA	
Data update period	20 ms	20 ms
Data size	56 bytes	50 bytes
Range	< 60 m	1–15 m
Packet receiving rate	99.92%	99.92%

With the communications, data from each truck are shared among the trucks in the platoon on a real time basis, and the communication unit and the vehicle control electronic control unit (ECU) communicate every 20 ms. The data shared among trucks includes the reference velocity, the reference acceleration, the velocity of each truck, the braking signal, platoon management data like the platoon ID and truck position within the platoon, obstacle locations, and the location of each truck. The message payload is about 50 bytes. The protocol is based on carrier sense multiple access (CSMA), and the real-time data transmission is realized by repetition of communications between communication units. The communication period between units is 3 ms, and the transmission is repeated 5 times in each communication period of 20 ms between the communication unit and the ECU). Since the control update period is 10 ms and the communication update period is 20 ms, the previous data may be used for vehicle control, and the delay is 10 ms at the longest. The power, 10 dBm, is based on the Japanese regulations.

The V2V communications with infrared are also highly reliable. The communication units can operate under various conditions including rainfall (up to 50 mm/h), fog (visibility at least 50 m), and direct sunlight. The units are attached at the bumpers to reduce the influence of low sun angles. The infrared

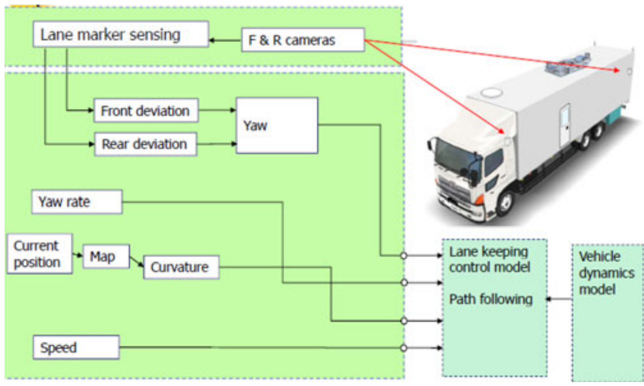

Fig. 4. Lateral control system for the Energy ITS automated truck.

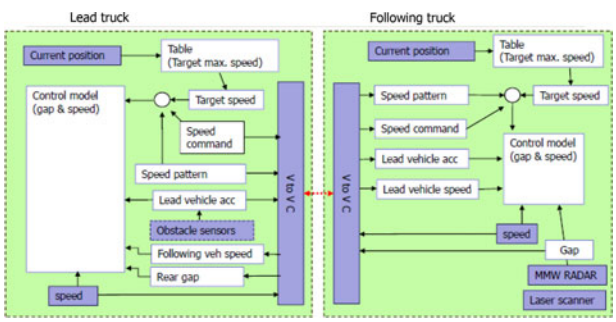

Fig. 5. Longitudinal control system for the Energy ITS platoon.

communication units on the intermediate trucks must include a relay function.

4) Lateral Control System: Fig. 4 shows the lateral control system, and each truck is laterally controlled independently from the other trucks. The lateral control algorithm is based on lateral deviation from a lane marker as a reference and yaw angle relative to the lane marker [14]. In addition, the following trucks have a function of tracking the preceding one in case of absence of lane markers [15].

5) Longitudinal Control System: Fig. 5 shows the longitudinal control system, which maintains truck speed and clearance gap [16], [17]. The control input for the longitudinal control is expressed as the speed differences and the gap differences relative to the preceding truck and the following one. The algorithm is designed by using Lyapunov stability theory.

6) Features of Sensing Systems, ECU, and Actuators: The sensing systems, the ECU, and the actuators are designed for high reliability, robustness, and fault detection for near future introduction. The sensing system for lateral control employs two kinds of vision sensors: ordinary passive sensors and new active sensors. Longitudinal control also employs two kinds of sensors: 76 GHz radar and lidar. The V2V communications based on DSRC have two independent channels for redundancy in addition to the separate medium of infrared. As shown in Table I, the communications are highly reliable; the source of errors is its protocol: in CSMA packet collisions cannot be avoided. The steering actuators have two independent motors, and the brake systems have also two independent units for redundancy. The ECU has a fault detection function.

TABLE II
PERFORMANCE OF THE ENERGY ITS VEHICLE CONTROL SYSTEM

Driving site		Test track		Expressway before public use	
		Goals	Results	Goals	Results
Speed [km/h]			80		80
Lateral control [m]		±0.2	±0.06	±0.20	±0.15
Longitudinal Control [m]	Steady state	0.10 ± 0.02	0.10 ± 0.01	0.10 ± 0.02	0.10 ± 0.01
	Braking at 0.5 G	0.10-0.03	0.10 ± 0.01	0.10-0.03	0.10 ± 0.01
Lane change (time required) (target path following)*		±7%	±10%	±7%	±15%
Platoon forming by splitting (time to form a platoon) [s]		15	32	N/A	N/A

*It is evaluated by the relative error between the time required for lane changing that is analytically calculated and that measured during the experiments.

Fig. 6. The Energy ITS automated platoon of 3 heavy trucks and a light truck.

The trucks have a HMI for the driver to monitor and manage the platoon. The automated trucks have three states: (1) manual driving, (2) semi-automation: driving with adaptive cruise control (ACC) (only longitudinal control is automated), and (3) full automation: driving with ACC and automated lateral control. The transitions between the states are initiated by a driver (operator).

The performance of the vehicle control system was assessed during experiments on a test track. The results are shown in Table II. Almost all the results are within the goals, but the algorithms for platoon forming and lane changing must be improved.

7) Experiments of Automated Truck Platooning: In order to examine the functions of the automated platoon, experiments were conducted on a test track with three heavy trucks and one light truck (see Fig. 6) with the gaps of 10 m and 4.7 m at 80 km/h in spring 2013 (in spring 2011, experiments were also conducted on an expressway before public use).

B. Electronically Coupled Truck Platoons "KONVOI"

In order to realize different platoon sizes, four experimental vehicles have been equipped with the required automation, information and automotive technology (see Fig. 7) [18]. The main components for the implementation of the system architecture in the experimental vehicles are the actuators (steering and powertrain), the sensors (object registration in close-up and far range, recognition of lane), the V2V-communication (WLAN),

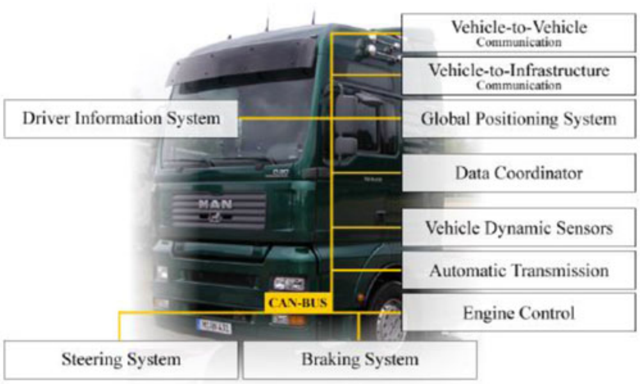

Fig. 7. Automation, information and automotive technology of a KONVOI experimental vehicle.

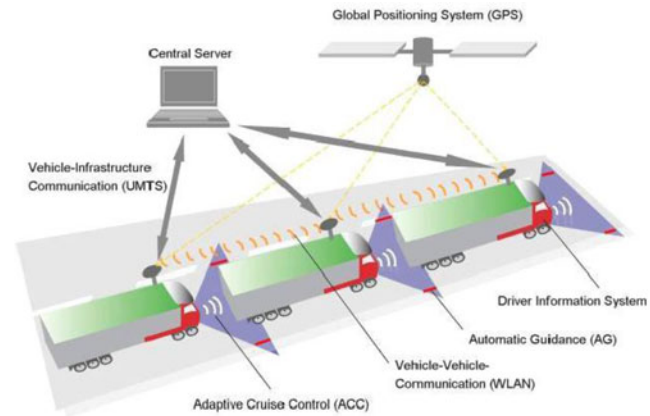

Fig. 8. The KONVOI PLATOON SYSTEM.

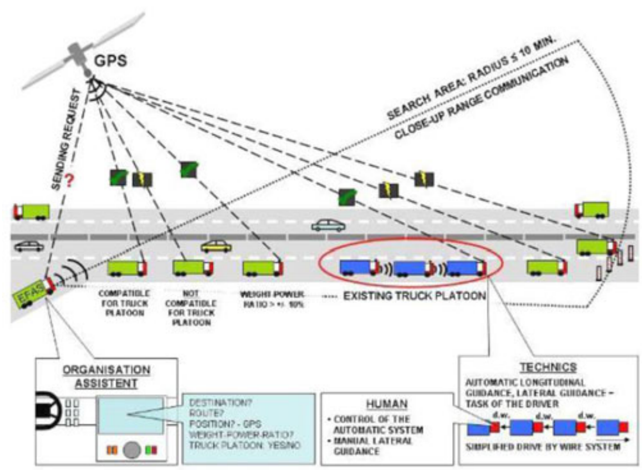

Fig. 9. Driver organized truck platoons.

the automation unit (coordination of the different vehicle states), the control unit (ACC and automatic lateral guidance) and the driver information system (DIS) (HMI, organization assistant, GPS and 3G cellular communications) [18], [19].

1) Lateral Control: The lateral guidance of the advanced driver assistance system (ADAS) is based on the lateral offset to the leading vehicle and the vehicle's own position relative to the lane markings detected by a complementary metal oxide semiconductor (CMOS) image processing system as well as on the data from the V2V-communication. The necessary steering moment for the automated lateral guidance of the trucks is realized via a steering actuator based on an electric motor in the vehicle, which is built as a dual circuit with detached energy supply [18].

2) Longitudinal Control: The longitudinal guidance of the ADAS is based on a lidar distance sensor, a CMOS camera and a radar sensor. The distance sensors are used to determine the distance in longitudinal direction and the lateral offset to the leading vehicle. The V2V communication transfers necessary vehicle data from all platoon members, which are required for the ACC to realize the target following distance of 10 m. In all trucks, a target acceleration interface is implemented, which automatically calculates the commands to the drivetrain and the management of the different brakes in the vehicles. The acceleration is either calculated autonomously for each vehicle or deduced from the data which is transferred via the vehicle-to-vehicle communications [18].

3) Sensing Systems, Actuators, and HMI: Every experimental vehicle is equipped with cameras which are able to identify the lane markers, thus determining the position of every truck within the traffic lane. A steering actuator using an electric motor delivers the necessary steering torque for the automated lateral guidance of the trucks [20].

With the help of the DIS, the truck driver plans his route, selects economic platoon participants as well as initializes and confirms the platoon maneuvers in order to build and to dissolve the platoon. The platoon organization is realized on a central server with a data-mining algorithm considering economic aspects. For this task, the DIS has to send the schedule, route plan and GPS position of the truck using vehicle-infrastructure communication via 3G cellular to the central server (see Fig. 8) [18].

4) Scenario of Truck Platoon Organization by Drivers: The project "KONVOI" is based on the scenario "driver organized truck platoons" (see Fig. 9) which was developed in the project "operation-scenarios for advanced driving assistance systems in freight transportation and their validation" (EFAS in German) [21]. In the scenario "driver organized truck platoons," the platoons can operate on existing motorways without extending the infrastructure and the driver has permanent control of the automated driving procedures [21]. The creation of a platoon depends on the initiating driver, who delivers the necessary data about time and place of meeting, the destination, as well as the required truck telemetric data (loaded weight, engine power etc.) with the help of a DIS. The high flexibility of truck transportation is not lost, because scheduling, like in rail traffic, is dispensable. After activating the ADAS, a selection of the best matching platoons is automatically shown. The ADAS informs the driver and prepares the participation in the selected platoon. The DIS acts as a HMI for the platoon system and helps the truck driver to plan the route and guides the driver to the meeting point [18], [20].

The driver has to initialize and confirm all of the platoon maneuvers in order to build and to dissolve the platoon. As soon as the final position in the platoon is reached, automated longitudinal control with a target distance of 10 m between the trucks and lateral control is possible. This target distance was chosen because the short distance was found during the KONVOI experiments to prevent most car drivers from driving between the platoons and the short distance also causes slipstream effects, which can lead to reduced fuel consumption. Since road markings are needed for lateral control, the platoon system is exclusively developed for use on motorways. Because of a limitation for most trucks of approximately 50 mph, the speed of the trucks on motorways differs only slightly. Therefore, the truck platoons are operated at a speed between 37 and 50 mph. This speed can be managed safely at 10 m distance by the KONVOI System [22].

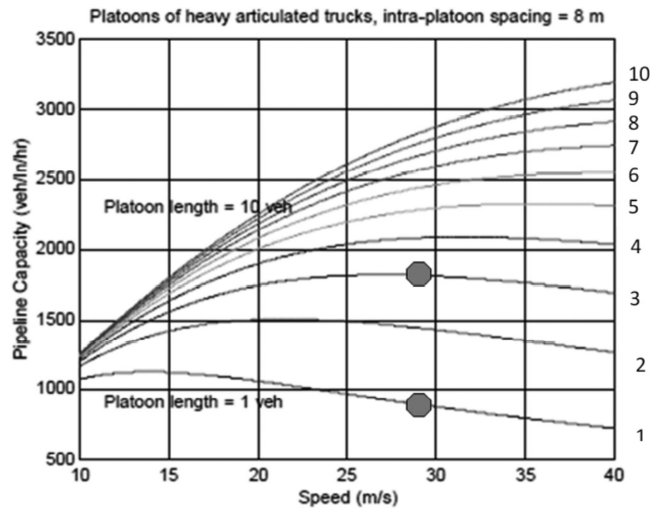

Fig. 10. PATH Kinematic analysis of capacity in trucks per lane per hour as a function of speed and platoon length.

C. PATH Development of Truck Platooning and CACC Systems

The University of California PATH Program has developed three generations of proof-of-concept prototype truck longitudinal control systems within the past fifteen years. This research has been motivated primarily by the need to reduce energy consumption and traffic congestion associated with truck traffic. Because of the dominance of Class-8 tractor-trailer operations for long-distance high-speed truck traffic in the U.S., the PATH prototypes have been of this class, using truck tractors with large sleeper cabs and forward engines. The first two generations of prototypes were based on Freightliner Century model tractors, while the third generation (which is implementing CACC rather than platooning) is based on a Volvo tractor.

As part of its research under the National Automated Highway Systems Consortium, the PATH research team did kinematic analyses of the potential increases in highway capacity that could be enabled by operation of trucks in closely coupled automated platoons. These analyses were based on maintaining the closest practical constant-clearance gaps between trucks within a platoon, while selecting large enough gaps between platoons to ensure that it would not be possible for the leading truck of any platoon to collide with the last truck of the preceding platoon even under worst-case failure conditions. The resulting estimates of the maximum achievable "pipeline" capacity per lane are shown in Fig. 10 for platoons up to ten trucks long. In order to allow gaps for merging and lane changing, separate simulation studies have shown that these capacity values need to be reduced by about 25% to estimate practical capacity. Note from Fig. 10 that three-truck platoons at 28 m/s provide double the capacity per lane of single-truck platoons (highlighted with symbols), and as the platoon lengths increase the gains in capacity become less significant. These close-formation platoon operations are intended for use on a dedicated truck lane where the trucks can be separated from the erratic behaviors of normal passenger car drivers and motorcyclists, so the truck platoon control systems do not need to be designed to respond safely to all of those erratic behaviors.

The first two generations of PATH truck platoon control systems were implemented on the Freightliner Century truck tractor, with modifications shown schematically in Fig. 11. The trucks were provided with an Eaton-Vorad EVT-300 ACC system based on a 24 GHz forward radar, and that radar was used for the direct measurements of range and range rate relative to the preceding truck. PATH had to retrofit these trucks with electronically actuated brake systems, which were not commercially available in the U.S. at the time this project was initiated, as well as a wireless LAN V2V communication system, a lidar for additional forward range measurements and a computer for control and data acquisition.

For the first generation of truck platooning studies, PATH equipped two trucks for experiments using 802.11b data modems at a 20 ms update interval for the V2V communication. The truck platoon was tested on a former military airfield that was no longer in use for aircraft operations, providing about 2.2 km of straight, wide paved area for testing, which made it possible to do steady-state cruising for 20 to 30 seconds after accounting for the time and distance needed to accelerate and decelerate to and from cruise speed. The trucks were tested at clearance gaps of 10, 8, 6, 4 and 3 m to measure energy consumption and criteria pollutant emissions [23], [24].

For the second generation of truck platooning tests, PATH added a third identical truck tractor and upgraded the wireless communications to an 802.11p DSRC system specifically designed for mobile applications [4]. In order to comply with the standards governing cooperative collision warning applications in the U.S., and to avoid generating excessive wireless channel communication traffic this was operated at a 100 ms update interval and the control system was modified to operate at this slower update rate. The second generation system was tested on an 8 km section of two-lane roadway that was temporarily closed to public traffic for testing. These tests included following varying speed profiles with accelerations and decelerations, positive and negative grade angles, and platoon join and split maneuvers. The nominal gaps between trucks for these tests

Fig. 11. Freightliner century truck tractor with PATH modifications for automation.

were 10, 8, 6, and 4 m and the gap accuracy was maintained within RMS errors of 22 cm between the first and second trucks and 25 cm between the second and third trucks [4].

PATH's third generation truck control system is a three-truck CACC system rather than a close-formation platoon, based on the desire of its sponsoring agency, the Federal Highway Administration, to have a system that would be suitable for public deployment in mixed traffic on a very short time scale. This system is based on Volvo's existing truck ACC system using a 77 GHz radar sensor, augmented with the data received over the 802.11p DSRC radio to provide enhanced string stability, faster responses and shorter gap settings than the production ACC [25].

IV. Impacts of Platooning

Platooning can contribute to energy saving in three ways: one is the reduction of aerodynamic drag especially during high speed driving, the second is the smoothing of traffic flow transients and the third is the increase of road capacity to provide more room for surrounding traffic. The former two are microscopic contributions, and the latter is a macroscopic contribution.

The energy savings from platooning can be predicted in several ways, and it can be complicated to compare the different predictions. Theoretical studies of fluid dynamics can estimate drag reductions for simplified representations of truck shapes at different separation distances. Experiments in wind tunnels or on test tracks can measure the changes in aerodynamic drag when trucks are driven at different separation distances. Finally, traffic simulations can take these estimates of energy savings on individual trucks or platoons and combine them with estimates of energy consumption by other vehicles to produce aggregate estimates of energy savings in all traffic.

Within the project "Energy ITS," the fuel consumption was measured during experiments on a test track under the conditions that the velocity was constant at 80 km/h, the gap was between

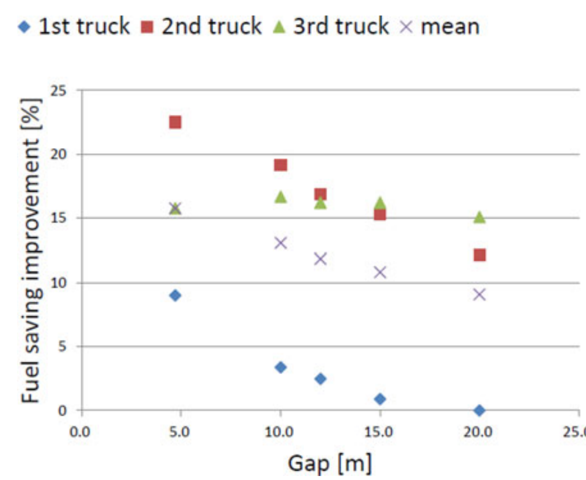

Fig. 12. Relationship between the fuel saving improvement and the gaps within the platoon for Energy ITS.

4 m and 20 m, and the trucks were empty. Fig. 12 shows the results. The measurements indicate an average 13% energy saving at a 10 m gap and 18% saving at a 4.7 m gap. When the trucks are ordinarily loaded and drive at 80 km/h, the average fuel saving will be 8% at a 10 m gap, and 15% at a 4 m gap.

The other theme of the Energy ITS project (in addition to the automated truck platooning introduced here) is to develop an evaluation method for estimating the effectiveness of a wide range of ITS alternatives on CO_2 emission reduction. Therefore a simulation study was conducted to evaluate the effectiveness of platooning regarding the macroscopic aspect. The results showed that, for example, when 40% of the heavy trucks on expressways drive within a platoon, the total CO_2 reduction along expressways will be 2.1% when the gap is 10 m and 4.8% when the gap is 4 m [26].

PATH made direct measurements of the fuel saving potential of truck platooning on its first and second generation truck platoon systems. The first-generation experiments were conducted

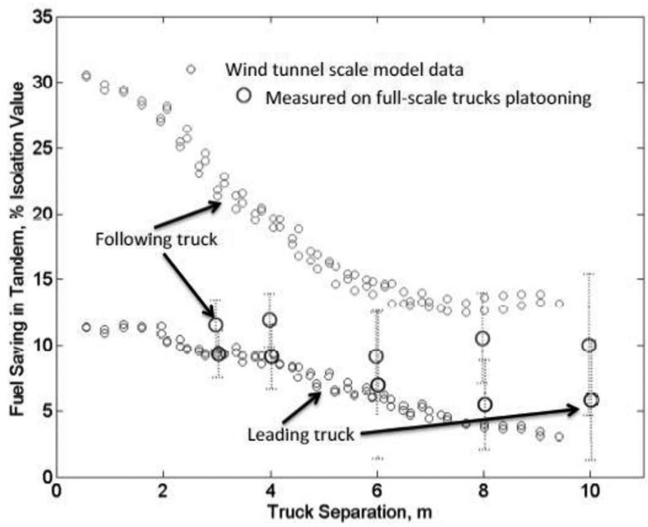

Fig. 13. PATH measurements of fuel savings by operating two trucks in platoon rather than independently, based on field tests of full-scale trucks and wind tunnel tests on scale model trucks [27].

in 2003 under more carefully controlled conditions, with less ambient wind, and with better lateral alignment between the trucks. The fuel consumption was measured during steady-state driving at a speed of 90 km/h (55 mph) with the trucks in the platoon configuration and then compared to the same trucks driving individually [27]. These results are plotted as the open circles in Fig. 13, showing savings in the range of 5% to 10% for the front truck and 10% to 15% for the following truck. Measurements of criteria emissions were also made during these test runs, but those results were so noisy that they did not show clear patterns, and the emissions measurement trailer, with its open back end and large engine to power its equipment, introduced some distortions into the patterns of air flow. Fig. 13 also shows measurements of fuel savings derived from wind-tunnel tests on scale models of trucks (the small circles on the plot) [27]. Those results extend to significantly shorter gaps since they were static, and they show larger potential energy savings because the simplified scale models represented a cab-over-engine configuration, in which the tractor is 3 m shorter and the trailers are therefore 3 m closer together for the same gap between the front of the following tractor and the rear of the preceding trailer.

In 2010 and 2011 PATH made further measurements of energy consumption with a three-truck platoon, but the results were less clear-cut than from the first set of experiments for several reasons [4]. Firstly, the ambient weather conditions during the testing period included higher wind speeds, adding disturbances to the air flow around the trucks and reducing the "drafting" effect of the close-formation platoon. Secondly, the DSRC radios used for these tests were not able to take advantage of "diversity," using the antennas on both sides of the trucks. With only one antenna being usable on each truck, the middle truck blocked wireless transmissions between the first and last truck when they were completely aligned with each other. This necessitated driving with the middle truck at a lateral offset of about 30 cm to ensure line of sight for all the antennas. That meant that the middle truck was not as well shielded by the front truck as it would have been with perfect alignment, but the third truck

TABLE III
REDUCTION OF FUEL CONSUMPTION BASED ON THEORY, SIMULATION AND TEST (FOR 14 TON AND 28 TON TRUCKS)

Fuel consumption	Theoretical [29]	Simulation by Daimler [29]	Measurement by Daimler [29]	Simulation with PELOPS [28] by KONVOI [30]
1st vehicle	2.17% (14 t) 1.64% (28 t)	2% (28 t)	6% (14 t)	2% (14 t)
2nd vehicle	38.1% (14 t) 28.8% (28 t)	19% (28 t)	21% (28 t)	11% (28 t)

was better shielded by both preceding trucks. Consequently, the measured energy savings need to be interpreted with caution. These showed that when driven at a 6 m gap and a speed of 85 km/h (53 mph), on average the first truck saved 4.3% of its energy, while the second truck saved 10% and the third truck saved 13–14.5%. In a well-aligned driving configuration we should expect the middle truck to save more and the last truck to save less than we measured here. These tests were conducted at an altitude of 1800 m, where the air density is only 80% of the density at sea level. If the same tests had been done at sea level and a speed of 115 km/h (71 mph), which is typical for long-haul trucking in the U.S., the energy savings would have been about 50% larger than what was measured in these tests.

Several simulations and measurements have shown that the theoretical predictions of energy savings cannot be achieved in practice and the speed variations in normal traffic lead to less energy savings than measured in constant-speed tests (see Table III, columns 1–3).

On account of this further simulation work was performed in the KONVOI project using the software PELOPS, which takes into account the three relevant elements of traffic—route/environment, driver and vehicle—and their interaction [28] and therefore produces more realistic values. With the aid of traffic flow simulations in PELOPS the fuel consumption reduction of the leading and the following vehicles was analyzed using the same settings as in [29]. Under conservative assumptions the fuel consumption saving for truck platoons is implied to be 2% for the 1st truck and 11% for the 2nd (see Table III column 4 [30].

These results all show the advantages of smaller gaps between the trucks for saving energy. The separate projects used different technical approaches and assumed different operating environments, leading to different gap sizes for their experiments. Shorter gaps are possible with higher performance sensors and longitudinal control systems and faster communication updates. Furthermore, if the trucks can be separated from other road users and operate in their own dedicated lanes they can avoid the need to respond to the erratic behaviors of the other drivers and can therefore safely operate at shorter gaps than if they need to mix with other road users.

V. Issues Impeding Introduction of Automated Truck Platoons

There are some issues that could impede the introduction of automated truck platoons, in addition to location-specific legal and institutional issues.

One of the issues is requirements on the reliability and the mean time between failures (MTBF) of the devices and systems for automated driving. MTBF of human drivers is usually extremely long, indicating high reliability. Current Japanese traffic accident statistics show that the fatalities and the injuries per 100 M vehicle-km are about 0.6 and about 113, (in 2012). In other words, assuming that a human driver drives 24 hours a day, 7 days a week at 30 km/h, MTBF by human drivers is more than 500 years between fatalities and more than 3 years between injuries. The safety statistics for other industrialized countries are within the same general order of magnitude but will differ by some factors. However, when a human driver is asleep or distracted, the MTBF will become on the order of seconds or minutes. This is the reason why driver assistance systems and automated driving systems could improve safety. If a driving automation system is designed to be used in combination with the driver, its vigilance can augment the vigilance of the driver, and the combined system (driver and driver assistance system) can gain the benefit of parallel reliability. In this case, an assistance system can improve driving safety even if it does not have as long an MTBF as an average human driver. However, if the automation system is intended to completely replace the driver it becomes fully responsible for safety and it needs to be designed with a longer MTBF than the average human driver (a very severe technical challenge).

In order to investigate the reliability of the automation devices and systems, long term field testing will be necessary. One possible method of acquiring large amounts of test data without compromising safety is to equip test trucks with the full complement of equipment needed for automated driving and comprehensive data acquisition systems, but have them actually driven by highly skilled drivers. The data acquisition systems can record the actions that would have been taken by the automated system and the actions that were actually taken by the drivers for comparison after the fact to develop improvements in the automation software.

The ability to transition from manual to automated driving depends on the capabilities of sensing devices and the quality of the objects they are detecting. If a lane tracking system cannot detect the lane markers, transition to automated driving should be prohibited. Similarly, the ability to transition from automated to manual driving will depend on ensuring the vigilance of the driver and his or her ability to resume control.

VI. Conclusion

This paper has reviewed the results of projects on automated truck platoons on three continents. The automated truck platoons and their configurations, sensing and control systems, experiments, and the effectiveness at energy saving have been introduced and the energy savings results have been shown to be quite consistent across the separate projects. In addition to the general objectives of automated driving to improve traffic safety and reduce congestion, truck automation could potentially, in the long term, reduce the personnel costs that are particular to the trucking industry. It is also worth noting that the introduction of platooning or CACC to trucks is easier than to passenger cars, because the direct economic incentives to the truck operators from energy savings can produce a much faster return on investment. The results of the experiments on platooning by the three projects that were reviewed show consistently that fuel consumption can be reduced, and it will make the implementation of the automation equipment economically practicable, particularly considering that the equipment costs for basic truck platooning (vehicle following only) are simply the cost of ACC plus the V2V communication system. Thus, truck automation including CACC has a possibility of near future introduction to public roadways and highways, after the location-specific legal and institutional issues are resolved.

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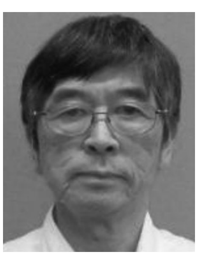

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