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# Influences on Energy Savings of Heavy Trucks Using Cooperative Adaptive Cruise Control

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## Abstract

An integrated adaptive cruise control (ACC) and cooperative ACC (CACC) was implemented and tested on three heavy-duty tractor-trailer trucks on a closed test track. The first truck was always in ACC mode, and the followers were in CACC mode using wireless vehicle-vehicle communication to augment their radar sensor data to enable safe and accurate vehicle following at short gaps. The fuel consumption for each truck in the CACC string was measured using the SAE J1321 procedure while travelling at 65 mph and loaded to a gross weight of 65,000 lb, demonstrating the effects of: inter-vehicle gaps (ranging from 3.0 s or 87 m to 0.14 s or 4 m, covering a much wider range than previously reported tests), cut-in and cut-out maneuvers by other vehicles, speed variations, the use of mismatched vehicles (standard trailers mixed with aerodynamic trailers with boat tails and side skirts), and the presence of a passenger vehicle ahead of the platoon.

The results showed that energy savings generally increased in a non-linear fashion as the gap was reduced. The middle truck saved the most fuel at gaps shorter than 12 m and the trailing truck saved the most at longer gaps, while lead truck saved the least at all gaps. The cut-in and cut-out maneuvers had only a marginal effect on fuel consumption even when repeated every two miles. The presence of passenger-vehicle traffic had a measurable impact. The fuel-consumption savings on the curves was less than on the straight sections.

## Keywords

adaptive cruise control (ACC), cooperative ACC (CACC), heavy-duty truck platooning, heavy-duty truck partial automation, vehicle control performance, heavy-duty truck fuel economy

## Introduction

Cruise Control (CC) has been in use for several decades for automated vehicle control to assist the driver with speed regulation without distance control. The driver remains responsible to maintain a safe distance with respect to any forward vehicles. Adaptive Cruise Control (ACC) uses a radar or lidar (laser radar), and sometimes with the addition of a video camera, to add relative distance and relative speed control. Some passenger cars and heavy-duty trucks are currently equipped with this capability. The main problem for ACC is that if three or more ACC vehicles are driven consecutively, the system is string unstable [1]. A string of ACC vehicles on highways is less stable than a string of manually driven vehicles because the forward ranging sensors lack the ability to perceive the actions of vehicles ahead of the immediately preceding vehicle. The larger and larger cumulative delays with the addition of greater numbers of vehicles to the string increases the unstable behavior. To solve this problem, cooperative ACC (or CACC) with V2V (vehicle-to-vehicle wireless communication) is a possible solution. With CACC, the simultaneous wireless communications broadcast from the lead vehicle to all the followers effectively removes the cumulative delay problem while the delay associated with the V2V communication is sufficiently small that it can be ignored.

In practice, the first vehicle of a CACC string can use ACC mode to follow other manually-driven vehicles in public traffic, or it can be driven manually. There are no special responsibilities or authority required for this leading vehicle or its driver. The second vehicle, and any subsequent vehicles, will be in CACC mode, assuming wireless communication is maintained and if there are no inter-vehicle cut-ins by other road vehicles. Ad-hoc joining and leaving by vehicles, when their drivers choose to do so, is accommodated without the need to request permission. A CACC string is controlled based on a constant time gap, similar to human drivers, which differs from the constant-distance following used in closely-coupled platoon systems.

ACC and CACC have the same control structure: an upper level control that is based on the kinematic relationship from the desired distance and speed to the desired acceleration/deceleration, and a lower level control is from the desired acceleration/deceleration to the desired engine/braking torque. The feedback-control design needs to guarantee fast response and stability for each individual vehicle and to maintain *practical* string stability (to be defined later) as a whole CACC string. The concept is designed to co-exist with conventionally-driven vehicles without requiring physical segregation from other traffic. The control system on each vehicle therefore also needs to handle interactions with other vehicles such as following other manually-driven vehicles, and responding to cut-in and cut-out maneuvers between the CACC vehicles.

An automated vehicle following a vehicle that lacks V2V communication capability can operate in ACC mode. An integrated ACC and CACC design is advantageous, as initially proposed by Lu et al. [2]. The pioneering CACC developed and implemented on four passenger cars, and field tested in public traffic, was presented by Milanés et al. [3]. The CACC was shown to have faster response and smaller speed and distance tracking errors than ACC control for the trailing vehicles. Follow-on work on modeling and simulation by Milanés and Shladover [4] indicated that a simple model representing a first-order lag response can be used to approximate the feedback loop of CACC.

The CACC concept has been applied to a set of three heavy-duty vehicles, forming the basis for the current work. Results from a separate closed-track fuel-economy test of this three-truck CACC system have been previously reported [5]. In that work, the minimum separation time tested was 0.6 s that corresponds to a separation distance of 17.4 m at the speed of 105 km/h (65 mph). A second set of closed-track fuel-economy tests have been undertaken, forming the basis for the current paper. For this second test campaign, the shortest time gap tested was 0.14 s corresponding to a distance gap of 4 m.

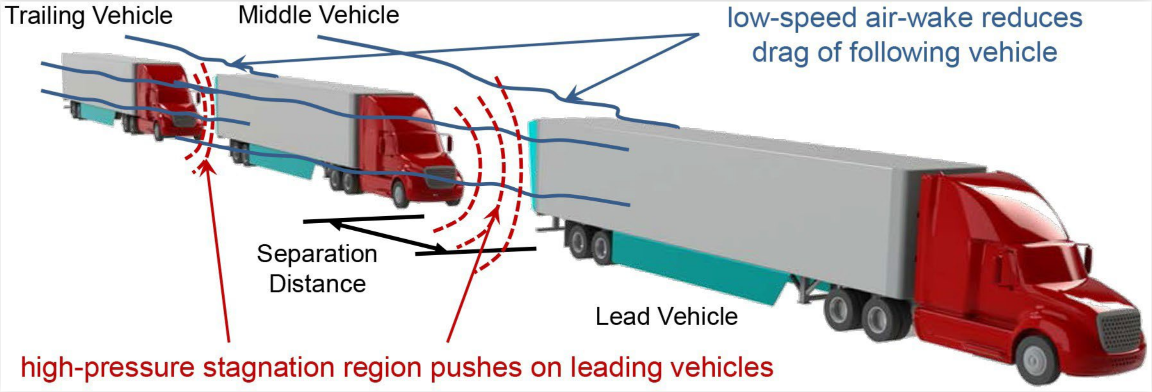
## Upper Level Control

The ACC and CACC feedback control share the same longitudinal control structure, which has been used by the CACC developers for many years [6, 7]. The upper level control is based on linear kinematics from distance and speed tracking errors to desired acceleration. The linear model is independent of vehicle type and size, and therefore many legacy or complex control design methods can be re-used and easily implemented. The inputs for upper level control are speed and acceleration of the lead vehicle and the immediately preceding vehicle, and distance measured to the preceding vehicle by remote sensors such as radar or lidar, that may be fused with video. The main control task has three aspects: (a) to track a synthetic speed of the lead and preceding vehicle and to maintain a proper distance to the preceding vehicle; (b) to maintain robust stability of the feedback control for speed tracking and distance tracking for (a); and (c) to render the overall system *practically* string stable in the following sense: for any external disturbances or uncertainty from the road, for any measurement errors from the sensor, for temporary communication packet drops, or for delays from the sensors and the control actuator, the overall system including all trucks in the CACC string needs to be robustly stable; and the robustness bandwidth must be sufficiently high to handle other vehicles cutting in and cutting out between any trucks in the CACC string.

## Lower Level Control

The lower level control maps the desired acceleration/deceleration to the desired net engine torque or braking torque. This implicitly requires that the engine torque be commanded through the CAN Bus. This control execution requires a functional relationship which consists essentially of an inverted-vehicle-driveline-dynamics model in the following sequence: wheel acceleration ⇒ driveshaft torque ⇒ final driving gear ⇒ propeller shaft ⇒ differential ⇒ transmission (gear box) ⇒ engine output shaft (as shown in Figure 1 of Lu and Shladover [7]). The braking torque is shared by the engine and foundation (pneumatic or service) brakes. The physical principle of the engine brake, or engine retarder, is to use the

**FIGURE 1** Schematic of a three-vehicle HDV platoon



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compression stroke without fueling to generate a braking torque, which has a much faster response than the service brake. Engine braking tends to have lower braking torque as the engine speed decreases. Therefore the engine brake is used for vehicle following most of the time. The foundation brake is used instead for emergency situations or stopping, which requires a high level of braking torque.

This lower-level control required detailed modeling of the driveline dynamics, and generally requires information from the vehicle manufacturer. If the non-linear relationship between the desired acceleration and the desired torque is known, the control design uses a *feedback linearization* approach.

One of the differences between the control strategies employed by ACC/CACC and platooning is in the vehicle-following definition. ACC/CACC uses a constant time gap that is inherited from common human driver behavior. Platooning uses a constant distance gap. Under constant-speed testing, as was undertaken for most of the fuel-economy tested described in this paper, time gap control is consistent with distance gap control from the perspective of energy savings due to aerodynamic drag reduction, as describe in the following section. However, for other maneuvers such as adapting to vehicle cutins and cut-outs, or speed variations, the distance gap changes as the vehicle speeds change.

## Energy Savings

A potential benefit of ACC/CACC and platooning is the energy savings that are possible for scenarios in which the multiple vehicles can safely travel in close proximity. This has been previously highlighted by numerous studies investigating the potential benefits of truck platooning, many of which were evaluated using constant-speed testing and are therefore equivalent to the CACC scenarios tested in the current work. Therefore, the physics associated with the energy savings of these two concepts is largely the same. The energy-savings discussions throughout this paper will interchangeably use the terms platooning and CACC to describe the energy savings of these systems. Based on previous investigations, the fuel savings associated with vehicle platooning and close-proximity driving has been attributed to an aerodynamic influence.

Wind-tunnel studies [8, 9, 10] and track-based fuel-economy studies [11, 12, 13, 14, 15, 16, 17, 18, 5, 19] have identified trends in aerodynamic drag reduction associated with vehicles in close proximity and linked them to the resulting fuel savings, whereas computational studies [20, 21, 22, 23, 24, 25, 17, 26, 27] have provided the insight on the aerodynamic mechanisms that lead to these beneficial effects. McAuliffe et al. [5] provide a literature survey of aerodynamic and fuel-consumption studies pertinent to truck platooning, from which it has been inferred that there are two dominant aerodynamic phenomena that lead to reduced drag and fuel consumption. Figure 1 identifies these drag-reduction mechanisms. The air-wake shed from a leading vehicle provides a region of lower airspeed, relative to the following vehicle, that results in lower aerodynamic drag over the front surfaces of the trailing vehicle. As a vehicle propels itself through the air, a region of high pressure is generated over its front surface due to stagnation of air over these areas, with a corresponding increase in static air pressure. This high-pressure region emanates forward of the vehicle and, when sufficiently close to another vehicle, increases the base pressure on the forward vehicle, essentially giving it a push. As highlighted by the literature survey of McAuliffe et al. [5], the magnitude of these two effects are influenced by the separation distance, the truck configuration, and the operational environment in which the vehicles are evaluated.

In the first phase of fuel-economy testing of the current CACC system, testing was performed for various three-truck platoon configurations, including different aerodynamic trailer configurations (conventional dry-van trailers and trailers outfitted with side-skirts and boat-tails), for various separation distances (17 m up to 43 m), for speeds of 89 km/h and 105 km/h, and for vehicle masses of 14,000 kg and 29,400 kg. Results of the fuel economy testing showed that, for the range of test conditions examined, the net fuel savings for the full vehicle platoon was measured to be between 5% and 8% compared to three vehicles travelling independently, and in isolation, from of each other. The greatest fuel savings were achieved at the shortest distance of 17 m. The aerodynamic trailer configuration experienced a greater fuel savings than the standard trailer, consistent with the computation study by Ellis *et al.* [24] for near-identical truck configurations. At all separation distances tested (17 m to 43 m), the trailing vehicles experienced the greatest fuel savings of the three vehicles, which is consistent with the three-truck-platoon study of Tsugawa et al. [16] at these separation distances. For the conditions tested by McAuliffe et al. [5], speed showed no appreciable effect on the percentage fuel savings, whereas weight reduction improved the percentage fuel savings.

To date, most investigation have focused on the influence of separation distance, with some studies evaluating vehicle configuration, weight and speed. The *Test Plan* section of this paper identifies the specific investigations undertaken as part of the current work and how they each expand on the current body of knowledge surrounding the potential energy savings of cooperative heavy-vehicle automation systems.

## Objectives of the Current Work

V2V-based cooperative heavy-vehicle systems are nearing commercialization. However, there is a knowledge gap in terms of the reliability and resiliency of these systems. Further testing and evaluation is required to help qualify and quantify their overall operational, safety, energy use, and environmental performance. Of particular interest in the current study is the potential energy savings of such system.

It is important to understand the energy saving benefits that can be achieved from operation of heavy trucks at smaller than normal separation gaps for multiple reasons:

- To provide decision makers in the truck manufacturing industry and their customers in the goods hauling industry with authoritative data to support economic assessments of the benefits that they can gain from reducing their fuel costs, so they can make well-informed decisions about investing in the technology;

- To provide public policy decision makers with information about the energy saving potential from truck platooning so that they can decide what incentives to offer to encourage its adoption by industry, particularly relative to other energy saving strategies; and
- To provide more fundamental understanding of the mechanisms of aerodynamic drag reductions associated with truck strings or platoons so that the best strategies can be developed and trade-offs can be assessed among different design alternatives (such as gap selection).

## Cooperative Adaptive Cruise Control System

The overall system structure and components of the CACC are depicted in Figures 2 and 3. The implementation of the CACC system has the following components:

- A central control computer (labelled as PC-104) that is an industrial-grade computer running the QNX real-time operating system. It is the interface for all the components connected to it. It reads all the onboard sensor data from the J-1939 Bus, receives information from other vehicles through Dedicated Short Range Communication (DSRC), calculates control commands (engine torque control, engine brake control, service brake control), detects and handles system faults, and sends the commands through the J-1939 bus for execution. It also logs all the necessary data for debugging and analysis.

**FIGURE 2** CACC components.

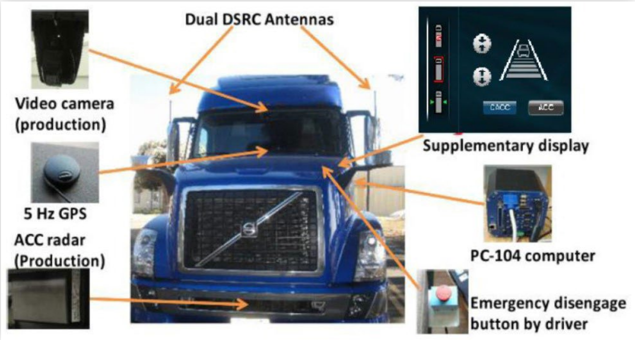

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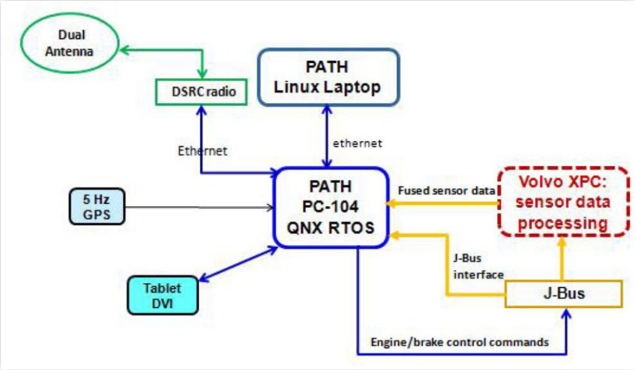
**FIGURE 3** CACC structure.



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- Radar and video camera data are fused for front target detection and tracking.
- DSRC-based V2V communication system: The inter-vehicle communication is achieved by using 5.9 GHz wireless for 2-way communication. Antennas mounted on top of both side mirrors guarantee line-of-sight communications even if any of the trucks was turning.
- A laptop computer with Linux as the real-time operating system for running high level scripts for process schedule handling of the central control computer for system development, debugging, and testing.
- An emergency switch that will cut off the physical connection between the PC-104 computer and the J-1939 Bus to force the system back to manual control.
- A driver-vehicle interface display using a touch-screen tablet was developed for the tests. It displayed necessary information to the driver such as the total number of vehicles in the platoon, relative position of the vehicle in the platoon, DSRC status, driving mode of each vehicle (manual, ACC or CACC), service brake use status, and actual time gap used. It also allowed the driver to select drive mode (ACC or CACC) and their corresponding time gaps.
- A 5 Hz GPS unit was used to assess the health of the DSRC signal independently of the inter-vehicle difference. This information was used in cases such as the detection of other vehicle cut-in situations.

## Test Plan

Track testing was undertaken using the SAE J1321 Type II Fuel Economy procedure [28] to investigate the fuel-savings potential of the three-truck CACC system. This test program was conducted to supplement a previous test program using the same system [5]. The following sections describe test configurations and conditions and the motivation for testing.

### Vehicle Configuration

The previous fuel-economy testing with the CACC system examined the effect of vehicle speed (89 and 105 km/h, or 55 and 65 mph), cargo weight (empty and 15,400 kg / 34,000 lb load), and trailer aerodynamics (standard compared to side-skirts and a boat-tail) on the potential fuel-savings benefits from platooning. It was therefore decided to use one configuration for the majority of testing, with the following representing the baseline configuration:

- Vehicle speed of 105 km/h (65 mph)
- Vehicle total mass of 29,500 km (weight of 65,000 lb)

- Same trailer make and model
- Trailers outfitted with side-skirts and a boat-tail (same make and models as previous test campaign)

This combination of vehicle speed and weight have also been used in some two-truck track-based platooning studies [15, 19], and thus provides cases for comparison. With the recent implementation of greenhouse-gas regulations for trailers in the U.S. [29], and similar regulations proposed for Canada [30], trailer aerodynamic devices such as side-skirts and boat-tails are expected to become common equipment on dry-van trailers over the next decade, providing justification that this aerodynamic trailer configuration is an appropriate baseline configuration for testing.

For the testing conditions described in the following, the vehicle speed, weight, and trailer configuration represent those listed above, unless otherwise noted.

## Reference Test Conditions

The SAE J1321 fuel-economy test procedure requires reference runs to be conducted to assess the relationship of the fuel use of the test vehicles to that of the control vehicle under baseline conditions representing the vehicles in isolation [28]. Eight such measurement runs were conducted throughout the test program to continually monitor the consistency of the test-to-control-vehicle fuel consumption relationship.

## Repeatability Measurements

Three of the test cases from the previous test campaign [5] were repeated as a verification exercise. Separation distances of 17.4 m, 34.9 m, and 43.6 m were re-tested (time gaps of 0.6 s, 1.2 s, and 1.5 s), covering the full range of separation distances previously tested with this CACC system. The intermediate separation distance of 34.5 m was re-tested as a reference case for some of the platoon variations discussed later.

## Shorter Separation Distances

Based on other truck platooning studies described in the literature [15, 16, 17], the CACC system was expected to experience greater levels of overall fuel savings at shorter distances than were previously tested with this system (previous minimum was 17.4 m). In particular, it was recognized that distances shorter than 17 m were likely required for the lead truck to experience a fuel savings. It is unclear, however, whether the trailing vehicle would experience increased or decreased fuel savings at shorter distances, as the published literature has not demonstrated consistent findings, as highlighted by the NACFE study [18]. The three-truck string/platoon was tested at closer distances of 4 m, 6 m, 9 m, and 12 m, representing time gaps at 105 km/h of 0.14 s, 0.21 s, 0.31 s, and 0.41 s, respectively.

## Longer Separation Distances

The longest separation distance tested previously with the three-truck CACC system (43.6 m at 105 km/h) showed significant fuel savings for the middle and trailing vehicles (6-10%), with a low decay rate with distance indicating the possibility for measurable fuel savings at much larger distances representative of typical non-platoon highway traffic conditions. A computational study by Humphreys and Bevly [17] demonstrated reduced aerodynamic drag for the trailing vehicle of a two-truck platoon at distances up to 152 m. It was therefore decided to undertake testing at larger separation distances of 58.1 m and 87.2 m, corresponding to time gaps of 2.0 s and 3.0 s at 105 km/h to characterize what vehicles may already be experiencing on the road.

## Comparison with Two-Truck Strings or Platoons

The recent NACFE confidence report on two-truck platooning [18] summarized fuel-economy test results of predominantly two-truck platoons. The variability in vehicle configurations and test conditions across the various test campaigns that they compared demonstrates significant uncertainty in the potential benefits between a two-truck versus three-truck string or platoon. To understand these potential differences, and provide a link to these large data sets of two-truck test data, four separation distances of 6 m, 12 m, 17 m and 58 m were tested with only two trucks in the CACC string, corresponding to time gaps at 105 km/h of 0.21 s, 0.41 s, 0.6 s, and 2.0 s, respectively.

## Contrast Platooning to Long Combination Vehicles

An important goal of platooning is to improve the efficiency and cost of long-haul freight delivery, not just to improve fuel efficiency. For a given payload, the net fuel efficiency of a platoon is improved compared to multiple vehicles driving in isolation. Another option to improve fuel and freight efficiency is to use long combination vehicles (LCV) whereby one tractor pulls multiple trailers, which has been described as having greater benefits in regards to freight efficiency [25, 31]. Fuel-economy tests of an LCV consisting of two 53-ft dry-van trailers, each with the same cargo weight as in each of the platoon trailers, were conducted to contrast the fuel savings of the two methods against two isolated single vehicles.

## Mismatched Trailers

The previous test program of the three-truck CACC system documented an improvement in the fuel-savings benefits up to 2% for trucks with aerodynamic trailer devices (trailer side-skirts and boat-tails) as compared to the CACC fuel savings when using the standard trailer [5]. Those previous tests were conducted with all three vehicles configured identically. On-road string or platooning scenarios will likely consist of combinations of differently-configured vehicles. To evaluate some of the potential variability in fuel savings due to strings or platoons of differently-configured vehicles, tests were conducted with the side-skirts and boat-tail removed from a single vehicle in the platoon.

## Speed Variations

Previous test programs have evaluated the influence of vehicle speed on string/platoon fuel savings, with differing results. The study of Bonnet and Fritz [11] using straight trucks demonstrated up to 5% difference in fuel savings between speeds of 60 and 80 km/h whereas more recent studies of class 8 tractor-trailer combinations [15, 5], which include the previous three-truck CACC test, have identified small differences in % fuel savings between speeds of 89 km/h and 105 km/h (55 and 65 mph) that are generally within the experimental uncertainty. Changes in speed will likely be encountered in real traffic scenarios that may lead to energy losses in the system due to frequent reaccelerations to the higher speed.

Data are presented for speed variations between 89 km/h and 105 km/h (55 and 65 mph) for the three-truck CACC system at a time gap of 1.2 s, representing a separation distance of 34.9 m at 105 km/h and of 29.5 m at 89 km/h. The change in separation distance with speed is due to the time-gap control nature of the CACC. The speed was changed every 100 seconds, with 30 to 40 seconds of constant speed travel before commencing an acceleration or deceleration phase. A set of reference runs were also performed whereby the vehicles performed the same periodic speed profile with the trucks spaced sufficiently far from each other (quarter track length) to consider them isolated.

## Travelling with Other Traffic

To put into context the fuel savings benefits of truck platooning, it is important to understand the fuel use of these vehicles on the road. With previous platooning test results identifying aerodynamic benefits and potential fuel savings for trailing vehicles at separation distances of multiple vehicle lengths (in excess of 50 m), the question arises as to whether trucks are already experiencing fuel savings from following other traffic. The work of Smith et al. [23] performed measurements indicating that in excess of 50% of the distance driven by long haul operations may operate in wake effects from other vehicles, whereas as the study by NREL [32] estimates 2% of travel distance of one typical fleet operation may benefit from “platooning” with other traffic based on encounters with a target vehicle within 300 ft while traveling at speeds over 60 mph.

To investigate the potential fuel-savings experienced from operating in the wake of other traffic, tests were conducted with combinations of a either a single truck, a two-truck string, or a three-truck string following an SUV.

It was also desired to understand how much of a penalty on fuel consumption is associated with vehicle cut-ins. Four sets of test runs were performed using a large SUV to perform periodic cut-ins between the trucks. All cut-in tests were performed using a baseline CACC configuration with a time-gap of 1.2 s (35 m separation distance at 105 km/h).

For each one-hour run, 30 cut-ins were performed at one of the CACC gaps (between lead and middle vehicle or between the middle and trailing vehicle). The cut-in vehicle remained in place between the trucks for about 25 to 28 s, during which time the truck following the cut-in vehicle adjusted its position to follow the SUV with a 1.2 s time gap. When the SUV exited the string, the CACC re-established its 1.2 s time gap between trucks. For each of the two cut-in locations, the same controller was used, which would automatically respond to different cut-in locations for representing gentle and aggressive control strategies. In general, shorter cut-in distance (more aggressive) with respect to the subject vehicle would lead to faster response.

# Test Setup and Procedures

## Test Vehicles

Four tractor-trailer combinations were used as part of the fueleconomy tests. Figure 4 shows the test trucks.

The control tractor differed from the test tractors, but used the same trailer specification. The use of different tractor models for the test and control vehicles does not strictly conform to the SAE J1321 requirements [28] which specifies identical vehicles are to be used, although both are aerodynamically-treated tractors with similar engine specifications that were expected to behave similarly in the controlled conditions of the tests. During testing, the test vehicles used about 2% more fuel than the control vehicle when not in platoon formation.

Each tractor was equipped with a boom for mounting a wind-speed sensor forward of the vehicle, as seen in Figure 4. These wind-speed measurements are not discussed as part of the fuel economy tests described herein.

The trailers were ballasted using concrete blocks aligned evenly along the centreline of the trailer, and fuel in the main tanks of the vehicles was adjusted to match the target vehicle weight for testing (29,500 kg / 65,000 lb).

For a majority of the tests conducted, the trailers were outfitted with two commercial aerodynamic technologies: side-skirts (shown in Figure 4) and a boat-tail (shown in Figure 5).

A converter dolly was used to connect two trailers for the long-combination-vehicle tests, as shown in Figure 6. For this arrangement, both trailers were ballasted to the same level. Side-skirts were installed on both trailers, with a boat-tail installed on the aft trailer.

**FIGURE 4** Photograph of CACC test trucks parked during fuel-weighing procedure.

**FIGURE 5** Boat-tail installed on test trailer.

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**FIGURE 6** Long-combination vehicle test arrangement.

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**FIGURE 7** Mid-size SUV for “other traffic” and “cut-in” testing, shown leading 3-truck string with a 58 m separation distance to the lead truck (separation distance of 12 m between trucks).

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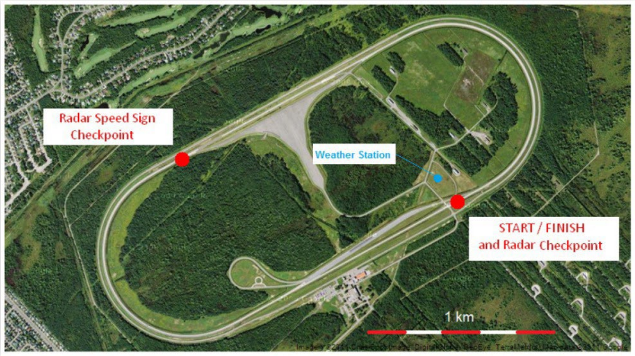
Testing with other traffic in proximity to the trucks was undertaken using a mid-size SUV, shown in Figure 7. The SUV was not instrumented for testing.

## Fuel Consumption Test Procedure

Testing took place at Transport Canada’s Motor Vehicle Test Centre (MVTC) in Blainville, Quebec, which is operated by PMG Technologies. The fuel consumption tests were performed on the high-speed test track (BRAVO) [33]. The track is a highbanked, parabolic oval with a length of 6.4 km (4 miles). Figure 8 presents the test site.

**FIGURE 8** Map of test track with radar checkpoints and weather station location.



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The test procedure was based on the SAE J1321 Fuel Consumption Test Procedure [28]. The series of tests compared the fuel consumption of vehicles operating under different conditions (test vehicles) with that of an unmodified vehicle (control vehicle). Fuel consumption was accurately measured by weighing portable tanks before and after each trip.

Figure 9 shows the installation of the portable tanks on a vehicle. The trailer ballast weights remained the same throughout the entire test period. The vehicles were in good working condition, with all settings adjusted to the manufacturers’ specifications.

The test consisted of a baseline segment (“infinite” distance between the vehicles on track) followed by several test segments (various distances between the test vehicles). For all segments, the representative results were the ratio between the average fuel consumed by the test vehicle and the average fuel consumed by the control vehicle (the T/C ratio).

The nominal values for fuel savings were determined from the analysis of the measured fuel data, and reflect the changes resulting from the modification being tested. These nominal fuel-savings values consisted of the percentage difference

**FIGURE 9** Installation of the portable fuel tanks.

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between the average of the baseline-run ratios $\left(\overline{(T/C)_{baseline}}\right)$ and the average of the test-run ratios $\left(\overline{(T/C)_{test}}\right)$:

$$\Delta F = \frac{\overline{(T/C)_{baseline}} - \overline{(T/C)_{test}}}{\overline{(T/C)_{baseline}}} \qquad (1)$$

Total platoon fuel savings was calculated using the same calculation of Equation 1, but with the combined total fuel weights from the three test vehicles for each *T*/*C* value.

The result was expressed for the confidence interval of 95%, complying with the SAE J1321 Fuel Consumption Test Procedure - Type II [28], and determined from the variation in the measured fuel consumption data relative to the nominal value and the number of data values obtained. For each test configuration, the fuel savings values of the individual vehicles were calculated based on data collected at the same time, and therefore represent simultaneous results, as do the total fuel savings values.

As described previously, the control tractor was not the same vehicle make or model as the test tractors, which introduces some uncertainty in the testing. Data collected during this and other test programs [15, 19, 5] have identified no measurable fuel savings for the lead vehicle for separation distances beyond about 20 m. For such cases, the lead vehicle is therefore experiencing conditions as if it was isolated from the other trucks, and can therefore be considered a "control vehicle" for the trailing trucks in the platoon arrangement. As a means of improving the quality of the measurements at these longer distances, fuel consumption data from the lead platoon vehicle has been used as the control data for the middle and trailing trucks at any test condition for which the separation distance was greater than 30 m (approximately 1 s time gap at 105 km/h). Using the lead truck as the control vehicle for these scenarios, calculated fuel-savings values of the middle and trailing trucks changed by no more than 1%, compared to using the control-truck data, but confidence intervals were reduced by up to 1%, therefore providing improved accuracy of the measurements. This procedure was not applied for "cut-in" or "other-traffic" test conditions where the SUV would be expected to influence the fuel savings of the lead vehicle. All lead-vehicle fuel-savings results presented herein were calculated using the control-vehicle fuel use as the control measure. When calculating the total platoon fuel savings for these cases, the lead-vehicle fuel weight is used in the combined fuel-weight value and as the control fuel-weight value, adding an assumption to the calculation that the lead vehicle experiences exactly 0% fuel savings.

To minimize measurement uncertainties, the only measured parameter used to calculate the test results was the weight of the portable tanks. Other parameters, such as vehicle speed, distance and time, were recorded for information purposes only. In order to avoid potential problems related to the instruments, two recently calibrated scales were available on-site. For each run, the portable tanks were weighed using the same calibrated scale that has a measurement uncertainty of 0.02 kg. Furthermore, the scale was periodically checked against a known weight of 120 kg . The scale was not moved between the initial and final weighing for a given test run.

Distance measurement was not a factor because for each run, all vehicles departed and arrived at the same point after travelling the same number of laps and following the same path along the track.

Ambient temperature, humidity, barometric pressure, and wind speed and direction were measured at the test site (location shown in Figure 8) and these data were verified using climate data from the Mirabel weather station, located 12 km from the test site.

## Fuel Consumption Driving Procedure

Each day, prior to testing, all vehicles were warmed up for the same amount of time (minimum one hour) at the test speed.

The drivers' influence on the results was minimized by conducting the tests on a closed circuit and by strictly controlling the driving cycle as follows:

- A fixed idling time was used.
- Drivers started with maximum acceleration.
- Drivers maintained a constant driving speed using the CC, ACC, or CACC.
- Drivers steered as close as possible to the painted line at the right side of the track, without touching it.
- After the established test duration was complete, drivers stopped using the cruise control at a designated point.
- During deceleration, drivers used only the service brakes.
- Once at the end point, the trucks idled before turning the engine off. All the vehicles in a test run idled for the same duration of time.

The time interval between two consecutive trucks, or platoon combinations, remained the same in order to avoid the wake effects caused by other trucks and to keep a constant distance between trucks on the test track. The driving cycle was controlled with two radars. A radar speed sign displayed the speed of the approaching vehicles using highly visible LEDs, and was checked by the test drivers at every lap. The other device was a radar gun, operated by test personnel, and placed on the opposite side on the track. Drivers received instructions by two-way radio, to ensure that the speed of the vehicles and the distance between the vehicles on the track remained constant. The duration of the runs was also checked periodically. The vehicles were instrumented with global positioning system (GPS) units, which were used to verify vehicle speed and distance.

## Results and Discussion

In the following presentation of the results, only pertinent data for the discussions are presented. The calculated fuel-savings values for each test vehicle of each test condition are provided in Appendix A. Unless otherwise noted, all results represent the vehicles travelling at 105 km/h (65 mph), with a total weight of 29,500 kg (65,000 lb), outfitted with trailer side-skirts and boattails.

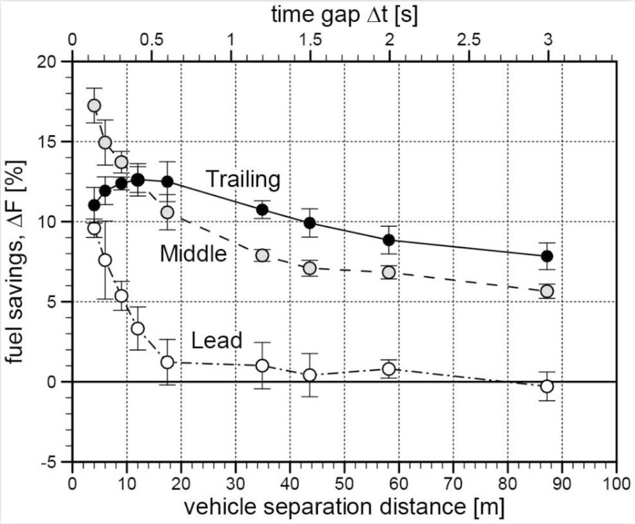
Repeatability of the setup and test procedures was verified by repeating three configurations of the three-truck CACC configuration from the previous test campaign [5]. For cases with separation distances longer than 30 m, the previous test data were re-evaluated using the lead vehicle as the control data set for consistency with the current analysis procedures. These data are also provided in Appendix A. Good agreement was found for all three vehicles at all three separation distances, with overlap of the confidence intervals for all fuel-savings values. These results serve as a validation that the three-truck platoon was behaving in a similar manner to the previous year's test campaign.

## Fuel Savings of a Three-Truck String or Platoon

A primary goal of the current test campaign was to perform fuel-economy testing of the three-truck platoon for longer and shorter separation distances than were evaluated in the first test program. Using the trailer configuration with aerodynamic treatments (side-skirts and boat-tails), the platoon was tested for separation distances as large as 87 m (3.0 s time gap) and as small as 4 m (0.14 s time gap). The fuel-savings measurements for the individual vehicles over this extended range are presented in Figure 10.

The lead truck experiences a significant increase in fuel savings as the separation distance is reduced below 15 m, reaching 10% fuel savings at 4 m separation distance. As will be discussed later, this is consistent with other studies. In accordance with the previous test campaign with the three-truck CACC [5], the lead vehicle has shown no measurable fuel savings at gaps beyond 20 m. The statistically-significant fuel savings of 0.8±0.6% measured at 58 m separation distance is assumed to be an anomalous measurement due to the differences between control and test vehicles, and the lead truck is not expected to consistently save fuel at this separation distance. This measurement therefore provides an estimate of the potential added uncertainty in the calculated fuel-savings measurements associated with the use of different tractors for the control and test vehicles.

**FIGURE 10** Individual-vehicle fuel-savings results for three-vehicle CACC tests (105 km/h vehicle speed, 29,500 kg vehicle mass).



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The middle truck demonstrated the highest fuel saving of all three vehicles at any separation distance, reaching 17% at a 4 m separation. The fuel savings for this vehicle decreased continuously with increasing separation distance, reaching its lowest fuel savings of 6% at 87 m separation.

The trailing vehicle demonstrates trends that differ from the lead and middle vehicles at the closest separation distances. The maximum fuel savings for the trailing vehicle was measured to be about 13% at the 12 m and 17 m separation distances. Below 12 m separation distance, the fuel savings of the trailing vehicle decreased as the distance is reduced, reaching a minimum value of 11% at 4 m. As will be discussed later, this trailing-vehicle trend is consistent with two-truck platoon studies as well. Beyond about 20 m, the trailing vehicle experiences decreased fuel savings with distance, in a similar manner as the middle vehicle, but with a 2% to 3% higher fuel savings. At 87 m separation distance, the trailing vehicle experienced 8% fuel savings.

At distances shorter than about 10 m, the middle vehicle demonstrated the highest fuel savings of the three vehicles, while beyond about 15 m the trailing vehicle experiences the highest fuel savings. At the 12 m separation-distance measurement, the middle and trailing truck experienced the same fuel savings. In a platooning study of three straight cab-over trucks, Tsugawa et al. [16] observed a cross-over in the magnitude of fuel savings between the middle and trailing vehicle in the range 12 to 15 m, similar to the current study.

Referring back to the introduction section in which the two dominant drag-reduction mechanisms were described (1 - lowspeed air wake, and 2 - stagnation-region push), the fuel-savings trends of the current study can be interpreted in an attempt to understand some of their characteristics. First, considering the lead vehicle, the lack of fuel savings beyond 20 m implies that the stagnation-region push effect is only experienced at separation distances below about 15 to 20 m. As explained with regards to the previous study of this three-truck CACC system [5], this implies that the middle vehicle will also not experience this effect from the trailing vehicle beyond distances of 20 m, and therefore the middle and trailing vehicles are only experiencing the low-speed air-wake effect for any separation distance beyond about 20 m. The higher fuel savings of the trailing vehicle is likely due to a compounding effect of the low-speed air-wakes of the lead and middle vehicles leading to a greater wind-speed deficit as experienced by the third vehicle.

The decrease in fuel savings of the trailing vehicle at the shortest distances (below 10 m) has yet to be fully understood. Some suggest that it may be due to additional power draw from the fans to compensate for the reduced flow rate through the front grille, but some studies have demonstrated this effect even without additional fan usage [15]. A computational study by Ellis et al. [24] of a three-vehicle platoon of nearly the same vehicles as those tested here, evaluated charge-air-cooler temperatures to identify when additional fan engagement may occur and concluded, based on data at 5 m and 9 m separation distances, that only at the closest separation distance of 5 m might the cooling system require additional fan usage. Data of fan usage, cooling flow rates, and engine bay temperatures have been acquired during the current study but are not discussed here, except to state the engine fan did not engage during testing so would not impact savings as with a previous study [15].

Some steady-flow computational studies have demonstrated that a lateral offset introduces a decrease in aerodynamic drag reduction at close distances, similar to the fuel-savings trend seen here, and suggested that this downturn may be due to a lateral wandering of the wake [26]. A small-scale wind-tunnel study [10] has also noted this effect below an equivalent of 10 to 20 m, but with a subsequent increase in drag reduction at the distances of 3 m or less. Further comparison of this to other data sets will be discussed in subsequent sections.

At separation distances below 20 m, the middle vehicle appears to experience both the low-speed air-wake effect from the lead vehicle and the stagnation-region push effect from the trailing vehicle, causing high fuel savings up to 17%.

The net-fuel-savings measurements for the full 3-truck platoon are presented in Figure 11 for the range of separation distances tested. At the shortest distance of 4 m, a net fuel savings of 13% was measured. The net fuel savings decreases with increasing distance, demonstrating 4.5% fuel savings at the largest separation-distance tested of 87 m. Beyond 40 m, the decay rate in fuel savings is low (approximately 0.3% / 10 m), suggesting that measurable fuel savings may be observed at even larger separation distances than those tested in the current study. Additional evidence to support this suggestion is the computational study by Humphreys and Bevly [17] that demonstrated reduced aerodynamic drag for the trailing vehicle of a two-truck platoon at distances up to 152 m. These data also suggest that heavy vehicles may be experiencing measurable fuel savings in general traffic conditions in which trucks can regularly be observed traveling in packs on major highways with inter vehicle distances on the order of 50 to 100 m or more. The influence of other traffic on the fuel savings of heavy trucks is discussed in a later section of this paper.

## Fuel Savings of a Two-Truck String or Platoon

The majority of multi-vehicle truck platoon studies to date have considered two truck platoons. To provide a benchmark against which this study can compare the benefits of three-truck to two-truck platooning, a select number of two-truck platoon cases were tested using the CACC system. Separation distances of 6, 12, 17, and 58 m were tested, corresponding to time gaps at 105 km/h driving speed of 0.21, 0.41, 0.6 and 2.0 seconds, respectively. These data also permit comparison against the other two-truck data sets, to be discussed in the next section.

The two-truck platooning data are shown in Figure 12 as green triangles, contrasted with the three-truck data shows as black circled. The lead vehicle of the two-truck platoon experiences nearly the same fuel savings as the three truck platoon for the separation distances tested. The trailing vehicle exhibits a similar trend as the three-truck trailing vehicle, except at a lower fuel-savings magnitude (2-4% lower) with the largest difference (4%) at the shortest separation distances. The fuel-savings measurements of the trailing truck are the same at 12 and 17 m, demonstrating that the peak fuel saving for the trailing vehicle for the two-truck platoon is likely in the 10 to 20 m range, as was also identified for the three-truck platoon.

Of particular note is the two-truck trailing-vehicle data at 58 m separation (2.0 s time gap) which is identical to the middle vehicle of the three-truck platoon at this distance. This

**FIGURE 11** Total-platoon fuel-savings results for three-vehicle CACC tests (105 km/h vehicle speed, 29,500 kg vehicle mass).

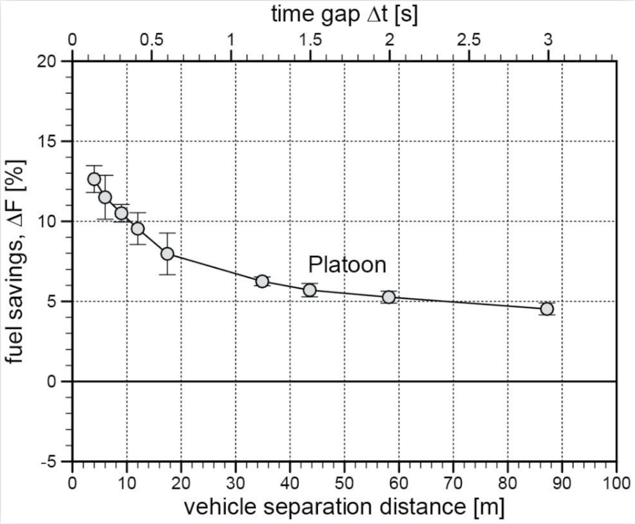

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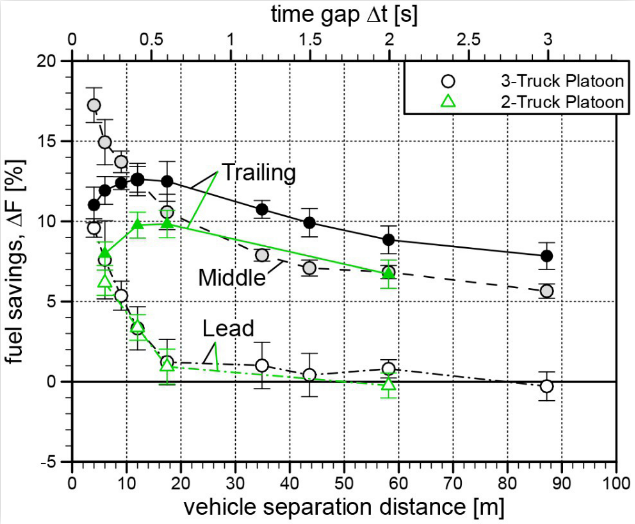
**FIGURE 12** Individual-vehicle fuel-savings results for two-vehicle and three-vehicle CACC tests (105 km/h vehicle speed, 29,500 kg vehicle mass).



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is further evidence to support the earlier claim that beyond a given separation distance, the middle vehicle is not influenced by the trailing vehicle. Essentially, at this distance, the two truck platoon can be considered identical to the lead and middle vehicle of the three-truck platoon.

The net fuel savings for the two-truck platoon is contrasted with the net fuel savings for the three-truck platoon in Figure 13. The two-truck platoon achieved a 7% fuel savings at 6 m separation distance, while the three-truck platoon achieved 11.5% for the same separation distance. At larger distances, these differences are reduced, with only a 2% net difference in fuel savings measured at 58 m. These results demonstrate that a three-truck platoon will provide a greater net fuel savings for the multivehicle system. This raises the questions as to how much fuel would be saved with a four-truck platoon, and whether the net fuel savings asymptotically reach a maximum after a certain number of vehicles?

## Comparison to Other Data Sets

As a means to further validate the observations of the current study, the authors were interested in evaluating the agreement of the results of this study to the growing body of reported platooning tests. Some literature indicates a wide range of reported results from platoon operation [18] and hence uncertainty regarding expected savings. To provide a representative set of data with which to compare, the authors selectively identified other data sets with similar operational variables, and as such only tests using conventional aero cab designs tested at 105 km/h (65 mph) and 29,500 kg vehicle mass (65,0000 lb) were compared. By eliminating studies at slower speeds, with different mass, and using cab over shapes or straight trucks, significant agreement is observed. Studies included in the current comparison include NREL's 2014 track test series [15], Auburn University's 2015 track test series [19], LLNL's 2015 wind tunnel series [10] and NRC/Path's 2016 track test series [5]. The track testing results for the lead and trailing vehicles are shown in Figure 14. The results for the lead vehicles all agree that no savings is realized beyond about 25 meters gap, but closer than 25 meters the savings rapidly ramp up to about 5%. The results for the trailing vehicle agree on a linear increase in savings from about 5% at 90 meters to 10% around 25 meters. At around 10-15 meters and closer the trailing trucks have reduced savings. As noted earlier, the specific mechanism for this reduction of fuel savings of the trailing vehicle at distances below about 10 to 20 m has yet to be identified.

**FIGURE 13** Total-platoon fuel-savings results for three-vehicle CACC tests (105 km/h vehicle speed, 29,500 kg vehicle mass).

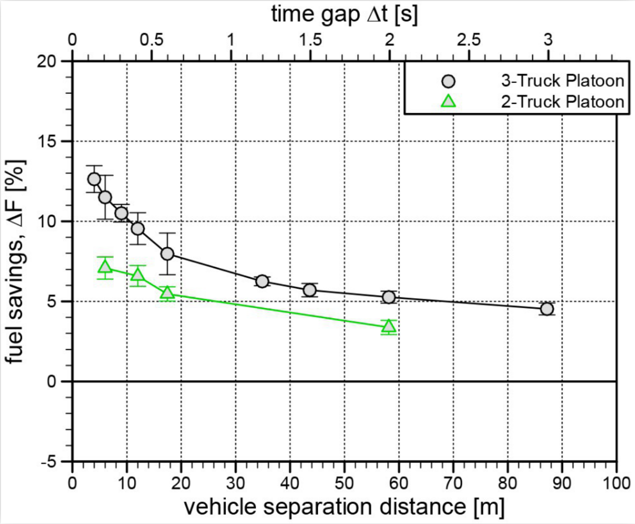

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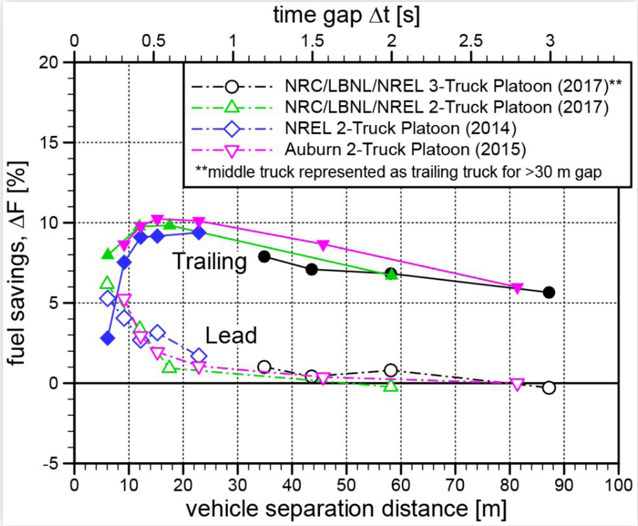
**FIGURE 14** Lead and trailing vehicle fuel-savings results for representing 2-truck-platoon performance for various track tests (105 km/h vehicle speed, 29,500 kg vehicle mass).



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Data from LLNL's 2015 platooning wind tunnel tests were converted to estimated fuel-savings values. The vehicle road load equation (presented in [5]) was used to calculate the fuel saving, by using the measured wind-averaged drag coefficient from the wind-tunnel tests (evaluated for 105 km/h ground speed), with an estimate of the rolling-resistance coefficient of the tires (of 0.0085), along with a vehicle mass of 29,500 kg and a vehicle speed of 105 km/h. A % road-load reduction was then obtained by comparing the single vehicle road load to the vehicles at various platooning distances. The results shown in Figure 15 have broad agreement in magnitude and trends with the track testing results.

Figure 16 shows track and wind tunnel results for the lead and middle vehicles in a 3-truck platoon. While the wind tunnel data for 3 truck platoons are limited at large separation distances, at distances less than 20 meters the track test results for the middle vehicle strongly agree with the wind tunnel results. The middle vehicle at these distances is experiencing the savings of both the low-speed air-wake effect of a lead vehicle and the high-pressure stagnation region push of a following vehicle and as such is continuously saving more the closer the vehicles are arranged. The middle vehicle does not experience the reduced savings that the trailing vehicle in both two and three vehicle formations demonstrate at these close separation distances.

**FIGURE 15** Lead and trailing vehicle track test fuel-savings results and wind tunnel road-load savings results (105 km/h vehicle speed, 29,500 kg vehicle mass).

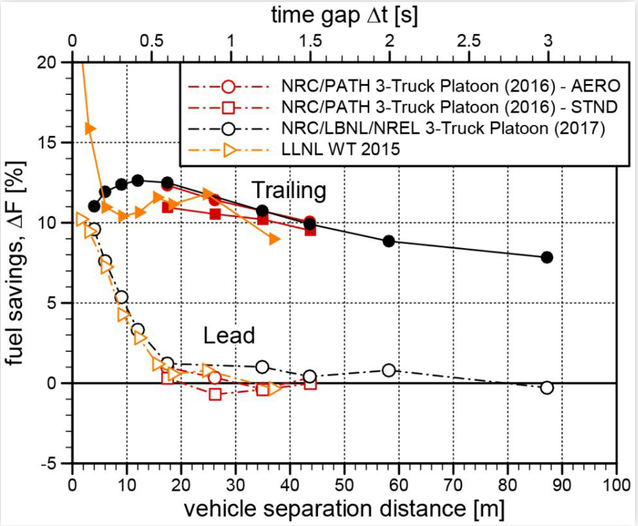


**FIGURE 16** Lead and middle vehicle track test fuel-savings results and wind tunnel road-load savings results (105 km/h vehicle speed, 29,500 kg vehicle mass).

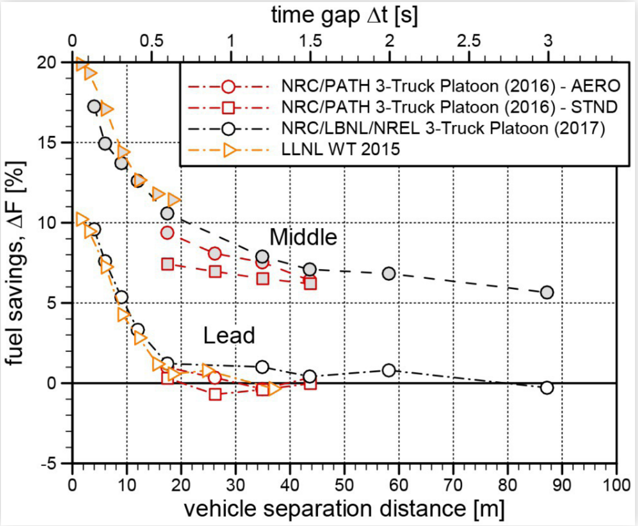
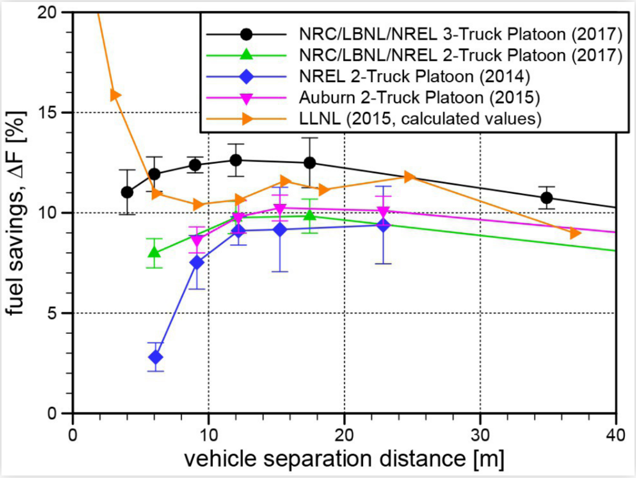


Figure 17 illustrates the reduction in fuel savings experienced by the trailing truck at distances less than about 12 meters. All reviewed track test series' testing at these distances have exhibited this result. The results for the trailing vehicle in a 3-truck platoon experienced less of a savings reduction than trailing vehicles in 2-truck platoons. The wind tunnel results also indicate a reduction in savings from 15 meters to about 9 meters at which point the savings return to a steeply positive slope. The circumstance surrounding this close following savings impact will be investigated further using a combination of J1939-Bus data and vehicle-mounted sensor data from this test campaign that have not yet been analyzed.

**FIGURE 17** Close following distance lead vehicle track test fuel-savings results and wind tunnel road load savings results (105 km/h vehicle speed, 29,500 kg vehicle mass).



# Fuel Savings of a Two-Truck Platoon Versus Long-Combination Vehicle

During the current test program, the fuel efficiency benefit of a two-truck platoon was contrasted with that of a single tractor pulling a set of tandem trailers of the same make and model, and ballasted to the same cargo load in each, thus representing the same freight-carrying capacity.

Table 1 presents the fuel savings of each concept compared to two single-trailer vehicles operating in isolation, which shows a significant increase in fuel savings using an LCV over a two-truck platoon with the same freight-hauling capacity. These data support the argument that fuel efficiency and freight efficiency can be improved using long-combination vehicles. Such configurations are present in some jurisdictions in North America (Canada and some US states) [31].

# Fuel Savings Using Mismatched Trailers

As an initial step towards understanding the change in fuel-savings performance of a platoon when mismatched vehicles are paired, as would be expected in an on-road environment, both the three-truck and two-truck platoon arrangements were tested with the aerodynamic trailer technologies removed from one of the vehicles.

For the three-truck configuration, tests were conducted for two separation distances (12 m and 58 m) with the aerodynamic trailer technologies removed from the middle

**TABLE 1** Fuel savings of a two-truck platoon compared to a long combination vehicle with the same total cargo weight.

| Vehicle Configuration | Net Fuel Savings |
|---|---|
| 2-Truck Platoon (maximum value measured) | 7% |
| 2-Trailer Long Combination Vehicle | 28% |

vehicle. No change in fuel savings was observed at the longer separation distance, compared to the identical-trailer configuration. At the shorter distance all three vehicles experienced reduced fuel savings from sign mismatched trailers (order of 2% reduction), with the confidence intervals for the lead and middle vehicles overlapping between the mismatched- and identical-trailer cases, and therefore not statistically different. However the aft vehicle demonstrated a distinct decrease in fuel savings of 2% for the mismatched-trailer case compared to the identical-trailer case.

Similar to the 12 m separation-distance case for the three-truck data, the two-truck data exhibited a decrease in fuel savings (1% to 2%) for both vehicles in the platoon at this separation distance when the aft vehicle had the aerodynamic devices removed. Here the lead vehicle shows a statistically significant difference but the trailing vehicle does not.

The total-platoon fuel-savings values for the mismatched platoon combinations are compared to the equivalent identicaltrailer cases in Table 2. Even though the mean fuel-savings values for the short-distance identical-trailer cases are larger, the mismatched-trailer cases have larger confidence intervals which overlap those of the identical-trailer test cases and therefore the results are not statistically different.

The data presented here suggest that mismatched vehicles in a platoon may have an influence on fuel savings at short distances, with negligible influence at longer distances. This is based on only a small number of data points and therefore would need to be verified through additional tests or other evidence.

## Influence of Within-Run Speed Variations

To evaluate the potential change in fuel savings due to changes in speed that may be encountered while driving in other traffic, a set of fuel-economy tests were performed with varying speed within the test run. The three-truck CACC system was tested with a separation time of 1.2 s with changes in speed between 89 and 105 km/h (55 and 65 mph) every 100 s. The results of this test case are shown in Figure 18, with the separation distance variable representing the mean distance and the horizontal error bars representing the range of separation distances encountered over the speed range tested.

The results of Figure 18 show a decrease is fuel savings associated with the three-truck CACC system when the periodic speed changes were introduced. Approximately 2% lower fuel savings were measured for these cases than would be expected for this range of separation distances. The net fuel savings for the three vehicle system was measured to be 5.2% compared to the 6 to 7% expected at this separation distance based on constant 105 km/h driving speed.

**TABLE 2** Fuel savings of a two-truck platoon compared to a long combination vehicle with the same total cargo weight.

| Vehicle Configuration | IdenticalTrailers | Mismatched Trailers |
|---|---|---|
| 3-Truck Platoon (12 m) | 9.5 % ± 1.0 % | 7.6 % ± 1.5 % |
| 3-Truck Platoon (58 m) | 5.3 % ± 0.4 % | 5.2 % ± 1.1 % |
| 2-Truck Platoon (12 m) | 6.6 % ± 0.6 % | 5.1 % ± 1.2 % |

## Influence of Other Traffic on Single-Vehicle and Platoon Fuel Savings

To investigate the impact of passenger traffic on heavy duty vehicles and truck platoons, a mid-size SUV was tested at three distances in front of a single truck using ACC. From 43 meters to 87 meters behind the SUV the single truck experienced fuel savings ranging from 1.5% to 2.6% as is illustrated in Figure 19. Note that when following another tractor-trailer combination at these ranges, the trailing vehicle would experience fuel savings of 7.5% to 10% and a middle vehicle saving 5.5% to 7%.

**FIGURE 18** Middle- and Trailing-vehicle fuel-savings results for three-vehicle CACC tests with 1.2 s separation time and speed variation (89 to 105 km/h), with changes in speed every 100 seconds. Horizontal error bars represent range of separation distances (29,500 kg vehicle mass).

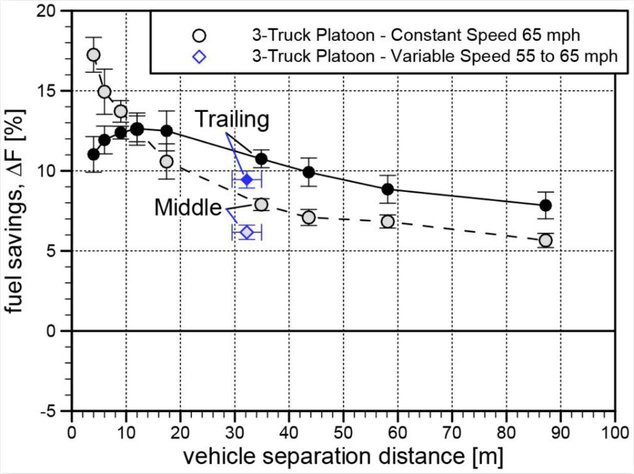


**FIGURE 19** Fuel savings of single truck following SUV compared to following trucks in two and three vehicle platoons (105 km/h vehicle speed, 29,500 kg vehicle mass).

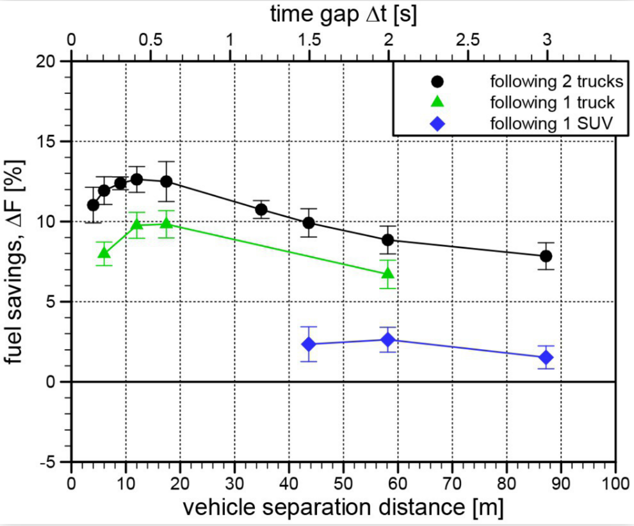


Figure 20 contrasts the single-truck fuel saving while following the SUV using ACC with the total-platoon fuel savings for the two-truck and three-truck CACC tests. Savings of around 2.6% for a single truck following the SUV at 58 meters is about the same as the 2-truck platoon team average savings at that distance and does raise the question of true baseline fuel consumption when driving in traffic. Figure 20 also includes two cases for which the multi-vehicle CACC configurations (each with 12 m internal separation distance) followed the SUV at a 58 m distance with the lead truck using ACC to do so. When following the SUV at a 58 m separation distance, platoon team savings is not impacted to a statistically significant level.

Figure 21 illustrates that the lead vehicle in a 2- or 3-truck platoon may experience the savings of following an SUV at this distance but the results are inconclusive. The lead truck of the 3-truck CACC system (with 12 meters separation distance) demonstrated a measurable increase in fuel savings while following the SUV at 58 m distance, as compared to the 3-truck CACC in isolation. However, the lead truck of the 2-truck CACC system (with 12 meters separation distance) did not experience the savings from the SUV ahead of it. Environmental data are still being investigated for a possible cause of this discrepancy, but this may indicate the fuel savings following an SUV may be less consistent than when following another truck. The nominal results for all following vehicles within the CACC configurations, while following the SUV or not, were within the confidence intervals of the results (not shown here, but data available in Appendix A). The middle vehicle in the 3-truck platoon had a nominal 1% savings increase while the trailing vehicle had no change. The trailing vehicle of the 2-truck platoon had a nominal 1% drop in fuel savings.

**FIGURE 20** Total-platoon fuel savings behind SUV (105 km/h vehicle speed, 29,500 kg vehicle mass).

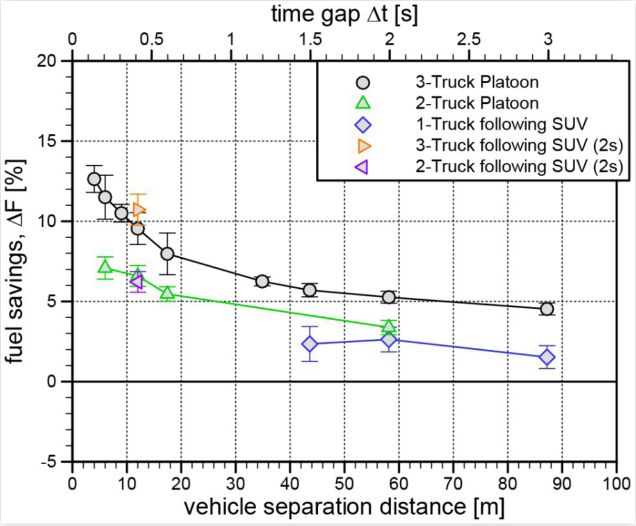
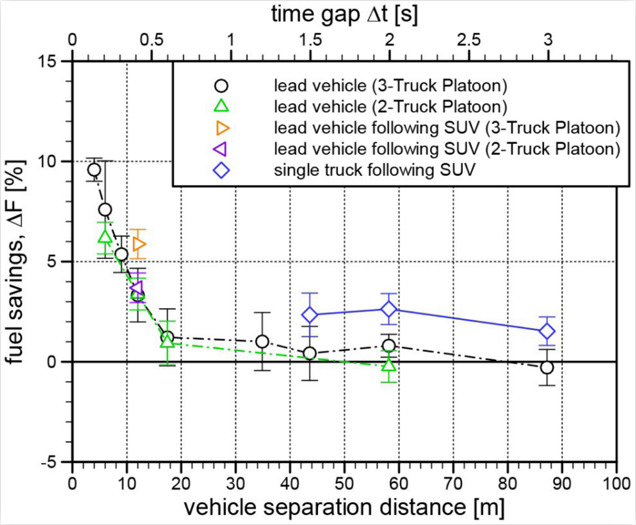
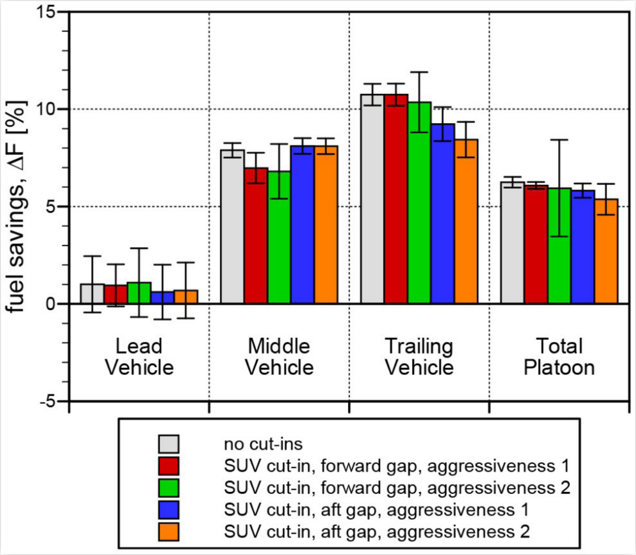


**FIGURE 21** Savings of lead truck in platoon following SUV (105 km/h vehicle speed, 29,500 kg vehicle mass).



To further investigate the impact of real-world traffic on realized platoon fuel savings, vehicle cut-ins were conducted using the compact SUV inserting between the first and second and second and third trucks in a 3-truck platoon with a 35-meter separation distance. Cut-ins were introduced at a rate of 2 incidences per test lap or once every 3.2 km (2 miles), with a 30 second duration. Two levels of control responsiveness were also investigated to determine if aggressiveness of controller response to the intrusion had a measurable impact. Figure 22 shows the matrix of results. For intrusions between the lead and middle trucks, the middle truck demonstrates a nominal 1% drop in savings that may not be statistically significant; the aggressiveness of controller response had no impact. For intrusions between the middle and trailing trucks, the trailing truck demonstrated a nominal 1.5-2.3% drop in savings. The aggressiveness of controller response did have a measurable impact of a nominal 0.8% with the more aggressive response being statistically significantly different from

**FIGURE 22** Bar chart comparing the impact of light-duty-vehicle intrusion into three vehicle platoons and controller-reaction scenarios (105 km/h target vehicle speed, 29,500 kg vehicle mass).



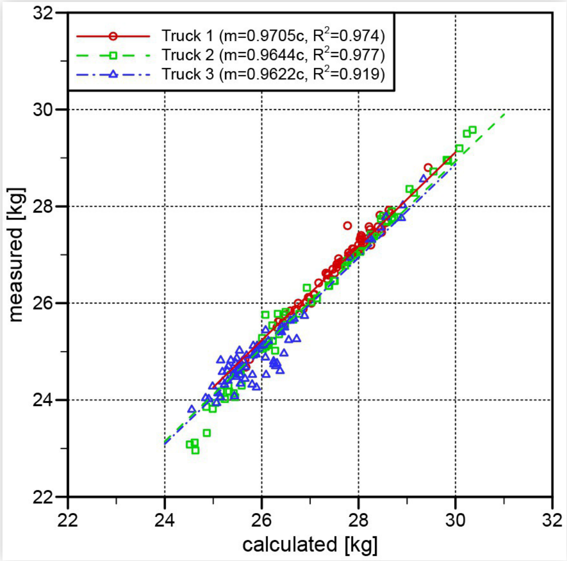
the no intrusion case while the less aggressive response was not quite statistically significant from the no-intrusion case. All four cut-in scenarios resulted in nearly identical nominal fuel savings for the full platoon.

## Effects of Road Curvature Using Fuel Injector Data

The test track used for the fuel economy tests is curved for half of the distance of each lap, as shown in Figure 8, with a radius of curvature of approximately 0.5 km. The percentage of curved sections on freeways is generally much lower, and the road curvature on a freeway is often much smaller. Therefore, it would make sense to understand how the road curve affected the fuel savings during testing, if at all. It is clear that this cannot be done simply based on the weighted fuel consumption since there is no way to tell what proportion of fuel was used on the curve. Instead, the fuel injector data from the J-1939 Bus was used to further analyze the fuel-savings characteristics of the multi-vehicle CACC system. The J-1939 Bus provides an estimated fuel-injection rate as a time flow rate of diesel fuel. Cumulated over time, it will provide total fuel consumption for each measurement run.

The cumulative fuel injector data for each measurement run were found to be reasonably consistent with the fuel-weight measurements, providing justification for the use of the fuel injector data for this analysis. Figure 23 represents the majority of test data collected from the 105 km/h (65 mph) measurement runs, for each individual truck. The higher fuel-use cases, which represent conditions in the absence of other vehicles or with large separation distances, demonstrate good correlation between the measured and fuel-injector data. The lower fuel-use cases for trucks 2 and 3, for which the correlation is less well defined, represent close-proximity cases during which a much greater within-run variance was observed in the fuel rate data. In general, the cumulative fuel-injector data was higher than the fuel-use measurements, so it needs to be multiplied by something on the order of 0.96 to 0.97, as seen in Figure 23, to recover the measured values. The fuel-injector analysis described herein assumes that these calibrations hold for the instantaneous fuelrate data for all measurement runs.

**FIGURE 23** Comparison of cumulative fuel injector data and fuel-weight measurements.



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**Yaw-Rate Approach** One approach towards understanding the potential differences in fuel use on the straight and curved sections of the track is to evaluate the data based on vehicle yaw rate, as provided through the J-1939 Bus. If we filter out the fuel data when the yaw-rate is above a certain threshold, we can eliminate the fuel consumption on the curve. Different yaw-rate thresholds can be applied to straightness of the road. Three yaw-rate thresholds were selected to separate the data based on road curvature: (a) no yaw rate limit (default case); (b) 0.01 [rad/s] = 0.573 [° /s]; (c) and 0.005 [rad/s] = 0.286[° /s]. The two non-zero thresholds provide different contributions from the road sections entering and exiting the curves. Once fully within the curve, the yaw rate is on the order of 3 ° /s. The analysis procedure is described as follows for each yaw-rate threshold:

- Calculate the cumulative fuel rate and distance for each scenario run and find the average (over distance) fuel rate for each test scenario for the above three yaw rate thresholds, respectively;
- Find the fuel savings with respect to the average fuel consumption of the single truck runs for the above three yaw rate thresholds, respectively;
- Compare the average single-truck fuel rate (over distance) and the average fuel rates (over distance) of other scenarios to evaluate the fuel savings of each scenario with respect to the single truck runs for the above three yaw rate thresholds, respectively;

Table 3 presents the aggregate fuel saving over most test runs and all the CACC following scenarios at 65 m, not including the cut-in/cut-out tests, the speed-variation tests, or the cases with the SUV preceding the trucks. The aggregate data set was used because a direct comparison of one measurement run to another in this manner does not account for run-to-run or day-to-day variations in environmental factors such as temperature and winds. This approach uses the aggregate CACC runs in comparison to the aggregate reference isolated-vehicle runs. The lead truck was in cruise control mode meaning that there was no other preceding vehicle for these cases.

It is observed, based on the data in Table 3, that a limit on road curvature, or more precisely on truck yaw rate, demonstrates improved fuel economy when the vehicles are

**TABLE 3** Average fuel savings of many test configurations compared to a single truck for different yaw rate limits.

| Vehicle | No Yaw-Rate Limit | Yaw-Rate < 0.573°/s | Yaw-Rate < 0.286°/s |
|---|---|---|---|
| Truck 1 | 5.0% | 5.2% | 5.1% |
| Truck 2 | 11.5% | 11.9% | 12.0% |
| Truck 3 | 11.0% | 12.0% | 12.1% |

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travelling in a straight direction. Using this aggregate approach for the large data set, the lead vehicle shows no significant change from straight to curved travel while the middle and trailing vehicles show approximately 0.5% and 1.0% higher fuel savings, respectively, considering straight travel only.

**Track-Segmentation Approach** In parallel with the yaw-rate approach to identifying the potential changes in fuel savings based on road curvature, a separate approach was investigated which makes use of the fuel-injector data along with GPS position data to separate data from the straight segments and the curved segments of the track. This approach also makes use of the fuel-weight measurement data to permit comparison to the control vehicle. Ideally, the fuel-injector data of the control vehicle would be used as the control data set, but these data were not acquired during testing. A fuel mass-flow-rate parameter has been defined that represents a relative instantaneous fuel flow rate of each test truck to the mean fuel rate of the control truck for each run. This parameter is defined as:

$$\frac{\dot{m}_T(t)}{\dot{m}_{C,avg}} = \frac{\rho \cdot FR(t)}{\Delta m / \Delta T} \cdot \frac{T}{C} \qquad (2)$$

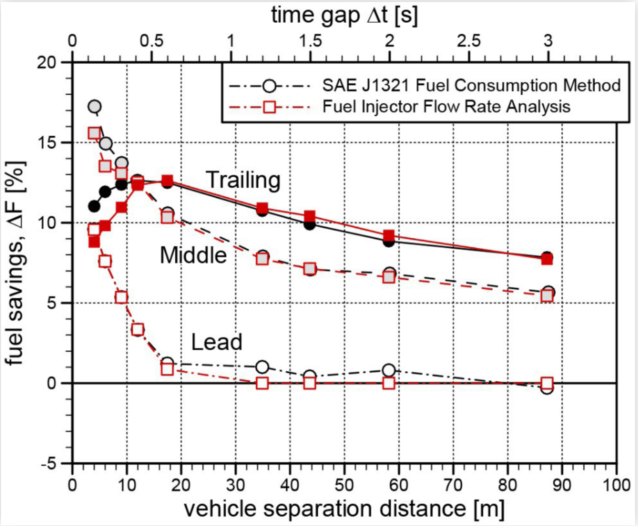
where $\rho$ is the fuel density, $FR(t)$ is the instantaneous fuel-injector volume-flow-rate, $\Delta m$ is the measured fuel mass from the fuel-consumption measurements, $\Delta T$ is the duration of the measurement run, and $T/C$ is the mean test-to-control fuel-weight ratio from the fuel-economy tests as used in Equation 1.

As a result of there being no fuel-rate data from the control truck, from which the specific segment-to-segment fuel-savings values could be determined, the fuel-rate data from the lead vehicle have been used to evaluate the segment-to-segment changes in fuel savings. For separation distances beyond 20 m, this is justified based on the arguments made previously in the paper that the vehicles are too far apart to feel the stagnation- pressure pushing effect from trailing vehicles. For separation distances shorter than 20 m, the instantaneous fuel rate data of the lead vehicle shows the same signature with track location as it does in the reference run cases or in the cases with greater than 20 m separation distance, whereas the middle and trailing vehicles demonstrate distinctly different trends with track location. This lead-vehicle trend is also consistent with the negligible yaw-rate effect described in the previous section. The lead vehicle has thus been used as a means to normalize the fuel-rate data for each segment of track, in the following manner:

$$R_{\dot{m},segment,i} = \frac{\dot{m}_{T,i}}{\dot{m}_{T,1}}\left(t_{segment}\right) \cdot \frac{(T/C)_{T,1}}{(T/C)_{Ref,1}} \qquad (3)$$

where $i$ represents the middle ($i = 2$) or trailing ($i = 3$) truck and <> represents an average of the time series ratio. This parameter $R_{\dot{m},segment,i}$ represents the ratio, for the middle or trailing vehicle, of fuel used over a track segment during a test run to the fuel used by the same vehicle the over the same segment during the baseline runs, while accounting for the run-to-run and day-to-day changes in environmental conditions. These values are then used in place of the $T/C$ parameter in Equation 1 to calculate the fuel-savings for a given segment of track.

**FIGURE 24** Comparison of fuel-savings analysis using fuel-weighing procedure and calibrated fuel-injector procedure.



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As a verification that this approach provides a reasonable approximation to the fuel-weight measurement approach, Figure 24 shows the comparison of the three-truck CACC results using both methods. By nature of the approach to use the lead vehicle as the reference, there is very little difference between the two methods for the lead vehicle below 20 m separation distance, and beyond 20 m the fuel savings is 0% by definition. The middle and trailing vehicles only exhibit noticeable differences in the methods at the shortest separation distances. These are the cases for which the fuel-injector calibration data of Figure 23 show poor calibration against the proportional fits at the lower mean fuel rates. Despite these errors in the calibration, the trend in the fuel-savings values using the fuel-injector data is in good agreement with the SAE J1321 fuel-weighing procedure.

The instantaneous fuel data were segmented into four parts of the test track: the north- and south-side straight segments, and the east- and west-side curved segments. The fuel-savings of the three-truck CACC tests for each of the four track segments are presented in Figures 25 and 26 for the middle and trailing vehicles, respectively. Under the primary assumption of these results that the lead truck shows no difference in fuel savings from segment to segment, it is evident from these two figures that the middle and trailing vehicles experience greater fuel savings (order of 2% to 5%) on the straight segments of the track than on the curved segments for separation distances beyond about 10 m. Below 10 m, the fuel-savings results converge to similar results regardless of track segment. The reason for this difference at short compared to long distances is not apparent in the data, but may be understood through future analysis of the on-board wind-speed and cooling flow measurements. Figures 25 and 26 also shows a greater difference in the results for the two curved segments than there is between the two straight segments.

**FIGURE 25** Fuel savings by track segment for the middle vehicle of the three-truck CACC tests (105 km/h vehicle speed, 29,500 kg vehicle mass).

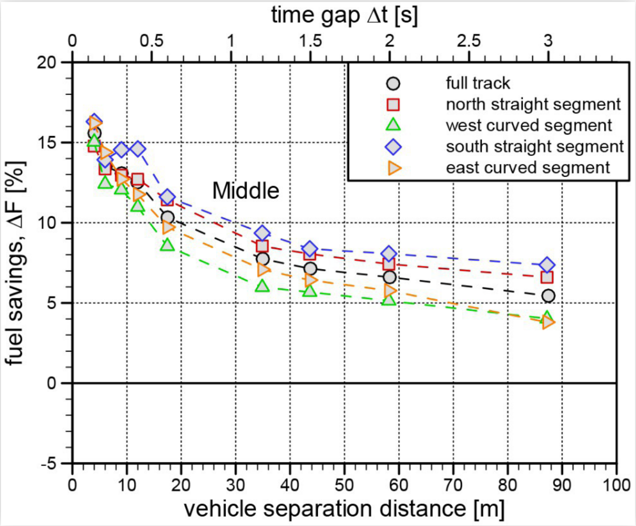

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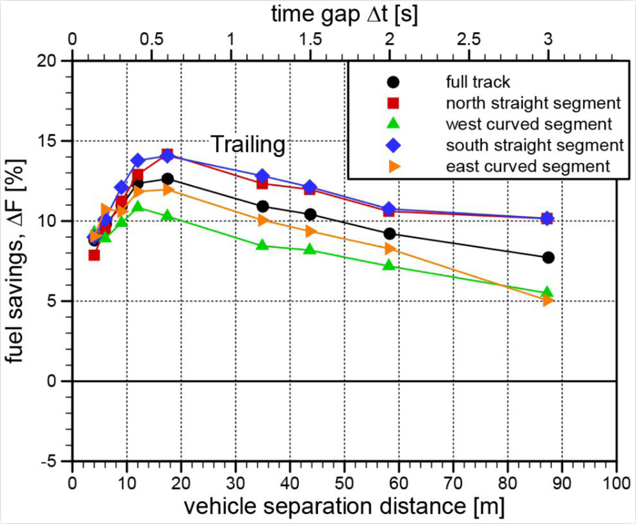
**FIGURE 26** Fuel savings by track segment for the trailing vehicle of the three-truck CACC tests (105 km/h vehicle speed, 29,500 kg vehicle mass).



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These results of Figures 25 and 26 are in agreement with the yaw-rate-based analysis of the previous section, which showed greater fuel savings during straight vehicle travel, but identify a greater magnitude of fuel-use differences between straight and curved vehicle travel than the yaw-rate analysis.

## Conclusions

The results reported here represent one of the most comprehensive assessments of the energy saving potential of cooperative vehicle automation systems for heavy trucks to be documented. The fuel consumption for each truck in the CACC string was measured using the SAE J1321 Type II procedure while travelling at 105 km/h (65 mph) and loaded to a gross weight of 29,500 kg (65,000 lb), at different distance gaps ranging from 3.0 s or 87 m to 0.14 s or 4 m, covering a much wider range than previously reported tests. Several other scenarios were also tested including cut-in and cut-out maneuvers by other vehicles, speed variations, the use of mismatched vehicles (standard trailers mixed with aerodynamic trailers with boat tails and side skirts), and the presence of a passenger vehicle ahead of the string of trucks. Furthermore, the effect of road curvature on the fuel consumption has also been quantitatively analysed from the test data, indicating potentially larger actual savings in energy on typical road geometry for long-haul trucking with limited road curvature.

Specific conclusions from the work are as follows:

- The three-truck data demonstrated a wide range of fuel savings with the lead vehicle experiencing up to 10% at the closest separation distance of 4 m, with the middle vehicle experiencing a maximum fuel saving of 17% also at the shortest distance, and with the trailing vehicle experiencing a maximum fuel savings of 13% within the range of 10- 20 m.
- Significant fuel savings for the middle and trailing vehicles were measured at the largest separation distance of 87 m, measuring 6% and 8%, respectively.
- Total fuel savings for the three-vehicle CACC was measured at 13% at the shortest separation distance of 4 m, with 4.5% savings measured at 87 m.
- The lead and trailing vehicles of the two-truck CACC demonstrated the same trends in fuel savings with separation distance as the three-truck CACC, with a lower magnitude for the trailing vehicle.
- A cooperative three-truck scenario was shown to have a greater team fuel savings than that of a two-truck scenario (order of 2% higher, or more), for the range of common separation distances tested.
- Trends in data compare well with other fuel-economy data sets for similar vehicle types, speeds, and weights. Three-truck data also match trends observed from a wind-tunnel test.
- A reduction in fuel savings in excess of 1% was observed at small separation distance (12 m) when mismatched trailers were introduced into the CACC configurations, although the differences were generally within the confidence intervals of the data. No change in fuel savings was observed at 58 m separation distance.
- For equivalent cargo weights, a two-trailer long combination vehicle provided a greater fuel savings than the bestperforming two-truck CACC scenario (28% for LCV compared to 7% for CACC).
- A reduction in fuel savings from CACC on the order of 1- 2% was measured when a periodic speed variation between 89 and 105 km/h was introduced every 100 seconds, with the CACC set to a 1.2 seconds time gap, as compared to constant speed driving at 105 km/h.
- Other road traffic can influence the fuel savings of cooperative heavy-vehicle automation systems. Some data showed beneficial effects of a string or platoon

following an SUV, while other data showed no such benefit. Periodic cut-ins between the trucks showed no appreciable change in the fuel savings of the three-truck CACC with a separation time of 1.2 s (target distance of 25 m). The variation in fuel-savings results for these "other traffic" scenarios suggest that energy savings are already being achieved while driving in general traffic, and that the cost benefits of cooperative truck automation systems may be influenced by the traffic scenarios in which such systems will be used.

- Two approaches to evaluating the difference in fuel savings between the straight and curved segments of the track revealed reduced fuel savings on the curved section of track than on the straight segments of track.

Although SAE Type II testing of truck platoons has become common practice to investigate energy savings of various truck-platooning scenarios, the current study introduced considerations not previously investigated. The novel investigations of the current study include the controlled vehicle cut-ins and speed variations, the mismatched trailer parings, and the use of fuel-injector data to identify differences in fuel savings on the straight and cured segments of the track. Furthermore, this test campaign significantly expanded knowledge of performance both at closer (down to 4 m) and further (out to 87 m) following distances than any previous tests performed at vehicle speeds of 105 km/h (65 mph). These data are intended to provide some context for fuel savings to be realized under operating conditions on public roadways and in real traffic scenarios.

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## References

1. Lu, X.Y. and Hedrick, J.K., "Practical String Stability for Longitudinal Control of Automated Vehicles," *Int. J. Vehicle Systems Dynamics Supplement* 41:577-586, 2004.
2. Lu, X.Y., Hedrick, J.K. and Drew, M., "ACC/CACC - Control Design, Stability and Robust Performance," In *Proc. of 2002 American Control Conference*, May 8-10, Anchorage, Alaska, 2002, 4327-4332.
3. Milanés, V., Shladover, S., Spring, J., Nowakowski, C.et al., "Cooperative Adaptive Cruise Control in Real Traffic Situations," *IEEE Transactions on Intelligent Transportation Systems* 15(1):296-305, 2014.
4. Milanés, V. and Shladover, S.E., "Modeling Cooperative and Autonomous Adaptive Cruise Control Dynamic Responses Using Experimental Data," *Transportation Research Part C: Emerging Technologies* 48:285-300, 2014.
5. McAuliffe, B.R., Ahmadi-Baloutaki, M., Croken, M. and Raeesi, A., "Fuel-Economy Testing of a Three-Vehicle Truck Platooning System," NRC Report LTR-AL-2017-0008, National Research Council Canada, 2017.
6. Rajamani, R., Choi, S.B., Hedrick, J.K., Law, B.et al., "Design and Experimental Implementation of Control for a Platoon of Automated Vehicles," In *Proceedings of the ASME Dynamic Systems and Control Division*, Volume 64, 1998, pages 681-689.
7. Lu, X.Y. and Shladover, S., "Integrated ACC and CACC Development for Heavy-Duty Truck Partial Automation," In *2017 American Control Conference*, Seattle, WA, May 24-26, 2017.
8. Marcu, B. and Browand, F., "Aerodynamic Forces Experienced by a 3-Vehicle Platoon in a Crosswind," SAE Technical Paper 1999-01-1324, 1999.
9. Tsuei, L. and Savas, O., "Transient Aerodynamics of Vehicle Platoons during in-line Oscillations," *Journal of Wind Engineering and Industrial Aerodynamics* 89:1085-1111, 2001.
10. Lammert, M. and Kelly, K., "Correlations of Platooning Track Test and Wind Tunnel Data," NREL Technical Report NREL/TP-5400-68897, National Renewable Energy Laboratory, 2018.
11. Bonnet, C. and Fritz, H., "Fuel Consumption Reduction in a Platoon: Experimental Results with Two Electronically Coupled Trucks at Close Spacing," SAE Technical Paper 2013-01-0767, 2000.
12. Browand, F., McArthur, J., and Radovich, C., "Fuel Saving Achieved in the Field Test of Two Tandem Trucks," California PATH Research Report UCB-ITS-PRR-2004-20, 2004.
13. Al Alam, A., Gattami, A., and Johansson, K., "An Experimental Study on the Fuel Reduction Potential of Heavy Duty Vehicle Platooning," In *13th International IEEE Annual Conference on Intelligent Transportation Systems*, Madeira Island, Portugal, 2010.
14. Roeth, M., "CR England Peloton Technology Platooning Test Nov. 2013," North American Council for Freight Efficiency (nacfe), Peloton, 2013.
15. Lammert, M., Duran, A., Diez, J., Burton, K.et al., "Effect of Platooning on Fuel Consumption of Class 8 Vehicles Over a Range of Speeds, Following Distances, and Mass," *SAE Int. J. Commer. Veh.* 7(2), 2014, doi:10.4271/2014-01-2438.
16. Tsugawa, S., "Results and Issues of an Automated Truck Platoon within the Energy ITS Project," In *2014 IEEE Intelligent Vehicles Symposium (IV)*, June 8-11, Dearborn, MI, 2014.
17. Humphreys, H. and Bevly, D., "Computational Fluid Dynamic Analysis of a Generic 2 Truck Platoon," SAE Paper 2013-01-0767, 2016.

18. Roberts, J., Mihelic, R., Roeth, M. and Rondini, D., "Confidence Report on Two-Truck Platooning," Technical Report, North American Council for Freight Efficiency, 2016.
19. Bevly, D., Murray, C., Lim, A., Turochy, R.et al., "Heavy Truck Cooperative Adaptive Cruise Control: Evaluation, Testing, and Stakeholder Engagement for Near Term Deployment: Phase Two Final Report," Technical report, Auburn University, 2017.
20. Hammache, M., Michaelian, M., and Browand, F., "Aerodynamic Forces on Truck Models, Including Two Trucks in Tandem," SAE Paper 2002-01-0530, 2002.
21. Tsugawa, S., Kato, S., and Aoki, K., "An Automated Truck Platoon for Energy Saving," In *IEEE/RSJ International Conference on Intelligent Robots and Systems* San Francisco, CA, 2011.
22. Davila, A., Aramburu, E., and Freixas, A., "Making the Best Out of Aerodynamics: Platoons," SAE Paper 2013-01-0767, 2013.
23. Smith, J., Mihelic, R., Gifford, B., and Ellis, M., "Aerodynamic Impact of Tractor-Trailer in Drafting Configuration," *SAE Int. J. Commer. Veh.* 7(2), 2014, doi:10.4271/2014-01-2436.
24. Ellis, M., Gargoloff, J., and Sengupta, R., "Aerodynamic Drag and Engine Cooling Effects on Class 8 Trucks in Platooning Configurations," *SAE Int. J. Commer. Veh.* 8(2), 2015, doi:10.4271/2015-01-2896.
25. Mihelic, R., Smith, J., and Ellis, M., "Aerodynamic Comparison of Tractor-Trailer Platooning and A-Train Configuration," *SAE Int. J. Commer. Veh.* 8(2), 2015, doi:10.4271/2015-01-2897.
26. Humphreys, H., Batterson, J., Bevly, D., and Schubert, R., "An Evaluation of the Fuel Economy Benefits of a Driver Assistive Truck Platooning Prototype Using Simulation," *SAE Paper 2016-01-0167*, 2016.
27. Gheyssens, T. and Van Raemdonck, G., "Effect of the Frontal Edge Radius in a Platoon of Bluff Bodies," *SAE Int. J. Commer. Veh.* 9(2), 2016, doi:10.4271/2016-01-8149.
28. SAE J1321, "Fuel Consumption Test Procedure - Type II," Surface Vehicle Recommended Practice J1321, 2012.
29. U.S. Environmental Protection Agency and U.S. Department of Transportation, "Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles - Phase 2," *US Federal Register* 81(206):73478-74274, 2016.
30. Environment & Climate Change Canada, "Regulations Amending the Heavy-Duty Vehicle and Engine Greenhouse Gas Emission Regulations and Other Regulations Made Under the Canadian Environmental Protection Act, 1999," *Canada Gazette Part I* 151(9), 2017.
31. Mihelic, R., "Fuel and Freight Efficiency - Past, Present and Future Perspectives," *SAE Int. J. Commer. Veh.* 9(2), 2016, doi:10.4271/2016-01-8020.
32. Muratori, M., Holden, J., Lammert, M., Duran, A.et al., "Potentials for Platooning in U.S. Highway Freight Transport," *SAE Int. J. Commer. Veh.* 10(1):45-49, 2017, doi:10.4271/2017-01-0086.
33. PMG Technologies, "The High-Speed Track," http://www.pmgtest.com/index.php/en/facilities/pistes/5-the-high-speed-track.html, accessed July 2016.

# Appendix A - Summary of Test Data

The fuel-savings results from the test campaign are provided in Table 4. Also included are the results from the first phase of the CACC fuel economy tests performed in 2016 [5] which have been re-analysed using the approach of the current paper whereby the lead-truck fuel-use measurements are used as the control measurements for the following trucks, for separation distances beyond 20 m.

**TABLE 4** Results from the SAE J1321 fuel consumption tests. The data represent vehicle speeds of 105 km/h (65 mph), vehicle masses of 29,400 kg (65,000 lb), and the trailer outfitted with side-skirts and a boat-tail, unless otherwise noted.

| Test Configuration | Separation Time [s] | Separation Distance [m] | Lead Truck Fuel Savings | Middle Truck Fuel Savings | Trailing Truck Fuel Savings | Platoon Fuel Savings | Notes |
|---|---|---|---|---|---|---|---|
| 3-Truck (2017) | 0.14 | 4.0 | 9.6 % ± 0.6 % | 17.2 % ± 1.1 % | 11.0 % ± 1.1 % | 12.6 % ± 0.8 % | |
| | 0.21 | 6.0 | 7.6 % ± 2.4 % | 14.9 % ± 1.4 % | 11.9 % ± 0.9 % | 11.5 % ± 1.4 % | |
| | 0.31 | 9.0 | 5.4 % ± 0.9 % | 13.7 % ± 0.7 % | 12.4 % ± 0.4 % | 10.5 % ± 0.6 % | |
| | 0.41 | 12.0 | 3.3 % ± 1.3 % | 12.6 % ± 1.0 % | 12.6 % ± 0.8 % | 9.5 % ± 1.0 % | |
| | 0.6 | 17.4 | 1.2 % ± 1.4 % | 10.6 % ± 1.1 % | 12.5 % ± 1.2 % | 8.0 % ± 1.3 % | |
| | 1.2 | 34.9 | 1.0 % ± 1.4 % | 7.9 % ± 0.4 % | 10.7 % ± 0.6 % | 6.3 % ± 0.3 % | |
| | 1.5 | 43.6 | 0.4 % ± 1.3 % | 7.1 % ± 0.5 % | 9.9 % ± 0.9 % | 5.7 % ± 0.4 % | |
| | 2.0 | 58.1 | 0.8 % ± 0.6 % | 6.8 % ± 0.4 % | 8.9 % ± 0.9 % | 5.3 % ± 0.4 % | |
| | 3.0 | 87.2 | -0.3 % ± 0.9 % | 5.7 % ± 0.4 % | 7.8 % ± 0.8 % | 4.5 % ± 0.4 % | |
| 2-Truck | 0.21 | 6.0 | 6.2 % ± 0.8 % | - | 8.0 % ± 0.7 % | 7.1 % ± 0.7 % | |
| | 0.41 | 12.0 | 3.4 % ± 0.8 % | - | 9.8 % ± 0.8 % | 6.6 % ± 0.6 % | |
| | 0.6 | 17.4 | 0.9 % ± 1.1 % | - | 9.8 % ± 0.8 % | 5.5 % ± 0.4 % | |
| | 2.0 | 58.1 | -0.2 % ± 0.8 % | - | 6.7 % ± 0.9 % | 3.4 % ± 0.4 % | |
| Long Combination Vehicle | - | - | - | 27.6 % ± 0.6 % | - | - | relative to 2 isolated trucks |
| 2-Truck Mismatched | 0.41 | 12.0 | 1.7 % ± 0.6 % | 8.5 % ± 1.0 % | - | 5.1 % ± 1.2 % | standard trailer - trailing truck |
| 3-Truck Mismatched | 0.41 | 12.0 | 1.6 % ± 0.7 % | 10.8 % ± 1.2 % | 10.5 % ± 0.7 % | 7.6 % ± 1.5 % | standard trailer - middle truck |
| | 2.0 | 58.1 | -0.8 % ± 0.6 % | 6.6 % ± 0.7 % | 8.9 % ± 0.8 % | 5.2 % ± 1.1 % | |
| 3-Truck Speed Variation 89-105 km/h | 1.2 | 29.5-34.9 | - | 6.2 % ± 0.5 % | 9.5 % ± 0.5 % | 5.2 % ± 0.3 % | |
| 1-Truck following SUV | 1.5 | 43.6 | - | 2.3 % ± 1.1 % | - | - | |
| | 2.0 | 58.1 | - | 2.6 % ± 0.8 % | - | - | |
| | 3.0 | 87.2 | - | - | 1.5 % ± 0.7 % | - | only 2 valid runs |
| 3-Truck following SUV with 2 s gap | 0.41 | 12.0 | 5.9 % ± 0.7 % | 13.5 % ± 1.2 % | 12.8 % ± 1.2 % | 10.7 % ± 1.0 % | |
| 2-Truck following SUV with 2 s gap | 0.41 | 12.0 | 3.7 % ± 0.7 % | - | 8.7 % ± 0.8 % | 6.2 % ± 0.7 % | only 2 valid runs |
| 3-Truck with SUV Cut-Ins | 1.2 | 34.9 | 1.0 % ± 1.1 % | 7.0 % ± 0.8 % | 10.7 % ± 0.6 % | 6.1 % ± 0.2 % | lead/middle, aggr. 1 |
| | 1.2 | 34.9 | 1.1 % ± 1.8 % | 6.8 % ± 1.4 % | 10.4 % ± 1.5 % | 5.9 % ± 2.5 % | middle/trailing, aggr. 1 |
| | 1.2 | 34.9 | 0.6 % ± 1.4 % | 8.1 % ± 0.4 % | 9.2 % ± 0.9 % | 5.8 % ± 0.4 % | lead/middle, aggr. 2 |
| | 1.2 | 34.9 | 0.7 % ± 1.4 % | 8.1 % ± 0.4 % | 8.4 % ± 0.9 % | 5.4 % ± 0.8 % | middle/trailing, aggr. 2 |
| 3-Truck (2016) | 0.6 | 17.4 | 1.0 % ± 0.7 % | 9.4 % ± 1.5 % | 12.3 % ± 1.3 % | 7.6 % ± 0.8 % | |
| | 0.9 | 26.2 | 0.3 % ± 1.0 % | 8.1 % ± 1.5 % | 11.4 % ± 1.6 % | 6.5 % ± 0.5 % | |
| | 1.2 | 34.9 | -0.4 % ± 0.7 % | 7.5 % ± 1.6 % | 10.7 % ± 1.7 % | 6.1 % ± 0.5 % | |
| | 1.5 | 43.6 | 0.3 % ± 1.2 % | 6.4 % ± 1.5 % | 10.1 % ± 1.6 % | 5.5 % ± 0.6 % | |
| 3-Truck (2016) Standard Trailer | 0.6 | 17.4 | 0.3% ± 1.1% | 7.4% ± 1.1% | 11.0% ± 1.2% | 6.2% ± 1.1% | |
| | 0.9 | 26.2 | -0.7% ± 0.4% | 7.0% ± 0.5% | 10.5% ± 0.5% | 5.8% ± 0.2% | |
| | 1.2 | 34.9 | -0.4% ± 1.2% | 6.5% ± 0.5% | 10.2% ± 0.5% | 5.6% ± 0.3% | |
| | 1.5 | 43.6 | 0.0% ± 1.1% | 6.2% ± 0.6% | 9.5% ± 0.9% | 5.2% ± 0.5% | |
| 3-Truck (2016) Standard Trailer 89 km/h speed | 0.71 | 17.4 | 1.6% ± 0.8% | 7.6% ± 1.1% | 10.5% ± 1.4% | 6.6% ± 1.0% | |
| 3-Truck (2016) Standard Trailer 14,000 kg mass | 0.6 | 17.4 | 1.4% ± 1.6% | 9.6% ± 1.8% | 12.1% ± 1.1% | 7.8% ± 1.5% | |

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