Impact of Mixed Traffic on the Energy Savings of a Truck Platoon

Preprint

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Impact of Mixed Traffic on the Energy Savings of a Truck Platoon

Abstract

A two-truck platoon based on a prototype cooperative adaptive cruise control (CACC) system was tested on a closed test track in a variety of realistic traffic and transient operating scenarios - conditions that truck platoons are likely to face on real highways. The fuel consumption for both trucks in the platoon was measured using the SAE J1321 gravimetric procedure as well as calibrated J1939 instantaneous fuel rate, serving as proxies to evaluate the impact of aerodynamic drag reduction under constant-speed conditions. These measurements demonstrate the effects of: the presence of a multiple-passenger-vehicle pattern ahead of and adjacent to the platoon, cut-in and cut-out manoeuvres by other vehicles, transient traffic, the use of mismatched platooned vehicles (van trailer mixed with flatbed trailer), and the platoon following another truck with adaptive cruise control (ACC). These scenarios are intended to address the possibility of “background aerodynamic platooning" impacting realized savings on public roads. Using calibrated J1939 fuel rate analysis, fuel savings for curved track sections versus straight track sections were also evaluated for these scenarios, highlighting differences in the implementation of the CACC control strategies compared to a stock ACC implementation. The use of different trailer types and the presence of passenger-vehicle traffic patterns showed a measurable impact on platoon performance in some conditions, but the basic fuel savings trends were retained.

Introduction

Wind-tunnel studies [1, 2, 3, 4, 5, 6] and track-based fuel-economy studies [7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17] have identified trends in aerodynamic drag reduction associated with vehicles in close proximity and linked them to the resulting fuel savings, whereas computational studies [6, 13, 18, 19, 20, 21, 22, 23, 24, 25] have provided some insight on the aerodynamic mechanisms that lead to these beneficial effects.

From the literature noted above, it has been inferred that there are two dominant aerodynamic phenomena that lead to reduced drag and fuel consumption. 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. 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. For two Class 8 combination vehicles with van trailers, both vehicles can experience a reduction in aerodynamic drag at separation distances below about 20 to 30 m, while the effect on the trailing vehicle is sustained to much greater separation distances.

This paper is the second in a series that focuses on a track-based investigation of the fuel savings of a truck platoon with increasing levels of real-world complexity. This is done, in an attempt to identify the variability of platoon energy savings that must be accounted for when modelling the large-scale environmental benefits of introducing these systems into North American highway networks. These track tests, based in large part on the SAE J1321 Type II fuel consumption test procedure [26], provide controlled conditions to reliably estimate and model the potential for energy savings while systematically introducing the complexities encountered on general roadways.

The first paper in this series [27] examined the influence of lateral alignment on the fuel-savings benefits of a two-truck platoon, and demonstrated for separation distances between 9 m and 23 m (30 ft and 75 ft) a measurable decrease of 3% to 4% in fuel savings (relative to about 10% when aligned), with a lateral offset between the lead and trailing trucks equivalent to half a truck width (1.3 m). Although the quarter-width-offset (0.65 m) results of that study were inconclusive due to large differences in wind conditions between the respective tests, these results and those of other wind-tunnel-based studies [4, 5] suggest that a moderate degradation on the order of 1% to 2% may be experienced for lateral offsets within a lane width (up to about 0.8 m). This is only one of many factors of real-world driving that must be understood.

Most of the published truck-platoon energy-savings investigations to date have considered homogeneous platoons of essentially the same vehicle shape (sleeper-cab tractor with a van trailer) travelling in isolation of any other traffic. In reality, these systems will be required to pull a range of trailer types and operate with surrounding traffic.

Platooning with Varieties of Trailer Shapes

Although the vast majority of combination vehicles on the road are comprised of van-type trailers, a CACC- or platooning-enabled tractor may be pulling other types of trailers such as flatbeds, dumps, tankers, belts, etc. An assessment of fuel-savings benefits with a platoon that includes non-van-type trailers is important to support the quantification of the potential large-scale energy-savings and environmental impacts of platooning.

Of the trailer shapes that most differ from van trailers, empty flatbeds or those with low-height cargo are a good example because their low geometric profile changes the aerodynamic behavior of the vehicle and changes the air wake behind the vehicle.

McAuliffe [28] provides aerodynamic drag-coefficient data for various flatbed configurations, with and without generic cargo shapes, and contrasts them to a standard dry-van trailer, which differs somewhat from the aerodynamic performance of the low-drag trailer configuration tested in the current study. Under low or negligible cross-wind conditions, the empty flatbed pulled by a high-roof tractor demonstrates a similar drag coefficient as the standard dry-van trailer under the same conditions. With an 11 km/h cross wind (standard value used for the U.S. wind climate, per SAE J1252 [29]) the flatbed exhibits a 10% lower aerodynamic drag than the equivalent dry-van condition. When considering the full wind climate through the use of the wind-averaged-drag coefficient, the data shows a 5% reduction in aerodynamic drag for the flatbed trailer, compared to a standard dry-van trailer, when pulled by a high-roof tractor. The addition of cargo to the flatbed trailer changes the shape of the vehicle and, depending on the shape and position, increases its drag [28].

The dry-van trailers used in many of the recent track-based fuel-consumption investigations, including the current one, were outfitted with drag-reduction technologies, such as trailer side-skirts and boat-tails, which provide lower baseline vehicle drag on the order of 10% to 20% [28, 30, 31, 32, 33]. The predecessor studies to the current track tests used the same aerodynamic products as the current study, which were demonstrated to reduce the drag of the vehicles by approximately 7% [15]. When compared to low-drag dry-van trailers, flatbed-configured vehicles may therefore exhibit aerodynamic drag on the order of 10% to 15% higher. From a fuel-use perspective, this might translate to increased fuel use on the order of 10% for an empty, or near-empty, flatbed trailer with a high-roof tractor in long-haul applications. These differences due to aerodynamic variations in vehicle performance may influence the characteristics of the air wake and therefore may influence platoon performance.

In the current experiments, the impact of introducing a flatbed trailer into a two-truck platoon was investigated. Fuel consumption tests were performed with a flatbed trailer placed in either the lead- or following-vehicle location, in lieu of a dry-van trailer, and results were compared to the platoon with two dry-van trailers.

Platooning with Surrounding Traffic

While the savings from two- and three-truck platoons in isolated, free-stream air flow are well established [11, 12, 15, 16, 17] there has been considerable question about platoon fuel savings performance in the real world of mixed highway traffic. It has been shown that trucks have significant fuel savings as far back as 87 m behind another truck or even a light-duty SUV [17] - distances well beyond planned coordinated "platooning" distances and assumed to be occurring on North American highways today. There has been concern that fuel savings that trucks commonly experience in traffic today, due to this "background platooning" effect, could negate some of the intended fuel savings from coordinated safe truck platooning.

Using the same two-truck CACC system as the current study, Smith and Bevly [34] attempted to evaluate the fuel savings benefits in real-use conditions. The data were inconclusive on whether fuel-savings benefits were achieved, but the study lacked a proper control vehicle to account for changes in the operational environment.

In a previous track-based study, McAuliffe *et al.* [17] demonstrated a single truck following an SUV at 43 to 87 meters experienced fuel savings in the range of 1.5-2.6%. In addition, two- and three-truck platoons following the SUV had savings that were not statistically different from their no-traffic performance.

As an extension to a wind-tunnel study of truck platooning, McAuliffe and Ahmadi-Baloutaki [35] examined the impact of close-proximity traffic on the aerodynamic drag experienced by a single tractor-trailer combination, and demonstrated drag reductions equivalent to their platooning results (upwards of 16% drag reduction) with patterns of up to five smaller vehicle models upstream and adjacent to the truck model.

As noted by Wang et al. [36] in their recent survey of research into longitudinal motion control of connected vehicles, in addition to energy savings, vehicle platooning has the potential to increase road capacity by permitting more vehicles on the road resulting from the reduced inter-vehicle spacing. Assuming that future platooning technologies target these dual benefits, this will provide an environment that not only differs significantly from the "isolated platoon" investigations that have become the foundation of energy-savings investigations, but that creates a more dense traffic environment in which the close-proximity effects may have a greater impact.

The following series of experiments are intended to address these concerns by simulating various "highway" traffic airflow disturbances in the controlled environment of the test track under steady-state repeatable conditions. Fuel-consumption measurements of a two-truck platoon were performed with several scenarios of surrounding traffic, including an individual upstream vehicle, a pattern of three upstream vehicles, and some dynamic conditions with periodic vehicle passing. Many of these scenarios were tested first for the individual trucks with the respective surrounding traffic, in order to reliably compare test results, and to account for the influence of the different control strategies of each of the vehicles (stock ACC for the lead vehicle and prototype CACC for trailing vehicle).

Background and Methods

CACC System Description

A cooperative adaptive cruise control (CACC) platooning system is used in the current test campaign. The system allows for automated longitudinal control of a following vehicle, while the lead vehicle operates using a stock adaptive cruise control (ACC). The CACC system was previously documented [34, 37, 27], but a few items are provided here for clarity. Overall, the system has three components: a dedicated short-range communication (DSRC) radio network for vehicle–to-vehicle (V2V) communication, the upper-level control system, and the by-wire kit. The upper-level system includes the software and algorithms necessary for CACC platooning. The by-wire kit is the vehicle interface where data are read from the CAN bus. Additionally, automated vehicle control is accomplished by generating controller-area-network (CAN) commands and controlling the vehicle through the by-wire kit.

The system is implemented for two heavy-duty trucks and enables CACC platooning. On the lead vehicle, the same CACC system exists even though control is accomplished by the stock ACC. The system collects and processes sensor data and then transmits them across the V2V network for the following vehicle to use. In the current work, a variety of mixed-traffic scenarios are introduced. These scenarios include tests where the "CACC controlled" second vehicle follows another vehicle, i.e. a passenger vehicle. This is accomplished by placing an external, mobile system that mimics the CACC system setup. The external system includes a GPS receiver, DSRC radio, and computer. Functionally, this system allows for the heavy-duty truck to "platoon" with any vehicle in which the mobile system is placed.

The CACC system objective is to follow the lead vehicle at the specified reference distance. In this testing, the fuel-savings results are quantified as a function of following distance. As documented in the first paper of this series [27], over an entire test the average and standard deviation of the error while platooning were 0.00 m and 0.34 m, respectively.

Test Setup and Procedures

Test Vehicles

Three Class 8 heavy-duty tractors with 53 ft dry-van trailers were used as test vehicles in the fuel-economy study. Both lead and follower tractors were Peterbilt 579's (model year 2015) and the control truck was a Freightliner Cascadia (model year 2016). Trucks 1 (lead) and 2 (follower) are shown in Figures 1 and 2 and the control truck is shown in Figure 3. The SAE J1321 fuel-consumption test procedure [26] requires identical vehicles to be used. In this study, however, the use of different tractor models for the test and control vehicles does not strictly conform to the SAE J1321 requirements. All tractors are aerodynamically-treated with high roof fairings, chassis skirts, side extenders, and aerodynamic bumpers, and were therefore expected to react similarly to changes in the environment that affect aerodynamic performance, particularly the ambient winds. More details about the test vehicles are presented in Table 1.

The trailers of all three vehicles were ballasted to provide a total vehicle mass of 29,500 kg (65,000 lb). The trailers were ballasted using concrete blocks aligned evenly along the centerline of the trailer. Fuel levels in the main tanks of the trucks were adjusted to match the weight amongst all three vehicles.

Figure 1. Side-view photograph of Trucks 1 and 2 with 53-ft dry-van trailer and 9 m (30 ft) spacing.

Figure 2. Offset front-view photograph of Trucks 1 and 2 with 53-ft dry-van trailer and 9 m (30 ft) spacing.

Figure 3. Photograph of control truck with 53-ft dry-van trailer.

Figure 4. Side-view photograph of Truck 1 with the 53-ft flatbed trailer and Truck 2 with the 53-ft dry-van trailer at 9 m (30 ft) spacing.

A single flatbed trailer was also used for some of the tests, and paired with either Truck 1 or Truck 2. The flatbed trailer was also ballasted using concrete blocks clustered near the middle of the bed, as shown in Figure 4.

To examine the impact of surrounding traffic, additional vehicles were introduced onto the track in a controlled manner. These vehicles were passive, in that they were introduced to modify the boundary conditions for the test and no measurements were acquired from them. Up to seven additional light-duty passenger vehicles were used: 1 compact SUV, 3 mid-sized SUVs, 1 compact sedan, 1 mid-size pickup truck, and 1 full-size pickup truck. Three of these vehicles (1 mid-size SUV, 1 compact sedan, and 1 full-size pickup truck) were used for a large portion of the testing to provide an arrangement of vehicles upstream of the trucks that would be representative of driving in highway traffic conditions.

Table 1. Test vehicle specifications.

Specification	Leader	Follower	Control Truck
Name	Truck 1	Truck 2	Control Truck
Manufacturer	Peterbilt	Peterbilt	Freightliner
Model	579	579	Cascadia
Year	2015	2015	2016
Engine	Paccar MX-13	Cummins ISX15	Detroit DD15
Brake System	Bendix	Meritor Wabco	Wabco 4s/4m
Transmission	Eaton Fuller Automated 10 speed	Eaton Fuller Automated 10 speed	Detroit DT12-DA-1750
Trailer	Manac 53' Dry-van Trailer with Transtex EDGE SKIRT 2330 and Stemco TrailerTail Trident or Manac 53’ Flatbed Trailer	Manac 53' Dry-van Trailer with Transtex EDGE SKIRT 2330 and Stemco TrailerTail Trident or Manac 53’ Flatbed Trailer	Manac 53' Dry-van Trailer with Transtex EDGE SKIRT 2330 and Stemco TrailerTail Trident
Trailer Load	29,500 kg	29,500 kg	29,500 kg

Figure 5. Track-side view of the test track showing a banked curved segment.

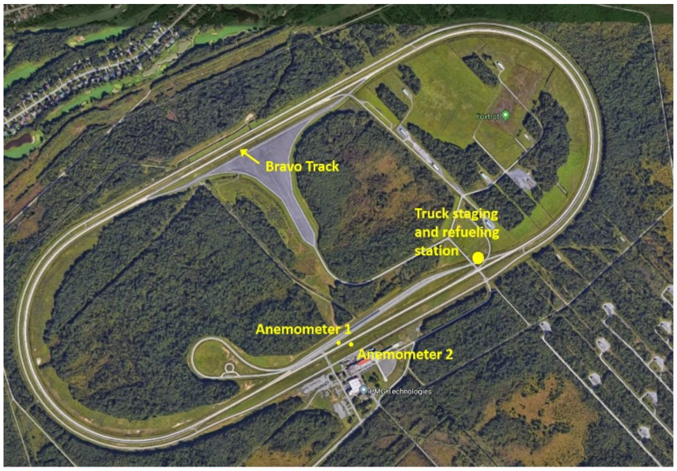

Figure 6. Aerial view of the test track; Location of Track-side anemometers and truck refuelling and staging are shown by yellow circles.

Test Site

Testing was performed at the Transport Canada Motor Vehicle Test Centre operated by PMG Technologies in Blainville, Quebec at 45.70 latitude and -73.87 longitude. The “Bravo” track was used for testing, which is a high-speed track with a primary surface of rain-grooved concrete. The track is 6.5-km (4.0-mile) long oval shape with two straight 1.6-km (1.0-mile) sections, and two 1.6-km (1.0-mile) constant-curvature banked sections. An image showing the level of curvature and bank is shown in Figure 5 and an aerial view of the test track is shown in Figure 6.

Measurements and Instrumentation

To understand the behaviour of the tested vehicles better, a variety of parameters on each truck were measured and recorded using an IMC data acquisition system. Measurements included geographical position, on-board wind measurements, cooling flow measurements, ambient and under-hood temperature measurements, engine-cooling performance, driveshaft torque measurements, in addition to several variables from the vehicle network using the CAN bus protocol. Geographical latitude and longitude of all trucks were recorded at a rate of 5 Hz using GPS antennas that were mounted on the roof of each tractor.

The gravimetric fuel-economy measurements were undertaken using auxiliary fuel tanks with re-routing of fuel lines with quick-connect couplings. The auxiliary fuel tanks were mounted on the frame rails in the tractor-trailer gap (see Figure 7), and were exchanged by forklift between each measurement run. The fuel tanks were weighed using a precise scale with an accuracy of 0.02 kg that was verified periodically throughout the test campaign.

Track-side wind measurements were undertaken using sonic anemometers at mid-truck height (approximately 2 m). A weather station, located approximately 100 m from the track at a height of 3.0 m (10 ft) acquired 10-second mean environmental conditions for the site. Additionally, a number of useful parameters pertaining to this study such as engine fuel rates were also recorded from the vehicle networks for all three trucks using the CAN bus protocol at a rate of 10 Hz.

Figure 7. Auxiliary fuel tanks mounted in the tractor-trailer gap.

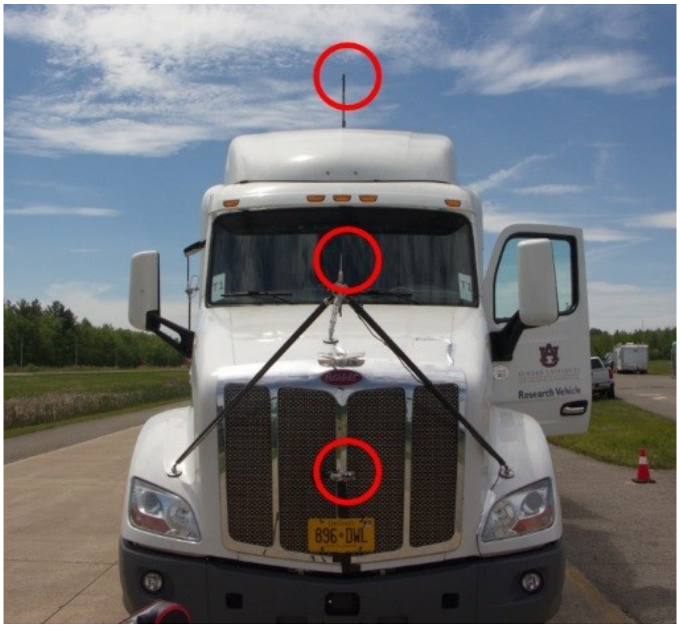

Figure 8. Location of grille vane anemometer (lower red circle), front Cobra Probe (middle red circle), and trailer Cobra Probe (top red circle) on Truck 1.

When platooning, the flow rate through the front grille is reduced in the trailing trucks. To evaluate the engine cooling capacity under these conditions, additional on-board wind measurements were undertaken, as mentioned above. Vane anemometers were mounted to the front grille of each test vehicle. On-board wind measurements were performed for Trucks 1 and 2 using “Cobra Probes” located at the front of the tractor on a tripod boom. Truck 1 was also equipped with an additional Cobra Probe mounted above the trailer at approximately 5 m above the ground. The Cobra Probe, manufactured by Turbulent Flow Instrumentation Pty Ltd., is a fast-response four-hole pressure probe that measures the fluctuations in wind speed, wind direction, and pressure [38]. Both vane anemometers and Cobra Probe data were sampled at 200 Hz. The locations of the vane anemometer and two on-board Cobra Probes on Truck 1 are shown in Figure 8. Due to the proximity of the vane anemometers and Cobra probes to the vehicle, their measurements do not represent the freestream wind conditions.

Test Procedures

The fuel consumption measurements were performed according to the SAE J1321 Type II procedure [26]. This procedure is designed to evaluate changes in fuel economy pertaining to modification to a vehicle. For the purpose of this test, the definition of “modification” has been extended to consider platooning as a modification to the aerodynamics shape of a vehicle. As noted earlier, the J1321 procedure requires the use of the same truck models and specifications, but the three vehicles were different. The J1321 procedure also requires the local winds to not exceed 20 km/h; however, some testing was completed with winds exceeding these limits. This test program is therefore not strictly valid as a J1321 result, but the J1321 procedure has been used as a guide in this research effort. To meet the minimum distance requirements of the J1321 procedure, each test run consisted of 13 laps providing 85 km (52 mi) of travel per run. A minimum of three test runs were performed for each condition, except for the dynamic mixed traffic tests (described below) for which a single test run was completed for each configuration.

Isolated Vehicle or Platoon Tests

For baseline test segments, the three vehicles (two test vehicles and a control vehicle) were spaced approximately 2 km from each other during testing. Nine baseline runs were conducted throughout the test campaign, and used as a verification check that the vehicle fuel-consumption performance remained consistent. For the isolated truck-platoon tests, the control truck was spaced between 2 km and 3 km from the truck platoon. The trucks maintained a speed of 105 km/h (65 mph) for the duration of the test runs, using their respective cruise-control systems, with independent checks by a track-side radar located on the north-side straight segment of the track.

Steady Mixed-Traffic Tests

For the steady-state mixed-traffic tests, the lead truck followed a mid-size SUV at 78 meters using the stock ACC system in the right (outside) lane, while in the left (inside) lane a full-size pickup truck and compact sedan were arranged longitudinally between the SUV and the truck as shown in Figures 9 and 10. This same “traffic” pattern was also used in the single-truck test and conducted independently for Truck 1 and Truck 2 to create “traffic baseline” performance for which to evaluate platoon effects on fuel consumption while travelling with other traffic.

Figure 9. Photograph of the side view of a truck platoon following the light-duty-vehicle traffic pattern.

Figure 10. Offset front-view photograph of the light-duty-vehicle traffic pattern in front of a single truck.

Figure 11. A view of transient traffic test #2 from inside an approaching pickup truck; dark-coloured SUV at a fixed distance in front of the platoon and the light-coloured SUV passing the platoon.

Dynamic Mixed-Traffic Tests

For two test runs, the seven passenger vehicles were introduced on the track, in addition to the two test trucks and the control truck, to assess the impact of transient traffic on the fuel-savings benefits for truck platooning. The trucks drove at a speed of 105 km/h whereas the passenger vehicles travelled at 130 km/h for most of the run. With this difference in the speeds, approximately half of these vehicle passed the trucks three times during a 13-lap run, while the others passed the trucks only twice. As the passenger vehicles approached the two-truck platoon or the control vehicle, they reduced their speed to 110 km/h and pass the platoon with a differential speed of 5 km/h, speeding up again to 130 km/h several truck lengths ahead of the platoon.

Figure 11 shows an example of the vehicle patterns used for one of the dynamic-passing tests. This photograph was taken from inside the mid-sized pickup truck. Note the dark-coloured SUV travelling in the outer lane at a fixed distance from the platoon and the light-coloured vehicle in the inner lane that had recently passed the platoon. The nominal spacing between passenger vehicles (approximately 900 m) was greater than that shown in Figure 11, which was taken at the start of the test run as vehicles were being deployed from this starting pattern behind the trucks.

Analysis Procedures

J1321 Gravimetric Fuel Consumption Analysis

The fuel-consumption data have been analyzed using the method described in the SAE J1321 Type II procedure [26]. The method was devised to minimize the influence of environmental and external factors that may change from run to run or from day to day. It makes use of fuel-use ratios between the test vehicles and the control vehicle, and relies on an assumption that the change in external factors affects the control vehicle in the same manner as the test vehicles. The ratio of test-vehicle fuel use (T) to the control-vehicle fuel use (C) is defined as:

$$T/C = \frac{m_{f,test}}{m_{f,control}} \tag{1}$$

where m_f represents the weight of the fuel consumed for the respective vehicle during a measurement run, as inferred through measurement of the fuel-tank weights before and after each test run. The fuel-savings measure is based on averages of the T/C ratios from the respective baseline runs and test runs and calculated according to:

$$\Delta F = \frac{\overline{(T/C)_{baseline}} - \overline{(T/C)_{test}}}{\overline{(T/C)_{baseline}}} \tag{2}$$

Data quality checks, described in SAE J1321 [26], are performed by means of a comparative statistical analysis to define the validity of a measured ΔF value, and to assign an uncertainty value associated with a 95% confidence interval.

For test cases for which the separation distance is greater than 25 m, the lead vehicle in these analyses is generally used as the control vehicle, as described in the first paper of this series [27].

When calculating the total platoon fuel savings, the mass used in Equation 1 consists of the summation of the fuel mass consumed by the lead and trailing trucks. Under conditions for which the lead and trailing truck baseline T/C values were measured at different times (flatbed and surrounding-traffic conditions), this summation could not be accomplished. Rather, the averaged T/C values for each truck's reference condition were added together to form the combined baseline T/C value for the full platoon. The confidence intervals for these full-platoon conditions were estimated by a perturbation-theory approach similar to that of Moffat [39], rather than by the comparative statistical analysis of the J1321 method. Uncertainties in the corresponding individual T/C values are represented by twice the standard deviation of their respective measurements to provide a 95% confidence interval.

Track-Segment Analysis

The Bravo Track at the Motor Vehicle Test Centre has straight and curved segments (see Figure 6). To evaluate differences in fuel use and fuel-savings performance between the two types of road segments, a fuel-rate-based formulation of the SAE J1321 procedure was developed and documented in the first paper in this series [27]. The analysis is based on a calibration of the J1939 CAN bus fuel-rate signal against the measured fuel use during the test. Linear calibrations were observed, resulting in the following approach for evaluating the mass flow rate of fuel compared to the indicated volumetric flow rate of fuel:

$$\dot{m}_f = C_f \cdot \dot{V}_f \tag{3}$$

where C_f is the linear calibration coefficient, evaluated separately for each vehicle. The uncertainty estimates of these calibration coefficients, which are on the order of 1%, have been carried through the analysis to ensure they are reliably accounted for in the results.

The track-segmented fuel-savings analysis was performed using the same data analysis procedures as the SAE J1321 analysis. The track was broken down into four segments (east curve, north straight, west curve, south straight). The fuel used for each segment of each lap was calculated, from the calibrated fuel-rate signals, for each test run. A T/C value was then calculated for each segment in the following manner:

$$T_i/C(lap, segment) = \frac{C_{f,i}\int_{t,i,start}^{t,i,end} \dot{V}_{f,i} dt}{C_{f,C}\int_{t,C,start}^{t,C,end} \dot{V}_{f,C} dt} \tag{4}$$

where the subscripts i and C represent the vehicle of interest (1 or 2 for the test vehicles, C for the control vehicle). The fuel consumed for each segment within a lap was calculated based on the duration over which the respective vehicle was within the respective segment of the track. To provide a measure of consistency, data for the first and last laps of each test run were excluded from the analysis, to eliminate the acceleration and deceleration transients, thus providing data that represents steady-state driving conditions (11 laps per test run). For some test configurations, large transients in fuel use were observed during a run, associated with either changes in the lead driver behaviour, or influences of the cruise-control system of the lead truck. Any such transients that exceed approximately ± 50% of the nominal fuel rate for a given location on the track (based on visual inspection of the fuel rate signals) were excluded from these analyses. A minimum of 20 laps of data were used for the the majority of test configurations.

Front-Grille Wind Speed Analysis

As described earlier, each of the two test vehicles was outfitted with vane anemometers on the front grille and wind-velocity probes (Cobra Probes). For the purpose of examining the wake influence of surrounding traffic, the grille-mounted vane anemometer measurements were used to characterize the wind-speed deficit experienced by the trucks when traveling behind other vehicles. Being the lowest-mounted wind measurement devices, these were assumed to best represent the wake effects of the smaller passenger vehicles. In isolated driving, the ratios amongst the speeds of all measurements (vane anemometer and wind-velocity probes) are consistent for a given vehicle for each test run, indicating similarity in the flow field of the vehicle relative to the free-stream winds.

A metric has been devised that relates the grille-anemometer wind speed while travelling in other traffic to that experienced when traveling in isolation:

$$R_G = \frac{U_G}{U_{G,iso}} \tag{5}$$

where U_G is the indicated grille-anemometer wind speed, and $U_{G,iso}$ is the value while driving in isolated conditions, in the absence of upstream vehicles. During a test with upstream traffic, U_G and $U_{G,iso}$ cannot be measured simultaneously, and therefore the similarity of the flow field in isolated scenarios is used for this purpose. The high-mounted wind-velocity probe at 5 m from the ground is assumed not to be influenced by upstream vehicles, and therefore the ratio of grille-anemometer wind speed (U_G) to the high-mount wind speed (U_H) will vary under conditions when the truck is experiencing wake effects. This ratio, under isolated conditions, was calculated from all baseline test runs:

$$R_{G,H} = \overline{\left(\frac{U_G}{U_H}\right)_{iso}} \tag{6}$$

from which R_G can be calculated during a test run by the following:

$$R_G = \left(\frac{U_G}{U_H}\right)\frac{1}{R_{G,H}} \tag{7}$$

A track-segmented approach was taken for this analysis such that a single value of R_G is calculated for each segment of each lap, and all respective lap/segment values subsequently averaged for the corresponding condition of interest. The grille-anemometer data for Truck 2 also uses the high-mount velocity-probe data of Truck 1 for this analysis, under the assumption that the ambient test conditions for the respective segment and lap are similar, comparable to the approach used for the track-segmented fuel-savings analysis.

Results and Discussion

Baseline Platooning Benefits

The current work deals with the impact of mixed-traffic scenarios on the performance of truck platoons. This work is related to a concurrent paper, the first in this series, that deals with other questions around platooning. The results and discussion of this

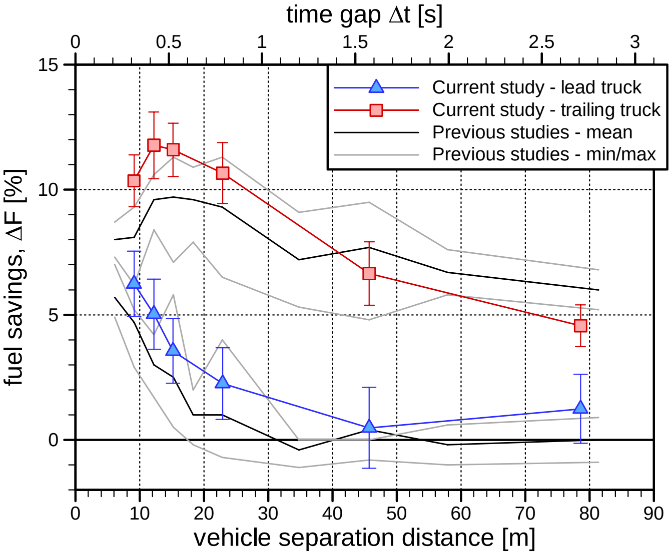

Figure 12. Current individual truck savings compared to past results
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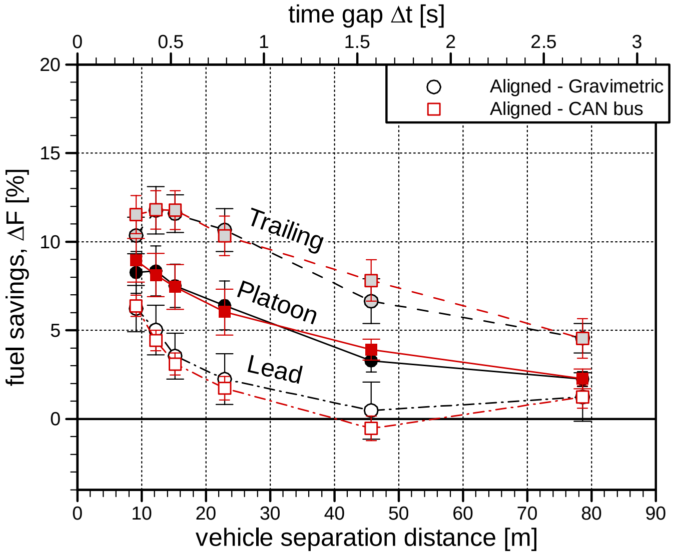

Figure 13. Comparison between the fuel economy results using the calibrated CAN-bus fuel-rate signal and the gravimetric procedure, for the aligned platoon.

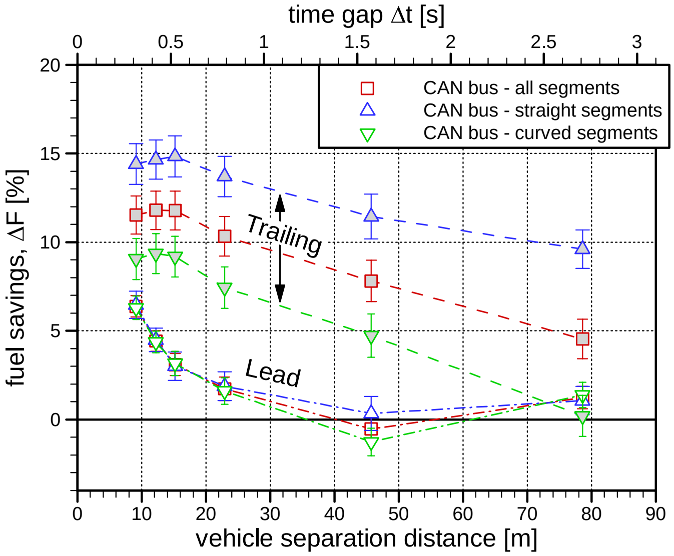

Figure 14. Comparison of the fuel savings of the aligned platoon for the straight and curved segments of the track to those of the full track.

section are summarized from that paper [27] to provide context for the remainder of this paper.

Figure 12 shows how the lead and trailing trucks in the current work compare to previous studies. Both trucks generally demonstrated 1% to 2% higher savings than the average of the previous studies at distances less than 46 m (150 ft). At most points the confidence intervals of the new work overlaps the maximum of the previous studies, indicating that the range of possible results includes a common answer. Both the lead and trailing trucks demonstrate the previously established savings trends as the separation distance is reduced - quickly increasing savings for the lead vehicle at distances less than 15 m (50 ft) and savings for the trailing vehicle steadily increasing to a maximum at about 12 to 15 m (40 to 50 ft) followed by reduced savings at closer distances.

Figure 13 compares, for the aligned platoon, the test results of the J1321 gravimetric fuel-savings analysis to that the equivalent analysis using the track-segmented CAN bus fuel-rate approach. The CAN-bus fuel-rate confidence intervals have been calculated to include the influence of calibration uncertainty in addition to the statistically-defined uncertainty due to variance of the data points. The two analysis methods compare well. The first paper in this series [27] describes potential reasons for the differences at some separation distances.

With the verification based on Figure 13 that the CAN-bus fuel-rate data can be applied with the J1321 fuel-savings-analysis procedures, the fuel-rate data were interrogated to identify the fuel savings for each segment of the test track (east curve, north straight, west curve, south straight), from which the differences in curved versus straight track segments have been evaluated. Figure 14 shows the differences in platoon fuel savings between the straight and curved segments of the track, compared to the track-averaged results. The lead truck shows no measurable difference between the straight and curved segments, whereas the trailing truck shows a 6% difference at the shortest separation distances and 10% difference at the largest separation distance, with larger fuel savings on the straight segments.

Platooning with a Flatbed Trailer

When platooning technology becomes commonplace on the road, platoons will inevitably be formed with different combinations of tractor types and trailer types. This study examined the replacement of a single dry-van trailer in the two-truck platoon with a flatbed trailer (see Figure 4) in either the lead or in the trailing position. The baseline fuel use of the flatbed-configured trucks differs from that of the dry-van-configured trucks. Table 2

Table 2. Change in fuel use for each truck when the dry-van trailer was replaced with a flatbed trailer, when driving in isolation.

Vehicle	**% Change**
Truck 1 (lead)	+11.5 ± 1.5
Truck 2 (trailing)	+12.1 ± 1.2

shows that the flatbed-configured trucks use approximately 12% more fuel. These results are of similar magnitude to the estimates provided in the introduction of this paper (up to about 10%) when replacing an aerodynamically-outfitted van trailer with an empty flatbed.

The fuel-savings results presented herein for the flatbed scenarios use the corresponding isolated-dry-van or isolated-flatbed test results as a baseline for each vehicle, such that the results represent differences associated with platooning only. Testing was completed at three separation distances for each of two platoon configurations (flatbed in lead or in trailing position).

The fuel-savings results for the platoon configuration with the flatbed in the trailing position are shown in Figure 15, for which the results are compared to the reference two-dry-van configuration results. Due to time constraints, only a single test run was conducted at the 46-m (150-ft) separation distance and therefore those results are not valid per the SAE J1321 analysis procedure. However, those data points provide an indication of the expected results and are included in the graphs for completeness. The CAN-bus fuel-rate analysis provides identical trends to those of the gravimetric test results of Figure 15 and are therefore not introduced here as supplementary data for the analysis.

The results of Figure 15 show slightly-reduced fuel use for the lead vehicle at the two closest separation distances tested of 9 and 15 m (30 and 50 ft), as compared to the two-dry-van case, however these results are within the corresponding confidence intervals. With the trailing vehicle having the same high-roof tractor, and therefore a similar influence on its upstream flow field, it was not expected that the lead vehicle would exhibit differences in the fuel savings regardless of the type of trailer being pulled by the trailing vehicle.

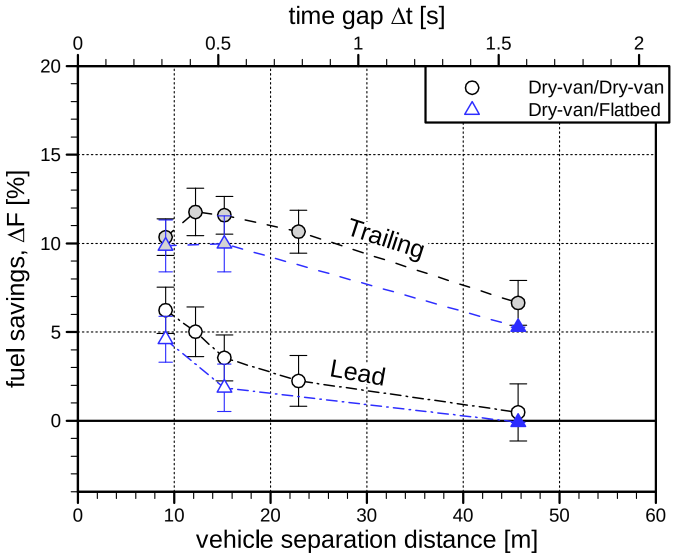

Figure 15. Gravimetric fuel-savings results for the flatbed trailer in the trailing-vehicle position (solid-filled symbols at 46 m separation distance are non-valid J1321 test results due to a single test run being conducted).

The trailing vehicle also shows similarity in fuel-savings results between the flatbed and dry-van configurations, within the confidence intervals of the experimental test data. Considering the confidence intervals, the data in Figure 15 indicate that when a flatbed is placed in the trailing-vehicle position, the fuel savings for a two-truck platoon are not expected to differ significantly from a platoon with two dry-van trailers. The consistency in the trend of slightly-reduced fuel savings for both vehicles may be an indication that this effect is real and that introducing the flatbed may provide a small decrease in fuel savings.

When the flatbed is moved to the lead-truck position, the fuel-savings trends differ from those of the two-dry-van platoon, as shown in Figure 16. The lead truck exhibits a significant reduction of fuel-savings benefit at the two closest separation distances. With reference to the aerodynamic mechanism that provides a benefit to the lead vehicle of a platoon, for which the high-pressure field forward of the trailing vehicles creates a pushing effect on the lead vehicle, the elimination of a large vertical surface against which the pressure field can act is the likely cause for the reduction of benefits at the shorter separations. Only the 9-m (30-ft) test case shows the full confidence interval exceeding zero, and is therefore the only separation distance at which these test results indicate a potential savings for the lead truck when it pulls a flatbed trailer.

The trailing vehicle results of Figure 16 show an interesting and unexpected trend. They exhibit a continuous increase in fuel-savings benefit as the separation distance is reduced, unlike the case with the dry-van in the lead position for which the benefit reaches a peak in the 12- to 15-m (40- to 50-ft) range. The physical mechanism that causes this change in fuel savings at close separation distance is unclear, but it is likely associated

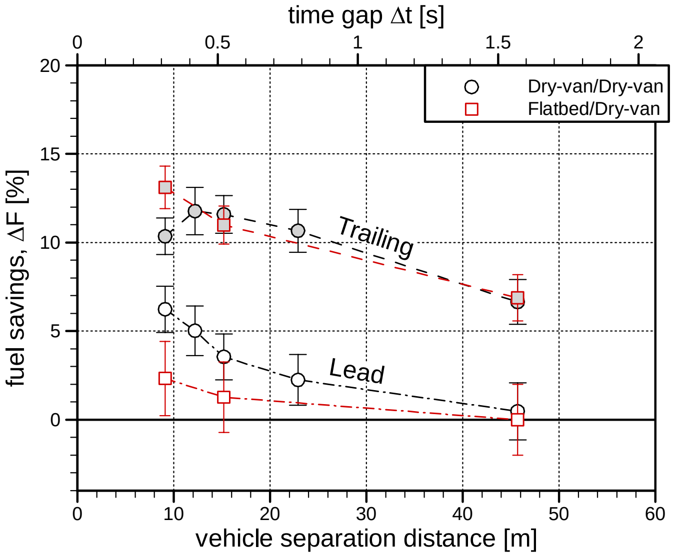

Figure 16. Gravimetric fuel-savings results for the flatbed trailer in the lead-vehicle position.

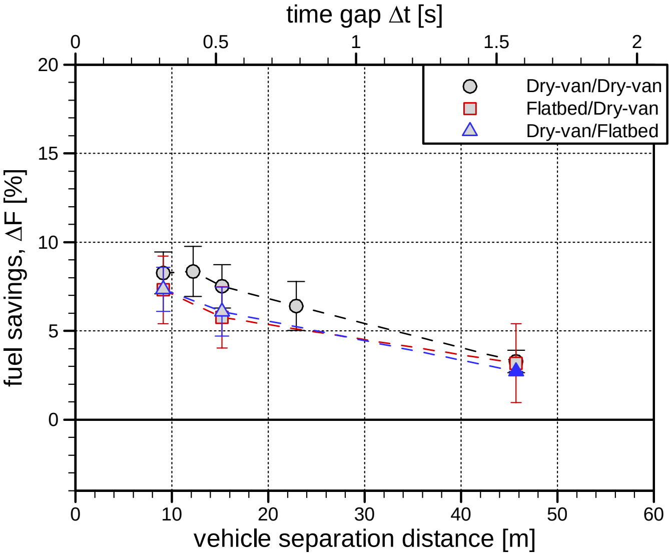

Figure 17. Gravimetric fuel-savings results for the flatbed-trailer platoon configurations compared to the two-dry-can configuration (solid-filled symbol at 46 m separation distance for dry-van/flatbed data is a non-valid J1321 test results due to a single test run being conducted).

with the manner in which the aerodynamic wake of the lead vehicle interacts with the rounded front surfaces of the trailing vehicle, as highlighted by recent aerodynamic studies of cab-over-type tractor shapes [6]. Those studies have identified a trade-off between the reduction in stagnation pressure on the body's perpendicular surfaces (positive drag) and the reduction in forward-oriented suction on the rounded corners (negative drag). More research is required to understand this phenomenon, particularly for North American truck shapes, and the differences between dry-van and flatbed air wakes.

Given the different trends observed for flatbeds in the lead or trailing position in a platoon, the total fuel savings for the platoon is of interest to understand the overall effects on the potential energy savings of platooning when introducing flatbed trailers into the mix of vehicles. Figure 17 shows the calculated fuel savings of the complete two-vehicle-platoon system for the flatbed test cases compared to the two-dry-van case. Both flatbed cases show a small decrease in the total platoon fuel savings, but the confidence intervals for all configurations overlap at each separation distance. Although the consistent trends of reduced fuel use for the flatbed cases at each of the tested separation distances suggests that flatbeds reduce the potential energy savings, a conclusion cannot be clearly made given the uncertainty of the measurements. It is also to be noted that these measurements represent a percentage fuel savings, not an absolute fuel savings. The higher fuel use of the trucks with the flatbeds (Table 15) provides a higher baseline fuel use for these mixed platoons (approximately 6% higher), and therefore a given percentage fuel savings for these cases will provide greater magnitude of absolute fuel savings (and proportional costs) than for the two-dry-van platoon by approximately 6%.

Platooning Benefits in Steady-State Mixed Traffic

Prior to discussing the impact of surrounding traffic on the fuel-savings benefits of truck platooning, the impact to a single truck should be understood. As noted earlier, there has been concern that trucks experience ambient "background platooning" savings in traffic today that could negate some of the intended fuel savings from coordinated safe truck platooning. The following series of experiments are intended to address these concerns by simulating various "highway" traffic airflow disturbances in the controlled environment of the test track under steady-state repeatable conditions.

Single Truck Following Single SUV

In a previous study, McAuliffe *et al.* [17] demonstrated a single truck following an SUV at 43 to 87 m experienced fuel savings in the range of 1.5-2.6%, and that two- and three-truck platoons following the SUV had no statistically-significant difference in savings from their no-traffic performance. In the current work, Truck 1 following an SUV at 78 meters (using the stock ACC system) demonstrated 4% fuel savings gravimetrically and 3.6% using the CAN bus calibrated results, as presented in Table 3. This is a significantly higher fuel savings than reported in the previous work, given the extended distance and the fact that this is a mid-sized SUV. However, the generally-higher platooning fuel savings observed in this study could be a result of the tractor shape in this test being better suited to benefiting from disturbed air flow, rather than the tractor shapes used in the previous study. Interestingly, the track-segmented results for Truck 1 showed 6.5% savings on the curved segments and no savings on the straight track segments. It is not known why this would be; recall that for the basic aligned isolated platoon case the following vehicle generally experienced higher fuel savings in the straight sections than in the curved sections and it would be expected that this pattern would hold while following a light-duty SUV.

Table 3. Single truck following single SUV - J1321 and CAN-bus fuel-savings results.

Calculation Method	**Truck 1 [%] (ACC)**
J1321	4.0 ± 0.8
Full Track CAN bus	3.6 ± 0.8
Straight Segment CAN bus	-0.1 ± 0.8
Curved Segment CAN bus	6.5 ± 0.8

Single Truck with Surrounding Traffic

For this test, an array of three light-duty vehicles was arranged in a pattern ahead of the single truck (and later the platoon). See earlier Figures 9 and 10 for photographs of this arrangement. Testing using this "traffic" pattern was conducted independently for Truck 1 and Truck 2 to create "traffic baseline" performance from which to compare platoon performance against in a later section.

Using the standard gravimetric fuel measurement method, Truck 1 demonstrated 7.4% fuel savings from the traffic while Truck 2 showed 4.6% savings. This range of savings is similar to what is expected following another truck at 40 to 80 meters. It is not known why the two trucks experience such differences in savings. It could be related to ambient conditions or the differences in their control systems used to set the following distance in the tests. Looking at the track-segmented CAN-bus data offers a clue. In Table 4 it is clear that the two trucks are performing differently. While the full-track CAN-bus results are close to the J1321 results, the track-segment analysis shows Truck 1 has much higher fuel savings in the curved sections than the straight sections, while Truck 2 has the opposite (and expected) trend of higher savings on the straight segment. The higher savings of Truck 1 in the curved sections is consistent with the results of Truck 1 following a single SUV in the previous section and probably shares a common cause for the observed behaviour.

Table 4. Single truck with surrounding traffic - J1321 and CAN-bus fuel-savings results.

Calculation Method	Truck 1 [%] (ACC)	Truck 2 [%] (CACC)
J1321	7.4 ± 1.2	4.6 ± 1.2
Full Track CAN bus	7.3 ± 0.6	5.6 ± 1.1
Straight Segment CAN bus	4.4 ± 0.8	7.9 ± 1.1
Curved Segment CAN bus	9.7 ± 0.7	3.7 ± 1.1

Single Truck Following Another Truck

With the counter-intuitive track-segmented trends observed between the two trucks when following the smaller passenger vehicles, the test program also offers the data to examine these differences when following a single truck at the same 2.7-second following time (78 m at 105 km/h). In addition to the platooning tests undertaken with the CACC system at 78-m separation, a similar test condition was run with this two-truck platoon following the control truck at 78 m forward of Truck 1. This condition, for which Truck 2 does not influence Truck 1, permits a comparison of the CACC of Truck 2 with the ACC of Truck 1. These results are presented in Table 5.

In contrast to the truck-following-passenger-vehicle cases, the segmented analysis demonstrates the same trends for both Trucks 1 and 2, with greater savings in the straight versus curved segments. This contradictory trend suggests there are factors at play that are not necessarily evident in the data analysed thus far.

Table 5. Single truck following another truck - J1321 and CAN-bus fuel-savings results.

Calculation Method	Truck 1 [%] (ACC)	Truck 2 [%] (CACC)
J1321	5.4 ± 1.3	4.6 ± 0.8
Full Track CAN bus	5.3 ± 0.6	4.5 ± 1.1
Straight Segment CAN bus	7.1 ± 1.0	9.6 ± 1.1
Curved Segment CAN bus	3.8 ± 0.8	0.2 ± 1.1

Upstream-Vehicle Wake Effects

There are many factors that may cause differences in the track-segmented fuel-savings trends between Truck 1 and Truck 2. The two most important would be 1) the environmental conditions experienced, or more specifically the wind environment experienced by the trucks, and 2) the control strategy of the respective ACC or CACC system. The wind conditions experienced throughout the test campaign were generally within the limits of the J1321 procedures, and would therefore not be expected to have a significant impact on the results, given the success of this test procedure for evaluating aerodynamic technologies applied to heavy trucks. However, the influence of the multi-vehicle scenarios being tested, that being the impact of air-wake interactions with the truck, may exhibit stronger sensitivity to ambient winds. A moderate cross-wind may advect the wake of a vehicle in a lateral motion such that its core no longer impacts the truck in the same manner.

The winds measured by vane anemometers at the front grille of the vehicles are useful for quantifying the reduction in wind speed experienced by the trucks with various upstream traffic conditions, and are useful as an indicator of the variability of wake conditions experienced by the trucks. These measurements were acquired to support other papers in this series that will examine aerodynamic and cooling-flow impacts of platooning, but a small sample of the results are used here to help clarify the source of discrepancies between Truck 1 and 2 when following other traffic. These results are presented in Table 6 as a wind-speed ratio relative to isolated-driving conditions, and identify the differences between the straight and curved segments of the track for each test scenario. These wind-speed ratios are all below 1, which indicates that the trucks are operating in the wakes of the upstream traffic. The single SUV case shows the smallest impact (approximately 5% deficit), while the three-vehicle traffic creates about a 10% deficit and the single truck generates a 12% deficit. The single SUV and single upstream truck scenarios show good consistency between the straight and curved segments, while the three-vehicle traffic shows a stronger wake effect in the curves (12% deficit) than on the straight segments (7%-8% deficit).

The reason for the difference in wind-speed ratios between straight and curved segments for the three-vehicle traffic scenarios can only be conjectured, without having larger-scale measurements of the wake patterns, but it is hypothesized that the impact of the pickup truck and sedan in the adjacent (inner) lane may have a greater impact on the trucks while in a curve as a result of a lateral movement of the wakes into the outer lane of the trucks due to the curved trajectory of the vehicles. Essentially, a packet of air that is dragged by a vehicle will follow a linear

Table 6. Front-grille wind-speed ratios, relative to isolated driving conditions.

Vehicles	Full Track	Straights	Curves
T1 follow SUV	0.95 ± 0.02	0.95 ± 0.02	0.96 ± 0.02
T1 follow Traffic	0.91 ± 0.02	0.93 ± 0.03	0.88 ± 0.02
T2 follow Traffic	0.90 ± 0.04	0.92 ± 0.04	0.88 ± 0.04
T2 follow Control	0.88 ± 0.02	0.88 ± 0.02	0.88 ± 0.02
T2 follow T1	0.88 ± 0.02	0.88 ± 0.02	0.88 ± 0.02

path, rather than the curved trajectory of the track, in the absence of external forces. These inner-lane wakes therefore move into the lane of the trucks in the curved segments of the track. However, based on this logic, the SUV wake might be expected to move outside the trajectory of the trucks and provide a lower benefit in the curves. Given that the single SUV case does not show a difference between straight and curved segments, and that the two trucks experience the same trends despite opposing trends in fuel savings, this wake effect cannot be the only mechanism that might cause differences in fuel savings when following other traffic.

Despite differences in fuel-savings trends for the two trucks, the results presented in Tables 3 through 5 show that heavy trucks travelling in everyday traffic scenarios are experiencing a measurable fuel savings, relative to driving in isolation. Based on the observation of reduced wind speed at the front grille of the trucks in these scenarios, observed in Table 6, this reduction in fuel use can be attributed to a reduction in aerodynamic drag resulting from travelling in the air wakes of the upstream vehicles.

Two-Truck Platoon with Surrounding Traffic (Platooning Effect)

With the baseline results established for the individual trucks driving with surrounding traffic, the two-truck platoon was tested across the full span of separation distances with the array of three light-duty vehicles arranged ahead of the platoon. As shown in Figure 18, the platoon fuel savings generally follow the same patterns as described for the isolated platoon, but with 1%-3% lower nominal savings than the isolated platoon demonstrated without the traffic pattern included. Only the following truck at 15-m separation shows a statistically significant difference between the isolated and traffic scenarios; however, the consistency in the trends for each vehicle suggests that performance degradation is a real effect. At each separation distance tested, the lead and trailing trucks show similar levels of degradation in fuel-savings from the respective isolated-platoon case. While a measurable difference in fuel savings is documented, it should be noted it falls far short of negating the fuel savings from truck platooning.

The track-segmented results from the fuel-rate analysis are presented in Figure 19. Apart from a discrepancy at 23-m separation, the lead truck (Truck 1) shows a negligible difference between the curved and the straight sections, but surprisingly the following truck (Truck 2) shows up to 4% higher savings for the curved segments, a trend reversed from its isolated-platoon case (see Figure 14).

The disparity in track-segmented results was studied further to explain the contradictory trends from the isolated-platoon cases. First, the lead vehicle's fuel rate was plotted as a function of track segment, as shown in Figure 20, where the fuel-rate traces are shown for each lap (in black) and the average shown in red. In this figure, the top plot shows a reference case with no forward traffic and the bottom figure shows a reference case with the surrounding upstream traffic. Note that both of these tests use the same stock Adaptive Cruise Control (ACC) system for the lead vehicle. In Figure 20, the fuel-rate signal is smooth in the straight sections and variable in the curves for the reference case. In contrast, the traffic reference case produces a fuel rate signal that is variable the entire track length (straight and curved segments).

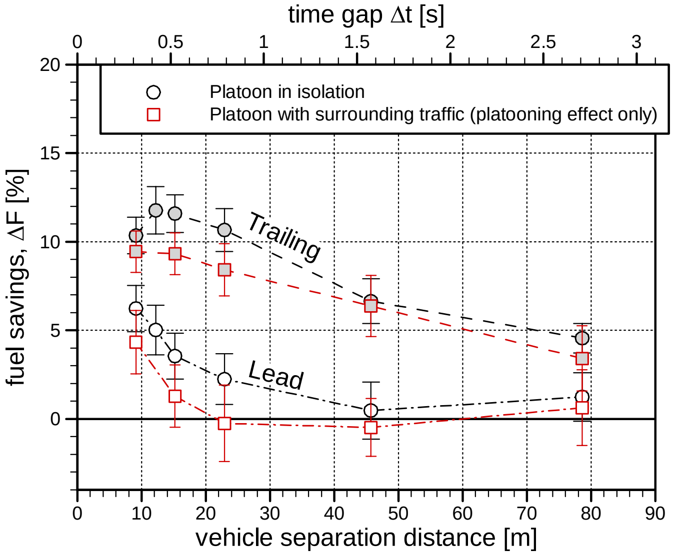

Figure 18. Two-truck platoon with surrounding traffic (platooning effect) fuel-savings results with single truck in traffic baseline compared to two-truck platoon in isolation (gravimetric).

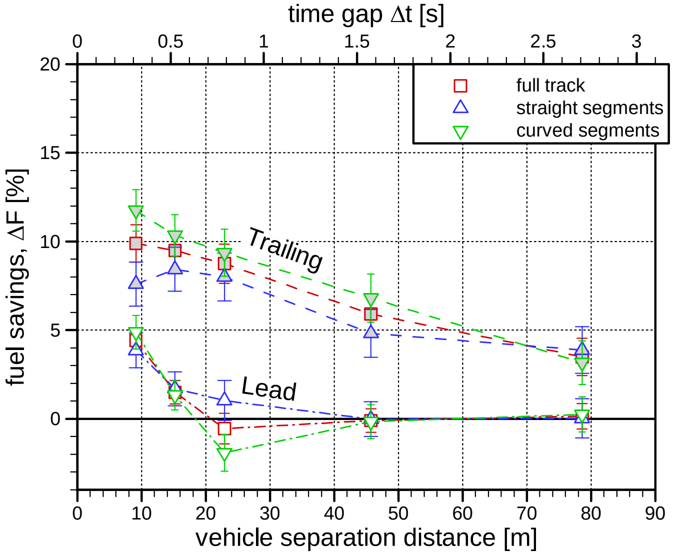

Figure 19. Two-truck platoon with surrounding traffic (platooning effect) track-segmented fuel-savings results with single truck in traffic baseline (CAN bus).

The added variability in the fuel rate was hypothesized to impact the expected straight-segment fuel savings. Next, the mixed-traffic cases were studied further to identify other differences. In these tests, the lead vehicle was influenced by the ACC system interaction with upstream traffic. A sample lap for the traffic reference run is shown in Figure 21. In the figure, the interaction of the ACC system and the forward SUV is shown in the wheel speed and target detection. In the curved sections, the SUV is detected in front of the lead vehicle, and the ACC con-

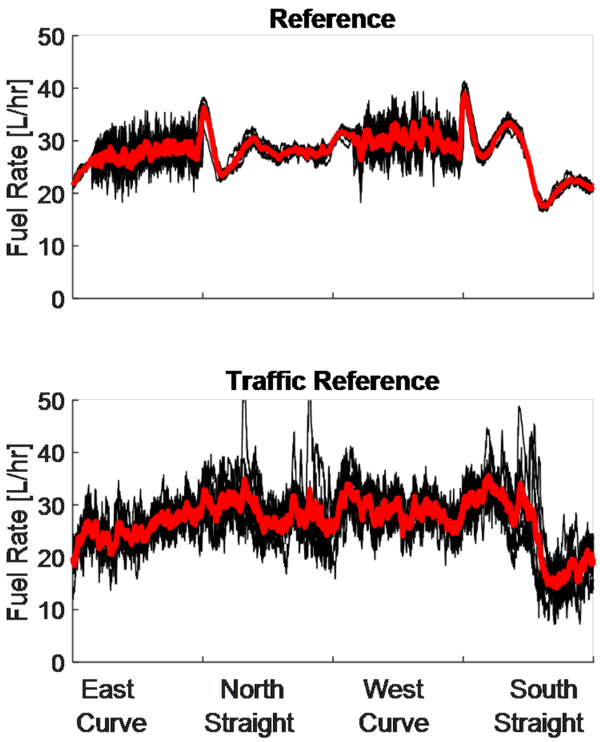

Figure 20. Comparison of lead vehicle's fuel-rate traces for reference case running cruise control (top) and surrounding traffic reference case running adaptive cruise control (bottom).

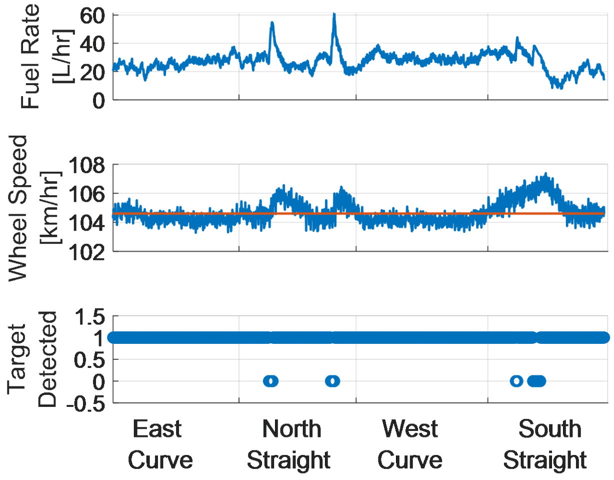

Figure 21. Example lap of lead vehicle and ACC interaction with forward SUV.

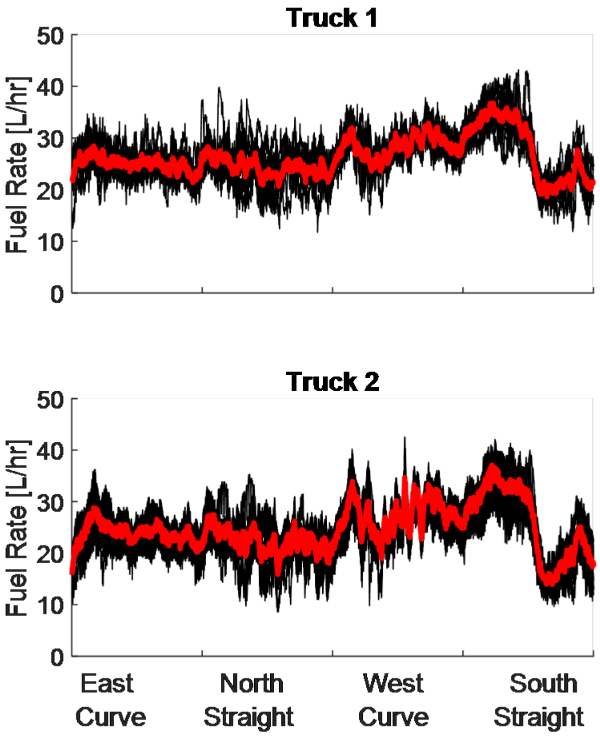

Figure 22. Comparison of fuel-rate traces for lead and following vehicles during surrounding-traffic platooning.

trol system adjusts the speed to keep a constant time gap (2.7 seconds or 78 m) relative to the SUV. In the straight sections, the ACC system loses detection of the SUV and speeds up towards the set speed (105 km/hr), shown in red. In these instances, the fuel rate spikes in order to speed the vehicle up, as shown in the top plot of Figure 21. It is important to note that the target detection and control response are characteristics of the ACC system and likely vary on the manufacturer's implementation. For this test configuration, the target detection worked best in the curves (seldom loss of SUV detection) and loses detection during short portions of the straight segments. This effect is hypothesized to be the cause of the increased variability in fuel rate, and thus reduced fuel savings, in the straight segments of the track for Truck 1.

In the first paper in this series [27] the authors showed that a trailing vehicle's fuel-rate profile is different than its baseline, or cruise-control, profile when in CACC mode and demonstrates the same control-response fuel-rate characteristics as the lead vehicle. Therefore, the previous discussion suggests that the lead vehicle's ACC has an effect on the response of the following vehicle. For surrounding-traffic platoon testing, an example of this similarity in fuel-rate behaviour between both trucks is shown in Figure 22. These results also help to explain the track-segmented anomaly for the following vehicle, whereby conflicting observations were found between the curved and straight segments, when following passenger-vehicle traffic. For the single truck with surrounding traffic shown in Table 4, Truck 2 has higher fuel savings in the straight versus curved segments, as expected. For the two-truck platoon in Figure 19, Truck 2 switches from this reference behaviour to following Truck 1's trend - higher savings in the curved versus straight segments. These results suggest that the lead vehicle's control system can have an impact on platooning in mixed traffic.

Two-Truck Platoon with Surrounding Traffic (Platooning + Traffic Effects)

The same test series with three light-duty vehicles ahead of the two-truck platoon can also be considered with the isolated single-vehicle results used as the baseline case, as is done for the isolated platoon scenarios, thereby measuring to what extent the platooning savings are additive to the ambient "background platooning" benefit from other traffic. As shown in Figure 23, the platoon fuel savings generally follow the same patterns but with 2%-7% higher nominal savings than the platoon demonstrated without the traffic pattern included. Recall that the individual trucks saw 7.4% and 4.6% fuel savings from the traffic pattern and as such, it is shown that truck platoons operating in a complex steady-state traffic pattern largely see the platooning aerodynamic benefit add to the "background platooning" benefit.

Two-Truck Platoon Following a Third Truck

For this test, the two-truck platoon was operated with a 15-m and 78-m separation distance while Truck 1 followed the control truck using the stock ACC system at a distance of 78 meters. At such a large distance the control-truck fuel-consumption performance is not impacted by the following truck, and as such it can be used both as the J1321 control truck and "other heavy-duty traffic" ahead of the platoon (or alternatively viewed as the aerodynamic lead vehicle of a large-gap three-truck platoon). Figure 24 shows the results for the lead and trailing trucks of the platoon compared to the isolated platoon results. While both the lead and trailing trucks of the platoon demonstrated improved fuel savings while following the control truck, the lead truck (Truck 1) is observed to experience the largest benefit. The trailing truck (Truck 2) in the 15-m case has a nominal improvement over the isolated case at the same distance, but there is not a statistically significant difference. It is reasonable to accept that the truck 15 m ahead has the dominant impact on its performance. In contrast, at 78 m the trailing truck does demonstrate a statistically-significant benefit over the isolated platoon, adding evidence to the idea that the benefits of other traffic ahead of the platoon are additive and the wake effects are sustained over long distances.

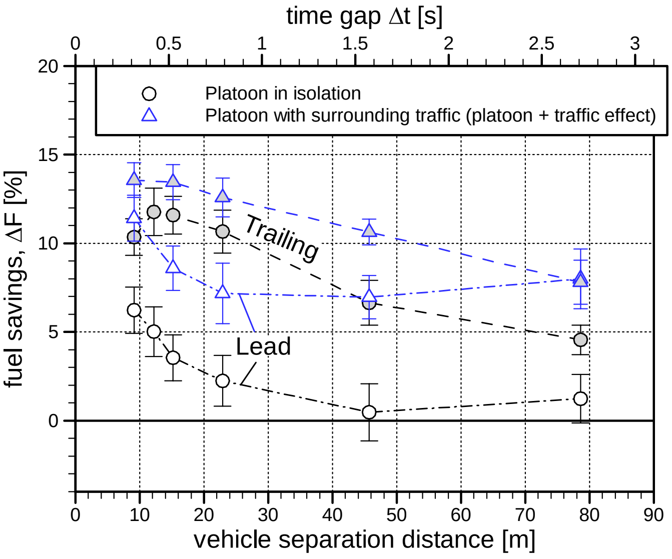

Figure 23. Two-truck platoon with surrounding traffic (platooning + traffic effects) fuel-savings results with single truck in isolation baseline compared to two-truck platoon in isolation (gravimetric).

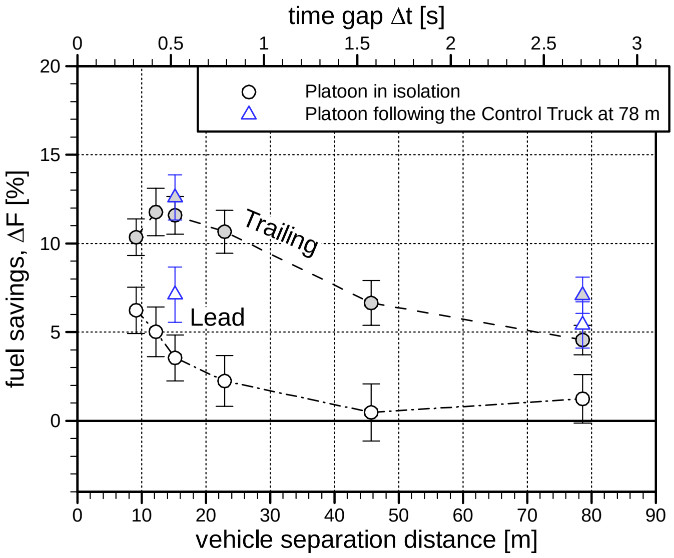

Figure 24. Two-truck platoon following a third truck compared to two-truck platoon in isolation (gravimetric).

Table 7. Two-truck-platoon fuel-savings results following a third truck compared to two-truck platoon in isolation (gravimetric).

Test	**Truck 1 [%]**	**Truck 2 [%]**
Isolated Platoon - 15 m gap	3.6 ± 1.3	11.6 ± 1.1
Platoon follow Control - 15 m gap	7.1 ± 1.6	12.6 ± 1.3
Added savings from "Other Traffic"	3.5	1.0
Isolated Platoon - 78 m gap	1.2 ± 1.4	4.6 ± 0.8
Platoon follow Control - 78 m gap	5.4 ± 1.3	7.1 ± 1.0
Added savings from "Other Traffic"	4.2	2.5

Table 7 shows that in this configuration the lead truck (Truck 1) demonstrates 3.5%-4.2% additional savings beyond the isolated case and the trailing truck (Truck 2) demonstrates 1.0%-2.5% additional savings beyond the isolated case. Both trucks experienced a higher additional benefit while at the larger platooning gap. This is additional evidence that the "background platooning" benefit adds to the coordinated platooning aerodynamic benefit rather than negating it.

Following from the prior discussion about ACC and the inconsistencies when following the SUV, the performance of ACC following another truck was also investigated. The resulting interaction is shown in Figure 25. From the figure, the ACC system detection is periodic, switching between distinct "on" or "off." This behaviour differs from the SUV ACC following, as shown in Figure 21, and again is likely due to the manufacturer implementation. Additionally, the target detection occurs opposite of the SUV: the heavy duty truck is detected through-

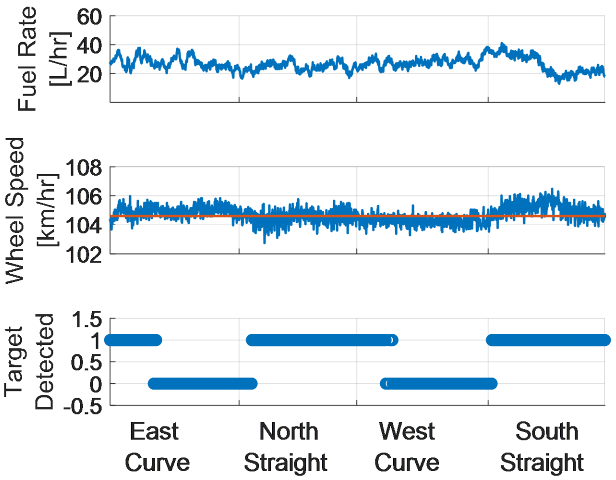

Figure 25. Example lap of lead vehicle and ACC interaction with forward heavy-duty truck.

Table 8. Two-truck platoon at 15-m separation distance with Control truck 78 m ahead - J1321 and segmented CAN-bus fuel-savings results.

Calculation Method	**Truck 1 [%] (ACC)**	**Truck 2 [%] (CACC)**
J1321	7.1 ± 1.6	12.6 ± 1.3
Full Track CAN bus	6.8 ± 0.6	14.3 ± 1.1
Straight Segment CAN bus	13.1 ± 3.8	22.0 ± 3.4
Curved Segment CAN bus	-0.7 ± 4.3	5.5 ± 4.3

out the straight sections but not the curves. The ACC switching here also causes less deviation in the cruise-control speed response. As a result, spikes in the fuel rate are not seen, unlike the SUV in Figure 21. The track-segmented fuel-saving results in this scenario also return to the isolated platoon trends: higher saving in the straight versus curved segments for both platooning vehicles, as shown in Table 8. The increased fuel efficiencies shown in the table are likely due to aerodynamic benefit of having a heavy truck ahead of the platoon, but the improved performance of the ACC system may have a positive impact as well. The results also show that the type of mixed traffic a platoon interacts with can have an effect on the fuel savings.

Platooning Benefits in Dynamic Mixed Traffic

Dynamic Cut-In Scenario

The steady-state response of truck platooning while travelling with surrounding traffic provides one of many real-world driving scenarios. Traffic is dynamic in nature and cut-ins between vehicles are a common occurrence, especially for larger separation distances between vehicles (20 m or greater [34]). To examine the impact of such transient events, a staged cut-in scenario was tested whereby a mid-sized SUV cut-in between the platooning trucks set for a 23-m separation distance. Twenty-four cut-in events were performed within the single run, once every 3.2 km (once every 110 seconds).

Table 9. Effect of periodic cut-ins - CAN-bus fuel-savings results.

Platoon Configuration	**Truck 1 [%]**	**Truck 2 [%]**
23-m separation	1.7 ± 0.7	10.7 ± 1.2
23-m separation with cut-ins	-0.4 ± 1.0	1.0 ± 1.8

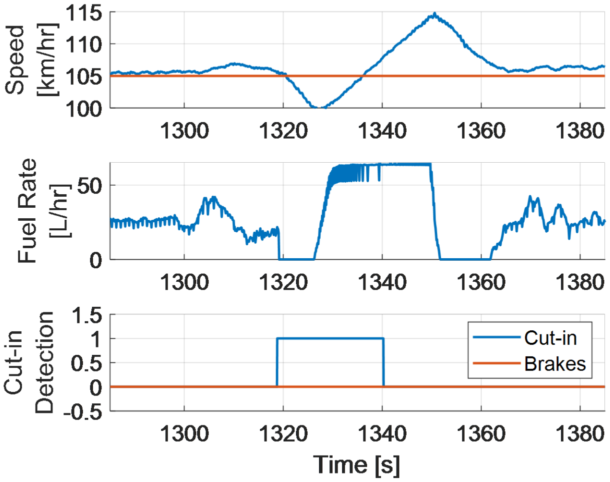

Figure 26. Following vehicle's response during CACC platooning with vehicle cut-in.

Table 9 presents the results of the CAN-bus fuel-savings results for the cut-in scenario compared to the equivalent steady-state platoon case. The results show a complete elimination of the fuel-savings benefit for both trucks. The lead truck experienced a small but statistically-measurable reduction in savings, likely due to the extension of the separation distance during cut-in manouvers, while the trailing truck experienced a 10% reduction in benefit. This rate of cut-ins is equivalent to that evaluated by McAuliffe *et al.* [17] with a three-truck platoon using a 35-m separation distance, for which only a 1% to 2% reduction in fuel-savings benefit was observed for the truck following the cut-in.

The cut-in detection of the CACC system has been identified as a potential cause for the loss of fuel-savings benefit. The cut-in detection and vehicle response is shown in Figure 26 for a passenger vehicle and a platoon at 23 m (75 ft). The CACC system is operating to follow the lead vehicle at the specified following distance, rather than the speed, and the normal fuel rate behaviour is shown when there is no cut-in. If a cut-in is detected, the system begins to range off the cut-in vehicle (like ACC) and follow it at the same reference distance as the lead vehicle, 23 m in this case. As soon as the cut-in is detected, the fuel rate drops to zero (i.e., no commanded torque) as seen at 1,320 seconds. Then, the distance between the truck and vehicle increases, and the fuel rate rapidly increases in order to regain speed and return to the set distance when the cut-in vehicle leaves, at 1,340 seconds. It is important to note that this system was designed to be functional, not fuel efficient. A number of important parameters exist for this dynamic scenario: system detection and control response, cut-in vehicle behaviour (relative distance and speed), and vehicle capabilities (i.e., isolated vehicle or platooning).

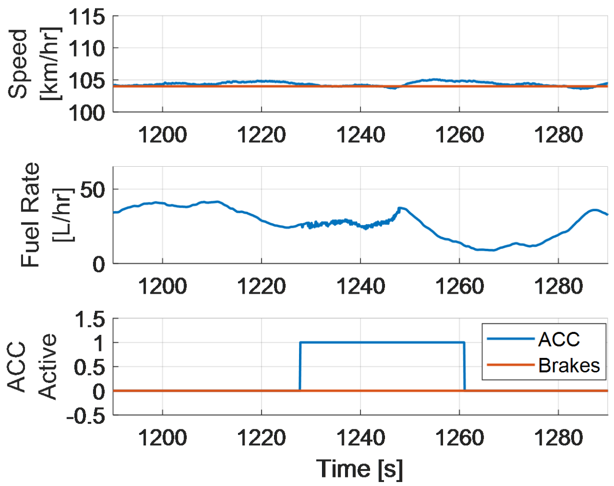

Figure 27. Lead vehicle's response during ACC with vehicle cut-in.

To further understand the above-mentioned parameters, a similar scenario was studied for a cut-in vehicle in front of the lead truck operating ACC. The resulting vehicle response is shown in Figure 27. Note that these data were selected to be a close representation of the platoon cut-in test, but the speed and relative distance of the cut-in vehicle differ slightly. In Figure 27, these results show quite a different control response once the cut-in occurs. First, the fuel rate begins to dither but stays relatively constant, rather than go to zero as it did for the platoon cut-in. Overall, there are no sudden changes in the fuel rate and thus the speed profile stays relatively undisturbed. These results show that similar vehicle control systems, with differing implementations, can have a significant impact on a vehicle's response to cut-ins. These data suggest that the cut-in strategy for current CACC system shows room for improvement with regards to energy efficiency.

Dynamic Passing Events

In real traffic, truck platoons may experience transient traffic quite often as other vehicles on the road tend to pass trucks at relatively low differential speeds. In this test campaign, platooning benefits were examined for two dynamic-passing scenarios whereby a platoon of two test trucks was passed by transient traffic, thus exposing the platoon to the aerodynamic wakes of passing vehicles for which any gains or losses in fuel savings could be investigated.

The first of the two transient-traffic test runs were performed for a truck platoon with separation distance of 15 m (50 ft), with all seven passenger vehicles travelling equally spaced around the track (approximately 900 m separation). The second test was performed for the same platoon but with a mid-sized SUV travelling in front of the platoon at a fixed distance of 79 m (258 ft), with Truck 1 using ACC rather than its standard cruise control. This later test was conducted to assess the impact of a mixed scenario of static and dynamic wake effects.

The CAN bus fuel-rate analysis was performed for these test runs, using the isolated-truck runs as the baseline data set. However, this is not strictly valid per Equation 2 because the control truck is experiencing different conditions than for any other test runs. The control truck is being passed by the passenger vehicle and therefore experiences the same wake-passing effects, if any, on its fuel consumption. Consider the following equation, which defines the standard approach for calculating the fuel savings per the J1321 method, if baseline tests for which the transient vehicle passing events had been conducted:

$$\Delta F = \frac{\overline{(T_{trf}/C_{trf})_{base}} - \overline{(T_{trf}/C_{trf})_{test}}}{\overline{(T_{trf}/C_{trf})_{base}}} \tag{8}$$

where the subscript *trf* represents "transient traffic" conditions. This equation can be reduced to

$$\Delta F = 1 - \frac{\overline{(T_{trf}/C_{trf})_{test}}}{\overline{(T_{trf}/C_{trf})_{base}}} \tag{9}$$

Considering only isolated-truck T/C values are available as baseline data for the analysis, Equation 9 can be rewritten as follows, which introduces the known baseline $\overline{(T_{iso}/C_{iso})_{base}}$ value:

$$\Delta F = 1 - \frac{\overline{(T_{trf}/C_{trf})_{test}}}{\overline{(T_{iso}/C_{iso})_{base}(T_{trf}/T_{iso})_{base}(C_{iso}/C_{trf})_{base}}} \tag{10}$$

If it can be assumed that the transient traffic has the same effect on the test trucks as it does on the control truck, then it can be reasonably assumed that:

$$\overline{(T_{trf}/T_{iso})_{base}} = \overline{(C_{trf}/C_{iso})_{base}} \tag{11}$$

and Equation 9 can be rewritten

$$\Delta F = 1 - \frac{\overline{(T_{trf}/C_{trf})_{test}}}{\overline{(T_{iso}/C_{iso})_{base}}} \tag{12}$$

which can be calculated from the available data. These results then have the "transient other traffic" as their baseline condition, for which the results then represent the impact of platooning in an environment with a "periodic passing wind front" as induced by the passing vehicles. Conversely, the results can be interpreted as the additive effect of platooning in the dynamic traffic environment.

The results from this analysis are summarized in Table 10 which, for the first case, shows the equivalent results for the platoon in isolation. For this case, there is no statistically significant difference in fuel-savings results for the following truck. This is perhaps due to the following truck being most affected by the aerodynamic wake of the lead truck, which is much larger and

Table 10. Platoon fuel savings in dynamic passing events - J1321 fuel-savings results.

Platoon Configuration	**Truck 1 [%]**	**Truck 2 [%]**
15-m separation + transient traffic	1.1 ± 1.0	12.0 ± 1.3
15-m separation + transient traffic + SUV at 78 m	4.6 ± 1.0	14.1 ± 1.3
15-m separation in isolation	3.1 ± 0.6	11.8 ± 1.1

stronger that the influence of the transient passenger-vehicle wakes. The lead truck experiences a measurable degradation of platooning benefit of 2% in this scenario, but the mechanism by which this occurs is unclear.

For the second test for which an SUV is travelling in front of the platoon at a fixed distance of 78 m, there were no comparable isolated-platoon results to assess the benefits of platooning in such conditions. However, by comparing the fuel saving results directly to the first scenario of Table 10, a benefit to both the lead and following vehicle is observed, with a larger incremental benefit to the lead truck than the follower. This trend is consistent with that observed for a platoon following the control vehicle at the same 78-m separation, for which a larger incremental benefit was observed for the lead truck (see Table 7).

Conclusions

The results reported here represent the first significant experimental effort to assess the energy savings impact of traffic and other trailer configurations on truck platoons. The fuel consumption for each truck 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 0.32 s, or 9 m, to 2.7 s, or 78 m, with a range of upwind traffic and test-vehicle configurations. These more realistic driving scenarios add significant knowledge to the expected truck-platooning performance on North American highways.

Regarding the use of flatbed trailers instead of dry-van trailers, specific conclusions include:

- Introducing a near-empty flatbed trailer in either the lead or following positions of a two-truck platoon was measured to have a small but statistically insignificant reduction in the team fuel savings, compared to a two-dry-van platoon, at separation distances of 9 m, 15 m, and 46 m.
- Replacing the dry-van trailer of the following vehicle with a near-empty flatbed trailer has no impact on the fuel-savings trend of either the lead or following vehicle of a two-truck platoon.
- Replacing the dry-van trailer of the lead vehicle with a near-empty flatbed trailer exhibits a continuous increase in fuel-savings benefit of the trailing vehicle as the separation distance is reduced, unlike with a dry-van configuration, which demonstrates a reduction in fuel savings at close distance. The increase in following-vehicle fuel savings at small separations is offset by a decrease in fuel savings of the lead vehicle.

Regarding the operation of trucks and truck platoons in mixed-traffic scenarios, specific conclusions include:

- The track-test results suggest that truck-platoon fuel-savings benefits are largely additive to the “background traffic platooning” fuel savings from both passenger vehicles and heavy trucks.
- Single trucks on North American highways are likely realizing 4%-10% fuel savings from surrounding steady state traffic patterns, compared to no-traffic conditions.
- While isolated truck platoons may consistently demonstrate higher savings on straight track segments than curved segments, the influence of complex traffic patterns and the turbulence patterns they generate on platooning fuel savings are not as easy to predict.
- The speed-control system of the lead vehicle in a platoon can have an impact on platooning fuel savings in mixed traffic.
- A small impact of dynamic passing events (one passing every two to three minutes) on the fuel-savings benefits of platooning was observed for the lead truck, but not for the following truck.
- The dynamic passing events (one passing every two to three minutes) seem to have little or no impact with the influence of "other traffic" (a single SUV) ahead of the platoon.
- The cut-in detection/control system of the CACC system demonstrated a complete loss of fuel savings for the 23-m platoon separation case, for cut-ins occurring once every 3.2 km. Comparison to other systems suggests room for improvement of this system in terms of fuel efficiency.

The results and conclusions developed from this study lead to several recommendations for future research activities:

- The flatbed-trailer results suggest that the air-wake structure and its interaction with the tractor flow field, have an important impact on drag reduction and fuel savings of truck platoons. Further investigation may lead to tractor and trailer shape combinations that take advantage of the close-proximity platooning effect to further improve fuel efficiency from automated vehicle systems, especially if increases in traffic-density become a principal driver for the implementation of vehicle platooning.
- The SAE J1321 procedure using only gravimetric fuel analysis may not adequately capture the impacts from modern advanced safety systems or connected vehicles. Segmented J1939 fuel-rate analysis should be considered for testing of vehicles with advanced safety features such as ACC and collision avoidance as such systems may behave differently on a test tracks than in a highway environment.
- The target dropping, and associated fuel-rate increases, of Truck 1’s stock ACC system on the straight track segments when following passenger vehicles suggests that ACC systems have room for improvement and may need to be investigated on their own for engine performance impacts.

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Appendix A - Summary of Test Data

The fuel-savings results from the test campaign are provided in Tables 11 through 14. The J1321 gravimetric results are presented in Table 11. The CAN-bus fuel-rate results for the full track, the straight segments, and the curved segments are presented in Tables 12, 13, and 14, respectively. The CAN-bus data sets were not complete for the flatbed test scenarios, and therefore only J1321 gravimetric results are presented for the flatbed test cases. Only full-track CAN-bus fuel-rate results are presented for the cut-in and dynamic-passing-events scenarios due to the transient nature of the test runs that prevent lap-to-lap or segment-to-segment consistency for the track-segmented analysis.

Table 11. Results from the SAE J1321 gravimetric fuel-consumption tests. The data represent vehicle speeds of 105 km/h (65 mph) and vehicle masses of 29,500 kg (65,000 lb).

Test Configuration	Separation Time [s]	Separation Distance [m]	Truck 1 Fuel Savings [%]	Truck 2 Fuel Savings [%]	Team Fuel Savings [%]
Dry-Van/Dry-Van	0.32	9.1	6.2 ± 1.3	10.4 ± 1.0	8.3 ± 1.7
	0.42	12.2	5.0 ± 1.4	11.8 ± 1.3	8.4 ± 1.9
	0.53	15.2	3.6 ± 1.3	11.6 ± 1.1	7.6 ± 1.7
	0.79	22.9	2.3 ± 1.4	10.7 ± 1.2	6.5 ± 1.9
	1.58	45.7	0.5 ± 1.6	6.6 ± 1.3	3.3 ± 0.6
	2.71	78.6	1.2 ± 1.4	4.6 ± 0.8	2.3 ± 0.4
Flatbed/Dry-Van	0.32	9.1	2.3 ± 2.1	13.1 ± 1.2	7.3 ± 1.9
	0.53	15.2	1.3 ± 2.0	11.0 ± 1.1	5.8 ± 1.7
	1.58	45.7	0.0 ± 2.0	6.9 ± 1.3	3.2 ± 2.2
Dry-Van/Flatbed	0.32	9.1	4.6 ± 1.3	9.9 ± 1.5	7.3 ± 1.3
	0.53	15.2	1.9 ± 1.3	10.0 ± 1.6	6.1 ± 1.4
	1.58	45.7	-0.1	5.3	2.7
Single Truck with Surrounding Traffic			7.4 ± 1.2	4.6 ± 1.2	
Single Truck Following Single SUV	2.7	78.5	4.0 ± 0.8		
Dry-Van/Dry-Van with Surrounding Traffic (Platooning Effect)	0.32	9.1	4.3 ± 1.8	9.4 ± 1.2	6.9 ± 1.6
	0.53	15.2	1.3 ± 1.8	9.3 ± 1.2	5.3 ± 1.5
	0.79	22.9	-0.2 ± 2.2	8.4 ± 1.5	4.1 ± 2.7
	1.58	45.7	-0.5 ± 1.6	6.4 ± 1.7	3.0 ± 1.9
	2.71	78.6	0.6 ± 2.1	3.4 ± 1.8	2.0 ± 2.6
Dry-Van/Dry-Van with Surrounding Traffic (Platooning + Traffic Effects)	0.32	9.1	11.4 ± 1.3	13.6 ± 1.0	12.5 ± 1.6
	0.53	15.2	8.6 ± 1.3	13.4 ± 1.0	11.0 ± 1.6
	0.79	22.9	7.2 ± 1.7	12.6 ± 1.1	9.9 ± 2.0
	1.58	45.7	7.0 ± 1.2	10.6 ± 0.7	9.1 ± 1.2
	2.71	78.6	8.0 ± 1.7	7.8 ± 1.2	7.9 ± 1.5
Dry-Van/Dry-Van Following Control Truck at 78 m	0.53	15.2	7.1 ± 1.6	12.6 ± 1.3	6.6 ± 2.0
	2.71	78.6	5.4 ± 1.3	7.1 ± 1.0	4.2 ± 1.7
Dry-Van/Dry-Van w/ Cut-Ins	0.79	22.9	0.4	0.9	0.7
Dry-Van/Dry-Van w/ Dynamic Passing Events	0.53	15.2	1.5	10.1	5.8
	0.53	15.2	4.9	12.4	8.6

Table 12. Results from the CAN-bus fuel-rate analysis for the full track. The data represent vehicle speeds of 105 km/h (65 mph) and vehicle masses of 29,500 kg (65,000 lb).

Test Configuration	Separation Time [s]	Separation Distance [m]	Truck 1 Fuel Savings [%]	Truck 2 Fuel Savings [%]	Team Fuel Savings [%]
Dry-Van/Dry-Van	0.32	9.1	6.4 ± 0.6	11.5 ± 1.1	9.0 ± 1.2
	0.42	12.2	4.4 ± 0.6	11.8 ± 1.1	8.1 ± 1.2
	0.53	15.2	3.1 ± 0.6	11.8 ± 1.1	7.4 ± 1.3
	0.79	22.9	1.7 ± 0.7	10.7 ± 1.2	6.2 ± 1.3
	1.58	45.7	-0.5 ± 0.7	7.8 ± 1.2	3.9 ± 0.6
	2.71	78.6	1.2 ± 0.6	4.5 ± 1.1	2.3 ± 0.6
Single Truck with Surrounding Traffic			7.3 ± 0.6	5.6 ± 1.1	
Single Truck Following Single SUV	2.7	78.5	3.6 ± 0.6		
Dry-Van/Dry-Van with Surrounding Traffic (Platooning Effect)	0.32	9.1	4.4 ± 0.7	9.9 ± 1.1	7.2 ± 1.3
	0.53	15.2	1.5 ± 0.7	9.5 ± 1.1	5.5 ± 1.2
	0.79	22.9	-0.6 ± 0.9	8.8 ± 1.1	4.1 ± 1.4
	1.58	45.7	-0.1 ± 0.7	5.9 ± 1.1	2.9 ± 1.3
	2.71	78.6	0.2 ± 0.7	3.5 ± 1.1	1.8 ± 1.3
Dry-Van/Dry-Van with Surrounding Traffic (Platooning + Traffic Effects)	0.32	9.1	11.4 ± 0.7	15.0 ± 1.1	13.2 ± 1.3
	0.53	15.2	8.7 ± 0.6	14.6 ± 1.1	11.6 ± 1.2
	0.79	22.9	6.8 ± 0.8	13.9 ± 1.1	10.3 ± 1.4
	1.58	45.7	7.2 ± 0.6	11.2 ± 1.1	9.2 ± 1.3
	2.71	78.6	7.4 ± 0.7	8.9 ± 1.1	8.2 ± 1.3
Dry-Van/Dry-Van Following Control Truck at 78 m	0.53	15.2	6.8 ± 0.6	14.3 ± 1.1	10.6 ± 1.2
	2.71	78.6	5.3 ± 0.6	7.2 ± 1.1	6.2 ± 1.2
Dry-Van/Dry-Van w/ Cut-Ins	0.79	22.9	-0.4 ± 0.7	1.0 ± 1.8	0.3 ± 2.1
Dry-Van/Dry-Van w/ Dynamic Passing Events	0.53	15.2	1.1 ± 1.0	12.0 ± 1.3	5.6 ± 1.6
	0.53	15.2	4.6 ± 1.0	14.1 ± 1.3	9.4 ± 1.6

Table 13. Results from the CAN-bus fuel-rate analysis for the straight track segments. The data represent vehicle speeds of 105 km/h (65 mph) and vehicle masses of 29,500 kg (65,000 lb).

Test Configuration	Separation Time [s]	Separation Distance [m]	Truck 1 Fuel Savings [%]	Truck 2 Fuel Savings [%]	Team Fuel Savings [%]
Dry-Van/Dry-Van	0.32	9.1	6.5 ± 0.8	14.4 ± 1.1	10.4 ± 1.4
	0.42	12.2	4.5 ± 0.7	14.7 ± 1.1	9.6 ± 1.3
	0.53	15.2	3.0 ± 0.8	14.8 ± 1.2	8.9 ± 1.4
	0.79	22.9	1.9 ± 0.8	14.2 ± 1.2	8.0 ± 1.4
	1.58	45.7	0.3 ± 1.0	11.4 ± 1.3	5.7 ± 0.6
	2.71	78.6	1.1 ± 0.8	9.6 ± 1.1	4.8 ± 0.5
Single Truck with Surrounding Traffic			4.4 ± 0.8	7.9 ± 1.1	
Single Truck Following Single SUV	2.7	78.5	-0.1 ± 0.8		
Dry-Van/Dry-Van with Surrounding Traffic (Platooning Effect)	0.32	9.1	3.9 ± 1.0	7.6 ± 1.2	5.7 ± 1.6
	0.53	15.2	1.7 ± 1.0	8.4 ± 1.2	5.1 ± 1.6
	0.79	22.9	1.0 ± 1.1	8.0 ± 1.3	4.5 ± 1.8
	1.58	45.7	0.0 ± 1.0	4.8 ± 1.3	2.4 ± 1.7
	2.71	78.6	0.0 ± 1.1	3.9 ± 1.3	2.0 ± 1.7
Dry-Van/Dry-Van with Surrounding Traffic (Platooning + Traffic Effects)	0.32	9.1	8.1 ± 0.8	14.9 ± 1.1	11.5 ± 1.4
	0.53	15.2	6.0 ± 0.8	15.6 ± 1.1	10.8 ± 1.4
	0.79	22.9	5.4 ± 1.1	15.2 ± 1.3	10.3 ± 1.7
	1.58	45.7	4.4 ± 0.9	12.3 ± 1.3	8.3 ± 1.5
	2.71	78.6	4.4 ± 1.0	11.4 ± 1.2	7.9 ± 1.6
Dry-Van/Dry-Van Following Control Truck at 78 m	0.53	15.2	13.1 ± 3.8	22.0 ± 3.4	17.5 ± 5.1
	2.71	78.6	7.1 ± 1.0	12.6 ± 2.0	9.9 ± 2.2

Table 14. Results from the CAN-bus fuel-rate analysis for the curved track segments. The data represent vehicle speeds of 105 km/h (65 mph) and vehicle masses of 29,500 kg (65,000 lb).

Test Configuration	Separation Time [s]	Separation Distance [m]	Truck 1 Fuel Savings [%]	Truck 2 Fuel Savings [%]	Team Fuel Savings [%]
Dry-Van/Dry-Van	0.32	9.1	6.3 ± 0.7	9.1 ± 1.2	7.7 ± 1.3
	0.42	12.2	4.4 ± 0.6	9.4 ± 1.1	6.9 ± 1.3
	0.53	15.2	3.2 ± 0.7	9.2 ± 1.1	6.2 ± 1.3
	0.79	22.9	1.6 ± 0.7	7.7 ± 1.2	4.6 ± 1.4
	1.58	45.7	-1.3 ± 0.8	4.7 ± 1.2	2.4 ± 0.6
	2.71	78.6	1.4 ± 0.7	0.2 ± 1.2	0.1 ± 0.6
Single Truck with Surrounding Traffic			9.7 ± 0.7	3.7 ± 1.1	
Single Truck Following Single SUV	2.7	78.5	6.5 ± 0.8		
Dry-Van/Dry-Van with Surrounding Traffic (Platooning Effect)	0.32	9.1	4.9 ± 0.9	11.8 ± 1.2	8.3 ± 1.5
	0.53	15.2	1.3 ± 0.8	10.4 ± 1.2	5.8 ± 1.4
	0.79	22.9	-1.9 ± 1.0	9.4 ± 1.3	3.7 ± 1.7
	1.58	45.7	-0.2 ± 1.0	6.8 ± 1.4	3.3 ± 1.7
	2.71	78.6	0.3 ± 1.0	3.2 ± 1.2	1.7 ± 1.6
Dry-Van/Dry-Van with Surrounding Traffic (Platooning + Traffic Effects)	0.32	9.1	14.1 ± 0.8	15.0 ± 1.2	14.6 ± 1.4
	0.53	15.2	10.9 ± 0.7	13.7 ± 1.2	12.3 ± 1.3
	0.79	22.9	7.9 ± 0.9	12.7 ± 1.3	10.3 ± 1.6
	1.58	45.7	9.5 ± 0.8	10.3 ± 1.3	9.9 ± 1.6
	2.71	78.6	9.9 ± 0.7	6.8 ± 1.2	8.3 ± 1.4
Dry-Van/Dry-Van Following Control Truck at 78 m	0.53	15.2	-0.7 ± 4.3	5.5 ± 4.3	2.4 ± 6.1
	2.71	78.6	3.8 ± 0.8	2.5 ± 1.4	3.1 ± 1.6