

Effect of Platooning on Fuel Consumption of Class 8 Vehicles Over a Range of Speeds, Following Distances, and Mass

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ABSTRACT

This research project evaluates fuel consumption results of two Class 8 tractor-trailer combinations platooned together compared to their standalone fuel consumption. A series of ten modified SAE Type II J1321 fuel consumption track tests were performed to document fuel consumption of two platooned vehicles and a control vehicle at varying steady-state speeds, following distances, and gross vehicle weights (GVWs). The steady-state speeds ranged from 55 mph to 70 mph, the following distances ranged from a 20-ft following distance to a 75-ft following distance, and the GVWs were 65K lbs and 80K lbs. All tractors involved had U.S. Environmental Protection Agency (EPA) SmartWay-compliant aerodynamics packages installed, and the trailers were equipped with side skirts. Effects of vehicle speed, following distance, and GVW on fuel consumption were observed and analyzed. The platooning demonstration system used in this study consisted of radar systems, Dedicated Short-Range Communication (DSRC) vehicle-to-vehicle (V2V) communications, vehicle braking and torque control interface, cameras and driver displays. The lead tractor consistently demonstrated an improvement in average fuel consumption reduction as following distance decreased, with results showing 2.7% to 5.3% fuel savings at a GVW of 65k. The trailing vehicle achieved fuel consumption savings ranging from 2.8% to 9.7%; tests during which the engine cooling fan did not operate achieved savings of 8.4% to 9.7%. "Team" fuel savings, considering the platooned vehicles as one, ranged from 3.7% to 6.4%, with the best combined result being for 55 mph, 30-ft following distance, and 65k GVW.

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INTRODUCTION

Vehicle automation is a promising petroleum reduction technology, and platooning systems for heavy-duty vehicles are likely to be a first step towards acceptance of vehicle automation. These systems may employ existing technologies such as radar or laser range finders, global positioning system (GPS), dedicated vehicle-to-vehicle communications (V2V), and braking and engine torque authority to enable vehicles to follow safely in close proximity with the goal of reducing fuel consumption, traffic congestion, and possibly collisions.

Early studies have consistently suggested significant fuel savings from the reduced aerodynamic drag; however, because platooning systems are still emerging technologies that are not yet commercially available, questions remain about how effective they will be at reducing fuel consumption in the real world and under what conditions they will perform best.

As part of the California Partners for Advanced Transportation Technology (PATH) program, Browand et al. found that platooning vehicles were able to achieve 8%-11% in fuel consumption savings from 3- to 10-meter following distance. Tests were conducted on an unused runway in two directions with a usable 220-350 meter overlap to collect data. Two

identical 2001 Freightliner Century Class trucks powered by Cummins N14 Celect engines were used in the testing with empty or lightly loaded trailers. The fuel rate was derived from on-board vehicle bus communication signals versus weighing tanks, and test speeds of 50-55 mph were employed. Spacing of 10 meters found 10% and 6% fuel consumption savings, respectively, for the trailing and lead truck. In the spacing range of 3-10 meters, fuel consumption was reduced in the range 10%-12% for the trailing truck and 5%-10% for the lead truck. Vehicle mass was not specified, but the test trailers were empty. [1]

Alam et al. found a maximum fuel reduction of 4.7%-7.7% depending on the following distance at a set speed of 70 km/h (44 mph) with two identical European cab-over trucks at 40,000 kg (88K lbs GVW) [2].

Tsugawa et al. showed through modeling and track testing that a three-truck platoon at 80 km/h (50 mph) and a 10-meter following distance could improve fuel consumption by an average of 14% with the lead truck experiencing a 7.5% reduction and the tail truck experiencing a 16% reduction. European style cab-over tractors were used, and vehicle mass was not specified. [3]

The New Energy and Industrial Technology Development Organization (NEDO) in Japan showed with track testing that a platoon of four cab-over straight trucks maintaining a 4-meter following distance and 80 km/h (50 mph) speeds attained a 15% average improvement. Vehicle mass was not specified. [4]

This research project, funded by the Department of Energy (DOE), evaluated the fuel consumption reduction of a pair of platooned Class 8 tractor-trailers on a track over a range of highway truck speeds, following distances, and weights that would represent driving on public road conditions under test track conditions. The project was managed by the National Renewable Energy Laboratory (NREL), and the tests were performed by Intertek Testing Services NA and LINK Engineering. Testing took place at the Continental Tire Proving Grounds [5] in Uvalde, Texas, which is an 8.5-mile (13.7-km)) asphalt oval with several small grade changes rather than a zero grade environment. As such, the constant-speed tests operated under cruise control had an average speed standard deviation of ± 0.6 mph and a maximum deviation of 1.0 mph as the heavy tractors responded to the small grade changes. The fuel consumption savings were recorded through methods prescribed in SAE J1321 Fuel Consumption Test Procedure [6]. Effects on engine cooling to the trailing vehicle from platooning were recorded with data logging devices through the use of J1939 controller area network (CAN) bus messages [7].

BACKGROUND AND METHODS

Test Track Selection

The Continental Tire Uvalde Proving Grounds track is a three-lane wide, 8.5-mile (13.7 km) oval with one-mile radius turns and a 1.1-mile straightaway between the turns. The oval track is shown in a satellite view in [Figure 1](#). The track is not perfectly level, but rather has several small elevation changes of approximately 15 ft, resulting in gentle grade changes throughout the lap.



Figure 1. 8.5-mile oval at Continental Tire Uvalde Proving Grounds (© Google Earth)

Vehicle Selection and Details

Several previous studies tested platooning on older tractors, which paid less attention to base aerodynamics than many tractors popular in the United States today or cab-over designs popular outside the United States, which may respond to platooning differently [1, 2, 3, 4]. In this study, modern "aero" model tractors with EPA's SmartWay-compliant [8] design packages and trailer side skirts were tested. The authors feel that this should be more representative of fleets that would adopt platooning technology in the United States if it becomes available, as many fleets are currently making aerodynamic packages standard across their fleet. EPA Phase 2 greenhouse gas emissions and fuel efficiency standards in preliminary rulemaking likely will make improved aerodynamics standard across the new Class 8 truck population. [Table 1](#) lists the test tractor and trailer specifications. [Figures 2, 3, and 4](#) show the lead, trailing, and control test tractor-trailer combinations, respectively.

Table 1. Test tractor and trailer specifications

Van Specification	Lead Tractor-Trailer	Trailing Tractor-Trailer	Control Tractor-Trailer
Manufacturer	Peterbilt	Peterbilt	Peterbilt
Model	386	386	579
Model year	2011	2011	2013
Vehicle Mileage at Test Start	325,367	360,334	43,618
Engine manufacturer	Cummins	Cummins	PACCAR
Engine model	ISX-15 450	ISX-15 450	MX-13 475
Engine model year	2010	2010	2010
Emissions equipment	DOC/DPF/SCR	DOC/DPF/SCR	DOC/DPF/SCR
Transmission	Eaton Fuller 10-speed	Eaton Fuller 10-speed	Eaton Fuller 10-speed
Retarder/regenerative braking	Engine Brake	Engine Brake	Engine Brake
Tires	Michelin XDA Energy	Michelin XDA Energy	Goodyear Fuel MAX
Cab Fairing to nose of trailer (visible space between tractor and trailer)	50"	50"	41"
Trailer Configuration	53-ft Van Trailer with angled side skirts	53-ft Van Trailer with angled side skirts	53-ft Van Trailer with angled side skirts
Trailer Manufacturer	Great Dane	Stoughton	Wabash
Trailer Model	74111 SSLAK	2GPVW-53ST-S-L-AR	TRA/ VAN
Trailer Height	13' 6"	13' 6"	13' 6"
Trailer Width	102"	102"	102"
King Pin Set Back	36"	36"	36"
Trailer Side Skirt	Freight Wing AeroFlex	Freight Wing AeroFlex	DuraPlate AeroSkirt
Distance from rear of trailer side skirt to front of trailer wheels	6.5"	8.5"	9.5"



Figure 2. Lead platoon tractor and trailer Photo by Alex Nicholson, Link Engineering Company

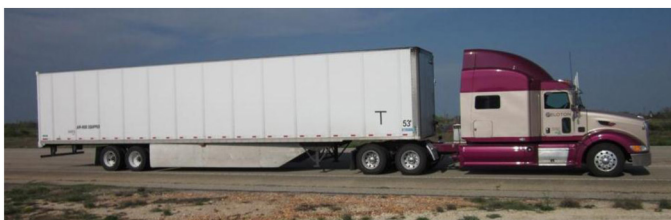


Figure 3. Trailing platoon tractor and trailer; Photo by Alex Nicholson, Link Engineering Company

The platooning demonstration system used is from Peloton Technology, Inc. [9], and includes radar systems, Dedicated Short-Range Communication (DSRC) [10] vehicle-to-vehicle communications, vehicle braking and torque control interface, cameras and driver displays. Table 2 lists the specifications of the platooning demonstration system tested. The system controls the throttle and braking on the rear truck using a combination of inputs including, but not limited to: radar-measured distance, GPS locations and speeds of both

vehicles, lead vehicle wheel-based speed, torque request and braking application. The system does not control lateral position so the trailing truck driver is still responsible for steering, which is a possible source of variation in the tests.



Figure 4. Control tractor and trailer; Photo by Alex Nicholson, Link Engineering Company

Table 2. Demonstration platooning system specifications

Category	Demonstration Platooning System Description
Manufacturer/integrator	Peloton Technology Inc.
Radar	Delphi Electronic Scanning Radar: Dual beams Short range +/- 45degree beam, 60m range Long range +/- 10 degree beam 175m range 20 Hz update rate Mounted in front bumper
Dedicated Short Range Communications	Denso DSRC Radio WSU 1.5 Dual antennas in diversity mode Omni-directional antennae mounted on mirrors Single 10 MHz channel Single-board computer and 5.9 GHz DSRC radio Supports IEEE 802.11p, P1609.3, P1609.4, P1609.2
Vehicle communication	CAN/J1939 interface through interface card in embedded PC Private Controller Area Network (CAN) for sensors J1939 for vehicle bus and actuation
ABS/Stability control	Meritor Wabco Brakes ESC with J1939 brake actuation capability

Variable Speed Track Testing

Because some of the nation's highway traffic flow may not enable constant-speed driving for extended durations, a variable speed test was desired. The system used for this testing disengages the platoon formation if a gear shift, transmission neutral, or brake pedal activation is detected. This necessitated a speed trace that the vehicles could accomplish while staying in top gear and using only engine braking to vary the speed. The "Cruise Mode" section of the California Air Resources Board (CARB) Heavy Heavy-Duty Diesel Truck (HHDDT) schedule [11] was used as a starting point, but the speed range was too low for top gear for a standard line haul tractor; therefore, 10 mph was added to all speed points of the HHDDT to bring the trace into the range of highway driving accomplished in top gear for these tractors. This modified HHDDT schedule was repeated roughly 2.5 times to approach 56 miles, intentionally short of the test distance of 59.5 miles. The variable-speed distance was set shorter than the normal test distance both to allow for error in meeting the trace and to allow the vehicles to enter and exit the test under 60 mph in the cruise control condition using normal test procedures. A heads-up driver's aid that displayed the desired speed for the next 30 seconds as well as current GPS speed, very similar to

driver's aids used in chassis dynamometer testing, was developed to enable the variable speed modified HHDDT testing program. Figure 5 shows a speed trace of the variable-speed program. Drivers were instructed to meet the trace as close as possible, but it was understood that the harder accelerations and decelerations would probably not be matched due to the limitations placed on each driver to remain in the same gear for the entire trace. Additionally, the grade changes of the track meant some accelerations/decelerations occurred on an up or down grade, which either mitigated or exacerbated the difficulty of meeting the trace. Because the trace was time based and started at the same point on the track, all vehicles experienced the same relative duty cycle at each location on the track.

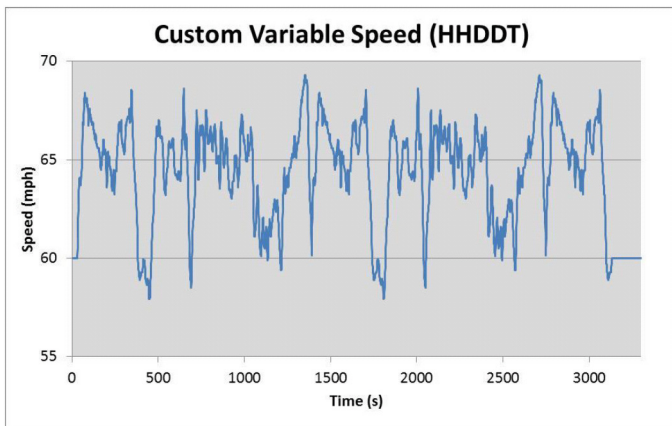


Figure 5. Custom variable-speed test trace based on the HHDDT

Track Testing Procedures

Track testing methods recommended in SAE J1321 Fuel Consumption Test Procedure - Type II (1986) [6] were used with some adaptations for platoon testing. The first modification to the procedure was to have two test vehicles compared independently to the control vehicle during baseline and test condition runs. Thus, two test-to-control (T/C) ratios were calculated for each test. The second modification was to utilize a solenoid valve to switch between vehicle fuel tanks for warm up and test tanks for test runs. As such, "run time" is the total elapsed time from energizing the fuel solenoid valve to de-energizing it (simultaneously triggering the J1939 data acquisition system). This was necessary to allow the test vehicles time to attain platoon formation prior to test start and to end platoon formation after test stop. Also, due to the nature of the dynamic interaction between the two test vehicles on test runs, additional variability outside the prescribed 2% was accepted on three tests. During the initial baseline test at 65 mph with 65,000 GVW and during the 70 ft. and 55 ft. following distance, the climate control and cab fan settings were kept constant with the air-conditioning clutch engaged and vent mode with a fan setting of "3" selected. For each baseline set and test set for the remainder of testing, the air-conditioning clutch was turned off while in vent mode and the fan speed remained at 3 to minimize variability between the control, lead, and trailing trucks. This adjustment was made to eliminate

possible variability from the air-conditioning compressor and was made possible by running tests outside the heat of the day. The test runs and respective baseline runs were always conducted using the same settings and as such all ratios were valid.

A full warm-up procedure was conducted at the start of each test day or after the vehicles had been parked for more than 30 minutes. The full warm-up procedure consisted of the following:

- The vehicles were driven for at least seven laps at the speed of the test segment that followed (55, 65, 70 mph, etc.).
- Fuel was drawn from the vehicle main tank (i.e., not the measured test tank) during the Full Warm-up Procedure.
- The vehicles were platooned together by the end of the warm-up period, allowing the test segment to start immediately upon reaching completion of the warm-up phase.
- Any set points such as cruise control, other speed locking settings, and/or platooning distance settings were set during the Full Warm-up Procedure.

A Partial Warm-up Procedure was conducted if the vehicles were parked for less than 30 minutes, which typically occurred at the end of a test segment. The Partial Warm-up Procedure consisted of the following:

- The vehicles were driven for 16.5 miles at the speed of the test segment to follow (55, 65, 70 mph, etc.).
- Fuel was drawn from the vehicle main tank (i.e., not the measured test tank) during the Partial Warm-up Procedure.
- The vehicles were platooned together by the end of the warm-up period, allowing the test segment to start immediately upon reaching completion of the Partial Warm-up procedure.
- Any set points such as cruise control, other speed locking settings, and/or platooning distance settings were set during the partial warm-up procedure.

A test run procedure was initiated without pause after the appropriate warm-up procedure was completed. The test run procedure consisted of:

- Three valid test runs are required for each series in the 65 mph, 65k GVW condition. Only two test runs per series for other conditions were performed due to budget considerations.
- By the end of the warm-up procedure/beginning of the test run procedure, all three vehicles were at the test speed and the spacing/distance with the cruise control and/or platooning system settings were engaged.

- As each vehicle crossed the 8.0-mile marker, the driver of each respective vehicle switched from drawing fuel from the vehicle main tank to the measured test tank. The tank switch solenoid also initiated logging by the data loggers. The data loggers were Isaac Instruments DRU-908 devices with 5 Hz GPS antennas and SAE J1939 CAN bus connections.
 - For the variable speed tests, the driver's aid trace was started as each vehicle crossed the 8.5-mile marker after having switched to the measured test tank. On platooning runs, only the lead platoon vehicle and control vehicle initiated the driver's aid.
- The test run consisted of seven laps (59.5 miles total). If conducting a baseline (non-platooning) run, each vehicle had significant spacing (3-5 min). If conducting a test (platooning) run, the control vehicle had significant spacing (3-5 min) behind the platooning pair.
- As each vehicle crossed the 8.0-mile marker after the seven test laps were completed, the driver of each respective vehicle switched from drawing fuel from the measured test tank to the vehicle main tank.
- Each vehicle then exited the track and parked in the staging area.
- The measured test tanks were quickly removed and replaced with a replacement measured test tank that had already been fueled and weighed.
- The vehicles were sent back out as quickly as possible to minimize cooling.
- Upon re-entering the track, the vehicles conducted the partial warm-up procedure (unless the transition time was longer than 30 minutes) and then initiated the next test run.

The measurement was defined as the T/C ratio, the ratio of the fuel used by test vehicle to that used by the control vehicle:

$T/C \text{ ratio} = \text{fuel used by test vehicle} / \text{fuel used by control vehicle}$

In this testing, there were two T/C ratios considered for validity checking: one for the lead platooning vehicle and one for the trailing platooning vehicle.

Lead Vehicle T/C ratio = T_L/C

Trailing Vehicle T/C ratio = T_T/C

If the desired number of consecutive runs did not comply with the 2.5% band, additional runs were completed until the desired number of consecutive runs fell within a 2.5% band.

Validity checks were completed for each of the test segments: the recorded fuel measurement ratios of three or two runs (per the test plan) were required to be within a 2.5% band of each other. Values above 2.5% were not considered valid. All baseline sets were within 1% variation. However, due to the nature of the platooning test and the need for air conditioning use due to ambient conditions during early testing, three test sets results were higher than the SAE J1321-prescribed 2%

band [5] but were still accepted; no results higher than 2.5% were accepted on steady-state test sets. The exception was the variable speed test set, where the previously discussed difficulty in meeting the trace led to a 3.8% variation on the test runs that were accepted.

An additional T/C ratio was calculated during post processing but was not considered during the validity check process. "Team" fuel savings were calculated in an effort to consider the total fuel savings of a pair of platooned vehicles, without introducing any bias via an averaging method. Team fuel savings were determined by summing both the leading and trailing vehicle fuel consumption and using that value to calculate a new T/C ratio measurement.

$$\text{Team T/C ratio} = (T_L + T_T) / C$$

Ambient Conditions Measurement

Ambient temperature, relative humidity, average wind speed, peak wind speed, wind direction, and barometric pressure measurements were provided by a weather station located at the test track, which recorded the information once a minute. Testing took place over 3 weeks and over much of the day and night; as such ambient conditions during testing ranged as well. Average wind speeds over the course of a test ranged from 2 mph to 11.7 mph. Average temperatures ranged from 13° to 32°C. Relative humidity ranged from 17% to 88%.

Fuel Consumption Measurement

The fuel consumption measurement in this project relied on a gravimetric approach. The engine fuel supply and return lines were connected to a fuel container placed on the frame rails behind the cab. The driver controlled a switch between the test tanks and main vehicle tanks. The difference between the beginning and the end of test mass measurement indicated the mass of fuel consumed during the test. Each day, the scale calibration was verified with a known calibration weight. A Sartorius ISI-10 scale with 0.002 kg readability and NIST traceable calibration on site at the Continental Tire Proving Grounds was used for this test. Engine fuel rate from the SAE J1939 CAN bus was also recorded as an investigative method, not to back up the gravimetric fuel measurement but rather to be evaluated alongside it. A sample of the fuel used for the testing was analyzed and the resulting specifications are presented in the appendix, [Table A1](#).

Engine and Vehicle Parameters Measurement

It was desired to understand the impact of close platooning of other engine and vehicle systems that could have negative unintended consequences such as engine cooling and selective catalytic reduction (SCR) exhaust aftertreatment performance. It was also of interest to evaluate whether the SAE J1939 fuel consumption rate reporting was accurate enough to replace gravimetric fuel measurement during investigative SAE Type II fuel consumption tests. The SAE data loggers were recording the GPS location and SAE J1939