Final Project Report

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Advancing Platooning with ADAS (Advanced Driver-Assistance Systems) Control Integration and Assessment

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Prepared by:

Hoseinali Borhan

Principal Investigator

Cummins Research & Technology

hoseinali.borhan@cummins.com

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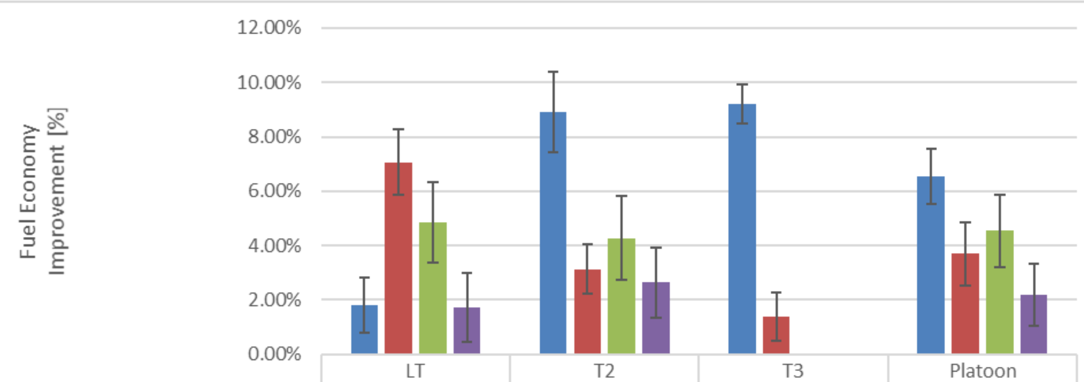
Executive Summary

Application of Cooperative Adaptive Cruise Control (CACC) to heavy duty trucks known as truck platooning has shown fuel economy improvements on the test track under ideal driving conditions. However, limited test data is available to assess the truck platooning under real-world driving conditions. Under this Cummins-led project that was funded by the U.S. Department of Energy, truck platooning with CACC has been tested on a real-world interstate highway and the results of the project are reviewed in this report. At first, the real-world driving conditions were characterized using National Renewable Energy Laboratory (NREL) Fleet DNA database to define test factors, including route, terrain, and highway traffic. Afterward, both test track and on-highway testing guided by SAE J1321 procedures were conducted to assess truck platooning under controlled and real-world driving conditions. On-highway testing was done on a highway route in Indiana, consisting of low, medium, and high road grade segments. The highway test results of 2-truck and 3-truck platooning showed considerably reduced fuel savings compared to the controlled test track data, which mainly stems from the traffic or high-grade portions of the route. However, integration of Cummins powertrain and vehicle eco-driving features such as predictive cruise control and neutral coasting called ADEPT™ on the lead truck showed an improvement of fuel saving for the trucks in CACC operation. Furthermore, the importance of tire connectivity in efficient and safe operation of the trucks in platooning is characterized.

A summary of the project achievements is listed below:

- **Fuel economy test results:** Figure 1 presents a summary of the fuel economy test results comparing CACC/platooning at 0.6s time gap target to Baseline (single truck) operation over the entire route in Indiana. More information about the truck specifications and route are reported in the subsequent sections. While there is fuel economy improvement with the combined platoon, the benefits are significantly reduced compared to the ideal test track fuel economy results. This is mainly due to the impact of real-world driving conditions, particularly road grade variations and highway traffic. A detailed list of identified issues and barriers with this technology are reported in the subsequent sections of this report. Integration of Cummins powertrain and vehicle eco-driving features on the lead truck improves fuel economy of the trucks in platooning as shown in 2 trucks testing.



	LT	T2	T3	Platoon
3 Truck SS vs BL (Test Track)	1.81%	8.93%	9.20%	6.54%
3 Truck ADEPT vs BL	7.06%	3.12%	1.38%	3.70%
2 Truck ADEPT vs BL (2020)	4.84%	4.27%		4.55%
2 Truck No ADEPT vs BL (2020)	1.73%	2.64%		2.18%

Figure 1 Fuel Economy Test Results Summary ("SS": Steady State; "BL": Baseline)

- **Advanced Platooning Solutions - Connected and Cooperative Eco-Driving:** Platoons consisting of automated convoys of heavy-duty trucks are designed to maintain close gaps between trucks and have traditionally been handled with classically-designed connected and adaptive cruise control

(CACC). Classic baseline control methods that enforce a gap can reduce energy use in steady-state uninterrupted operation. During transients induced by traffic or road grade, however, maintaining a desired gap may require application of brakes, thus wasting energy, or may lead to platoon disengagement when the trail truck falls behind as shown in the test results.

The Clemson University (CU) collaboration addressed some of the above challenges of classical CACC by devising optimization-based control algorithms that are predictive in nature rather than reactive. These methods provide the capability to optimize the balance between gap tracking and powertrain efficient operation to minimize energy use. The team focused on devising variants of a Model Predictive Controller (MPC) that optimized the longitudinal motion and lane decisions of each truck over a receding horizon and showed improvement in fuel economy compared to the baseline methods in high fidelity simulations and virtually imposed traffic conditions in test track testing of the solutions experimentally. The benefits were higher when V2V connectivity allowed communication of future intentions by the preceding trucks to the following trucks. In heterogenous platoons, road tests showed that in hilly roads and during gear shifts, the platoon may still split due to a truck falling behind. To address this experimentally observed issue, a considerate MPC variant is introduced that enables the leading trucks to accommodate those behind them by slowing down for them when necessary. The project team demonstrated the performance of the considerate strategy in a real-world driving scenario against a similar non-considerate control strategy. Overall, the team found that the considerate strategy significantly improved harmonization between the platooning trucks and prevented platoon disengagement.

While a constant target speed for the platoon is energy efficient on relatively flat roads, in hilly scenarios where maintaining a constant speed requires brake actuation, a variable target speed is more energy efficient. Test data showed that for truck platooning in situations with high grade variation, when the Cummins ADEPT eco-driving features including predictive cruise control were integrated on the LT, significant fuel savings resulted. An important analytical contribution by the team is the successful formulation of target speed optimization over the remaining route to the destination as a Linear Program that is solved an order of magnitude faster than previously proposed methods in the literature. Therefore, the proposed method has considerable energy saving potential for commercial implementation, not only in platooning but also in long-haul trucking automation.

The team also identified opportunities for energy savings by more systematic and optimized lane change decisions. The team proposed an optimal lane change algorithm, tailored for the complex geometry of a class-8 tractor-trailer, and successfully simulated realistic scenarios in dense traffic microsimulations. The proposed algorithm allows a single truck or a truck convoy to safely initiate and complete a lane change or take-over maneuver with energy efficiency consideration at its core.

- **Importance of Tire Connectivity:** In 2021, through collaboration with Michelin North America, the project team studied the impact of steer tire (in the front axle position) and drive tire (in the drive axle position) constructions on the stopping distance performance of loaded and unloaded tractor-trailer Class 8 trucks running on dry asphalt road pavements. The tests indicated that the stopping distance between the two tire sets can vary by as much as 4.7% when the trailer is fully loaded and as much as 1.2% when the trailer is empty. The test data in 2020 show that this difference in stopping distance can increase to more than 20% under wet conditions.

  The individual tire characterization with respect to braking performance was used to create tire models. The tire models were then coupled with vehicle simulation models to predict the stopping distances on dry pavements. The simulations predicted the correct tire set ranking, although the amplitude was higher than that obtained through vehicle tests. A subsequent slip histogram analysis showed that this discrepancy was probably due to a model versus actual vehicle difference in how the anti-lock brake system is tuned with the tire peak friction coefficient.

This project has shown that information in real time about the tire adherence capabilities can increase the fuel savings of vehicles running under platooning configurations. This improvement is because the tire characteristics have a considerable effect on the vehicle braking performance. Specifically, this work has shown that differences in tires can cause the stopping distance of a Class 8 vehicle to vary by as much as ~5% on a dry road and as much as ~20% on a wet road. In fact, these variations on wet surfaces placed the tire construction and wear state ahead of other variables such as the vehicle load. Furthermore, tests also showed that on dry asphalt pavements, differences in tire construction can lead to variations in vehicle stopping distance as high as 5%. Additional tests indicated that the variations noted were due to differences in the friction capabilities on wet and dry pavements provided by tires of different constructions. To capitalize on these findings, the project team developed tire models to determine in real time the friction coefficient generated between the tire and the road as a function of the tire construction, road pavement and vehicle usage conditions. The project team then used these friction coefficients in vehicle models to predict the optimum platooning distance between Class 8 vehicles running different duty cycles. The simulations indicated that knowing the tire friction capabilities in real time allows the platooning distance to be further optimized by advanced predictive and optimal platooning control, thus increasing the vehicle fuel savings. For the trail platooning vehicle, these gains are predicted to be between 2% for low traffic and low road grade conditions and 5% for duty cycles that include road grade variations.

In summary, the results indicate a few issues and challenges of the implementation of truck platooning technology under real-world driving conditions comparing to the prior results done under ideal test track driving conditions. A few solutions are assessed, and tire connectivity benefits are quantified in this project. While there are challenges and technology barriers to be addressed for the deployment of this technology with the current powertrain, V2V connectivity and vehicle automation level in the market (which is highly dependent on driver decisions and operation), assessment of the technology with emerging powertrain technologies in HD truck applications e.g., hybrid, EV and Fuel Cell and higher level of vehicle automation and V2X connectivity is recommended.

Accomplishments

a) Major goals and objectives of the project

This project assessed the benefits of platooning for fuel consumption reduction under real-world driving scenarios for 2 and 3 trucks platooning. In addition to platooning baseline control, Cummins ADEPT^{TM} (Advanced Dynamic Efficient Powertrain Technology) fuel economy control features and Michelin tire connectivity technology were integrated and the impact was assessed.

The project objectives were:

Objective 1: To assess baseline platooning control integration for class 8 linehaul truck applications under real-world driving scenarios and identify barriers and issues through analyzing data from vehicle, engine, transmission, aftertreatment, control software, connected tires, braking system, and fuel economy test sensors (2 and 3 trucks platooning).

Objective 2: Technology integration assessment with platooning control including Cummins ADEPT^{TM} fuel economy control features in cruise and throttle operation and Michelin's tire connectivity technology to monitor tire conditions and estimate braking capabilities under different tire/road conditions.

Objective 3: Develop and demonstrate solutions to overcome barriers and issues for advancing platooning/cooperative adaptive cruise control (CACC) technologies.

The program met its goals drawing upon the strengths of the assembled team: Cummins, Michelin, Clemson University, and the National Renewable Energy Laboratory. The project heavily focused on testing and data analytics of the test results with simulation models verified and used to develop solutions.

The project was conducted in 3 budget periods as listed below.

Budget Period 1 (completed): Integration of CACC for baseline. Tuning, instrumentation, and data collection of 2-truck baseline platoon.

Budget Period 2 (completed): Assessment of baseline performance for 2-truck platoon and identification of barriers and solutions.

Budget Period 3 (completed): Tuning, instrumentation and data collection of 3-truck baseline platoon and proof of concept of the proposed solutions for advanced CACC/platooning system. Tire connectivity impact reported.

The project's overall timeline is presented in Figure 2. The project is successfully completed per the plan and the goals and deliverables are achieved.

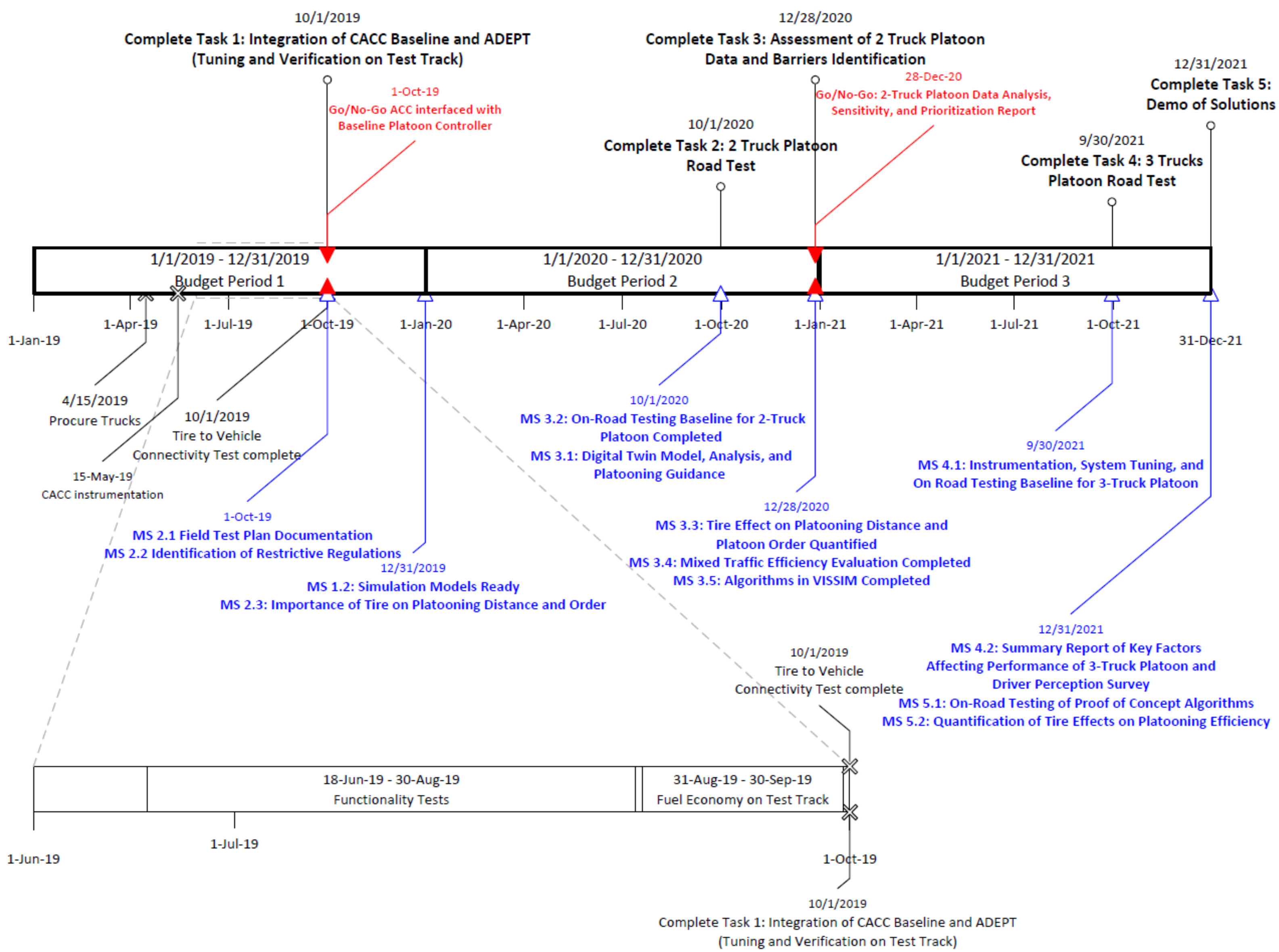


Figure 2 Project Timeline Overview

b) Technical Report

1. Introduction

Truck platooning has been considered as one of the most mature connected and autonomous vehicle technologies to be employed on heavy-duty vehicles. The fuel saving from truck platooning mainly comes from two dominant aerodynamic phenomena (McAuliffe et al., 2017). 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 is propelled 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.

Reported fuel savings results for trucks platooning from controlled track studies are appealing to fleets operating primarily on highway. Early studies have consistently suggested significant fuel savings from truck platooning. A demonstrated benefit of Cooperative Adaptive Cruise Control (CACC) /platooning is the energy savings that are possible for scenarios in which multiple class 8 heavy-duty vehicles can safely travel in close proximity. This has been highlighted by numerous studies investigating the potential benefits of truck platooning. Based on the previous investigations, the fuel savings associated with vehicle platooning and close-proximity driving has been attributed to an aerodynamic influence. Wind-tunnel studies (Lammert et al., 2018b; Marcu & Browand, 1999; McAuliffe & Ahmadi-Baloutaki, 2018; Salari & Ortega, 2018; Tsuei & Savaş, 2001) and track-based fuel-economy studies (Al Alam et al. 2010; Ashley, 2013; Bevly et al., 2015; Bonnet & Fritz, 2000; Browand et al. 2004; Hammache et al., 2001; Humphreys & Bevly, 2016; Lammert et al., 2014; McAuliffe et al., 2018; Robert et al., 2016; Roeth, 2013; Tsugawa et al. 2011; Tsugawa, 2014) have identified trends in aerodynamic drag reduction associated with various heavy-duty vehicle configurations in close proximity and linked them to the resulting fuel savings. The trends identified through comparable studies above include:

- The lead truck of a 2 or 3 truck platoon experiences a significant increase in fuel savings as the separation distance is reduced below 15 m, reaching 10% fuel savings at 4 m separation distance, while no savings will be experienced at 20 m or longer
- A middle truck in a 3-truck platoon may experience the highest fuel saving of all three vehicles at any separation distance, reaching about 17% at a 4 m separation. The fuel savings for a middle vehicle will decrease continuously with increasing separation distance, reaching around 6% at 87 m separation.
- The maximum fuel savings for the trailing vehicle in a 3-truck platoon may reach 13% in the 10 m to 20 m separation distance range. Below 10 m separation distance, the fuel savings of the trailing vehicle will decrease as the distance is reduced, reaching a minimum value around 11% at 4 m. Beyond about 20 m, the trailing vehicle experiences decreased fuel savings with distance, in a similar manner as the middle vehicle, but with a 2% to 3% higher fuel savings. At 87 m separation distance, the trailing vehicle should achieve about 8% fuel savings.
- The trailing vehicle of a 2-truck platoon exhibits a similar trend as the three-truck trailing vehicle, except at a 2-4% lower fuel-savings magnitude.

A number of computational studies (Davila et al., 2013; Ellis et al., 2015; Gheyssens & Van Raemdonck, 2016; Hammache et al., 2001; Humphreys et al., 2016; Mihelic et al., 2015; Smith et al. 2014; Tsugawa et al., 2011) have provided insights on the aerodynamic mechanisms that lead to these beneficial effects. Additional studies (Lammert et al., 2018a; MacKenzie et al., 2014; Muratori et al., 2017) have attempted to extrapolate individual platoon performance from wind tunnel and track studies to operation of commercial vehicles to understand the fuel savings that are achievable at a fleet or national scale. One study (MacKenzie et al, 2014) considered all truck miles platoonable and estimated 10-25% total energy reduction from platooning heavy trucks. Others (Lammert et al., 2018; Muratori et al., 2017) incorporated real world driving conditions to estimate that 63%-65% of miles driven were at platoonable speeds. Another study (Muratori et al., 2017) considered the geospatial availability of platooning partner trucks to estimate 55.7% of trucking miles were platoonable.

As highlighted by the previous literature survey (McAuliffe et al., 2017), the magnitude of fuel saving from platooning is influenced by the separation distance, the truck configuration, and the operational environment in which the vehicles are evaluated. 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. Understanding the implications and limitations of platooning technology in real-world driving scenarios is of great importance to truck and powertrain manufacturers to design, integrate and calibrate the platooning control system accordingly. This can also enhance user acceptance and successful market penetration and widespread use of the platooning technology.

Given these considerations, Cummins teamed up with National Renewable Energy Laboratory (NREL), Clemson university, and Michelin North American, and conducted a study to assess ***real-world*** fuel savings and evaluate real-world barriers for platooning. In this project, truck platooning with CACC was tested under real-world driving scenarios with 2 and 3 truck platoon configurations. Fuel economy impacts and technology barriers with a few potential solutions are identified. The objectives of this project were:

- ***Objective 1*****:** Assess baseline platooning control integration for class 8 line-haul truck applications under real-world driving scenarios and identify barriers and issues through testing and data analysis.
- ***Objective 2*****:** Assess technology integration with platooning control, including Advanced Driver Assistance Systems (ADAS) fuel economy control features in cruise and throttle operation, along with tire connectivity technology to monitor tire conditions.
- ***Objective 3:*** Develop and demonstrate solutions to overcome barriers and issues for advancing platooning/CACC with technology integration.

In this report, detailed test procedures, test results and corresponding data analysis will be presented. In the following sections, a comprehensive characterization of the real-world driving environments will be conducted. Three factors, including route terrain, road grade and traffic influence, were identified as the most significant test factors for platooning through the data science technique. Afterward, the test procedure is described in detail, including the information of the test vehicles, test route and fuel economy test protocol. Then, the test results and related data analysis will be presented to provide insightful information related to the truck platooning in real-world conditions. Given the on-road test experience, the existing technology barriers and issues related to the truck platooning are described. In the end, the report will be wrapped up by offering a few solutions achieved from the study.

2. Test Factors Characterization

To define the test plan for on-road fuel economy assessment of platooning, the team developed a methodology to rank test factors that represent real-world driving conditions of line-haul truck operation and are likely to impact truck platooning performance. These test factors influence the selection for test routes, helped refine the logging parameter list, were used to calculate route and performance indices, and define test conditions to conduct the appropriate test for a given test factor. Furthermore, criteria were defined to assess the importance of the identified test factors for the goal of the project. Test factors were evaluated based on their importance to line-haul truck operations, likely impact on platooning fuel economy and operation, prior test data availability, level of difficulty to model, and feasibility to test. In this study, each candidate test factor was assessed separately based on prior test data, publications, and the experience of the entire team. The results are summarized in Table 1.

Table 1. Selection Matrix for Test Factors

	Rating of Importance to Customer		10	10	8	6	8	4	
			1	2	3	4	5	6	
Test Category	Test Factor	Group	Importance to Line Haul Trucking	Platooning Fuel Saving Impact	Platooning Operation Impact	Past Test Data Availability	Feasibility of Testing	Maturity of Alternative Methods to Assess Platooning e.g. Simulation	Total
Traffic	Highway traffic induced speed fluctuation		9	9	9	9	1	9	350
Route	Terrain (Flat/non-Flat (>1%))		9	9	9	9	3	3	342
Vehicle Configuration	GVW Differences (within platoon)		9	9	9	9	3	1	334
Traffic	Lane change	1	3	9	9	9	9	3	330
Powertrain Calibration	ADEPT enabled/disabled on Lead		9	9	1	9	9	3	326
Environmental Conditions	Road Surface Condition		3	9	9	9	3	9	306
Tire	Tire wear (new/worn)		3	9	9	9	3	9	306
Platooning Operation	Following Time / Distance Gap		9	9	9	1	3	3	294
Vehicle Configuration	Trailer Aero Treatments		9	9	1	3	9	3	290
Environmental Conditions	Weather conditions (tempt/wind)	2	9	9	3	9	1	3	278
Platooning Operation	2 vs 3 trucks		3	9	9	3	3	9	270
Tire	Tire inflation pressure		9	3	3	9	3	9	258
Tire	Tire Performance (Traction vs LRR)		3	3	3	9	9	9	246
Traffic	Vehicle cut in front / behind of Lead		3	3	9	3	9	3	234
Route	Curvature		3	9	3	3	3	9	222
Platooning Operation	Lead driver speed control (CC vs non-CC)		3	3	3	9	9	1	214
Vehicle Configuration	Tractor Type (Daycab/Sleeper)		3	9	1	9	1	3	202
Traffic	Aerodynamic impact of surrounding vehicles	3	1	9	1	3	3	9	186
Powertrain Calibration	Engine Rating Difference		3	3	3	3	9	1	178
Route	Road Speed Limit (High / Low vehicle speed)		3	3	1	3	9	3	170
Environmental Conditions	Altitude		3	3	1	9	3	3	158
Vehicle Configuration	Final Drive Ratio		1	1	3	9	3	1	126
Vehicle Configuration	Truck Weight Class		1	3	1	9	1	3	122

Group 1 is the list of high priority test factors selected for further characterization and testing, Group 2 is the lower priority test factors to be tested if time and resources allowed. Group 3 are the list of test factors that are not selected to be tested due to their low priority and impact.

As shown, the test factors are grouped into three categories. The first group includes the high priority test factors that were selected for further characterization and testing. The second group shows the lower priority test factors. Test factors from the second group were to be tested if time and resources allowed. The last group (group 3) are the test factors that were not selected for testing in this project. The selected high priority test factors are further analyzed and characterized. The characterization of the top factors will be reported in the following sub-sections.

2.1. Highway traffic induced speed fluctuation

This test factor was investigated by leveraging the existing Fleet DNA database (Walkowicz et al., 2016) and applying the state-of-the-art machine learning techniques to cluster the trip data for line-haul truck application. The Fleet DNA data was developed by the Commercial Vehicle Technologies team at NREL, which has collected and stored data from MD/HD vehicles operating since 2010. Data collection activities were largely funded by the U.S. Department of Energy (DOE) fleet evaluation projects, aimed at investigating real-world efficiency improvements from emerging vehicle technologies[1].

[1] The entire FleetDNA data is available at http://www.nrel.gov/fleetdna.

For this study, a subset of Fleet DNA database representing line-haul truck operation were extracted, as shown in Figure 3. The three sets of colored lines show data from three different line haul fleets. The data from the three selected fleets include total 74 vehicles and 1011 vehicle days. Due to the long-haul truck driving behavior, each vehicle day consists of over 10 hours of driving and thus the entire sub database contains over 600,000 driving miles.

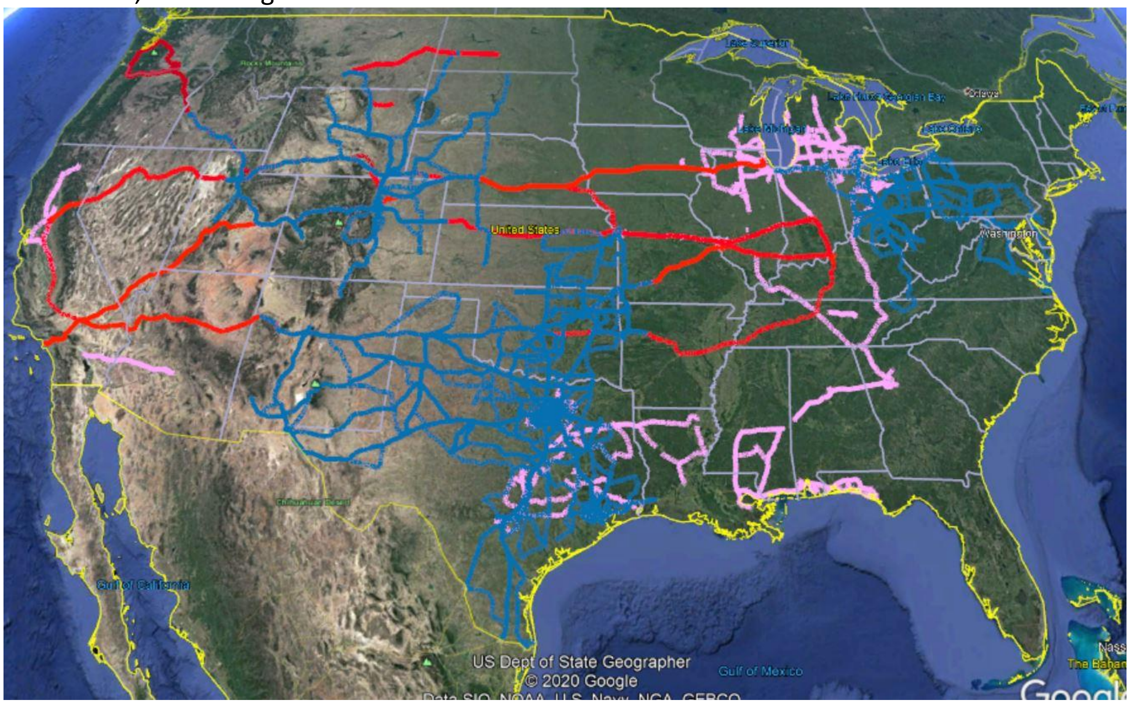


Figure 3. Line haul operation data in Fleet DNA database

Data preprocessing is a critical step for almost all the data analysis techniques. In this study, the following preprocessing steps were employed:

- Check and interpolate the missing and erroneous data
- Convert the day-basis raw data into trip-basis data
- Remove any trip with a distance less than 10 miles or duration less than 10 minutes
- Selecting the trips on a road section in the top 25% of annual vehicle mile traveled (VMT) based on traffic volume estimation from the Freight Analysis Framework (FAF) (Hwang et al., 2016)

After applying the above pre-processing steps, more than 21,000 original trips from the raw data have been reduced to 4563 representative trips. High-level statistics distributions of those trips are shown in Figure 4, which include trip-based brake energy consumption, travel distance, fuel economy, total fuel consumption, average speed, and distance above 55 mph. These statistics describe the typical driving behavior of line haul trucking, especially the average speed and the trip distance above 55 mph.

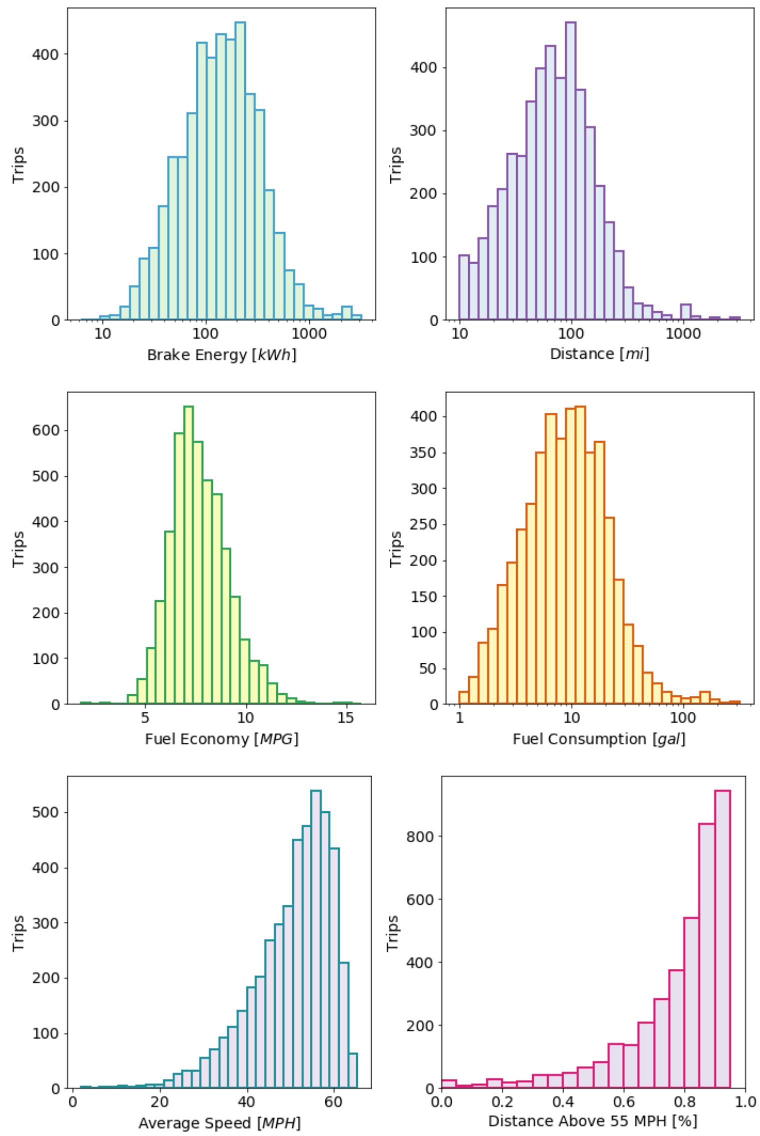


Figure 4. Statistical distributions of selected 4563 representative vehicle trips.

2.1.1. Clustering Analysis

After determining the representative trips, we conducted an unsupervised clustering analysis via K-mean cluster method. The K-mean algorithm clusters data by separating samples in *n* groups of equal variances. Usually, it divides a set of *N* samples *X* into *K* disjointed clusters *C*, each described by the mean μ_j of the samples in the cluster. The means are commonly called the cluster "centroids". Then the K-mean algorithm aims to choose centroids that minimize the within-cluster sum-of-squares criterion:

$$\sum_{i=0}^{n} \min_{\mu_j \in C}(\|x_i - \mu_j\|^2) \quad (1)$$

One disadvantage of this method is that the number of clusters must be specified manually. In unsupervised data analysis, the number of clusters within the data is usually unknown. Thus, it may generate irrational results if the specified number of clusters is not correctly chosen. To avoid this situation, a Silhouette analysis is applied to determine the optimal number of the clusters for K-mean. The Silhouette analysis sweeps the number of clusters for K-mean and calculate the corresponding Silhouette Coefficient. The Silhouette Coefficient (SC) is a metric used to calculate the effectiveness of a clustering technique:

$$Silhouette\ Coefficient = (x - y)/\max(x, y) \quad (2)$$

where, *y* is the mean intra cluster distance: mean distance to the other instances in the same cluster. *x* depicts mean nearest cluster distance i.e., mean distance to the instances of the next closest cluster.
The value of SC ranges from -1 to 1. A value near +1 indicates that the sample is far away from the neighboring clusters. A value of 0 indicates that the sample is on or very close to the decision boundary between two neighboring clusters. Negative values indicate that those samples might have been assigned to the wrong cluster. Given that, the optimal number of clusters achieved from the K-mean method should be determined by the largest SC.

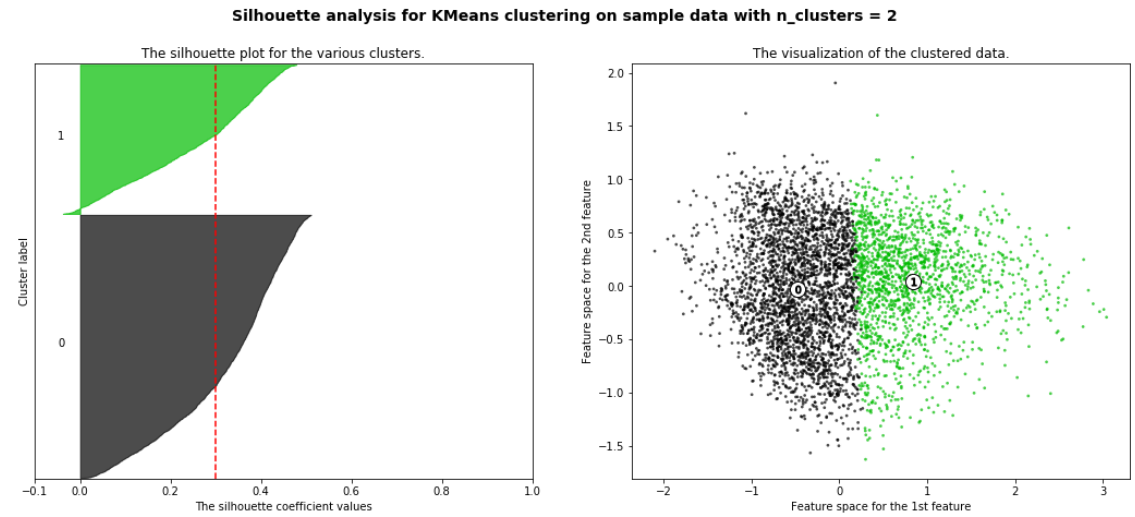


Figure 5. K-mean and related Silhouette analysis for this study with prescribed 2 clusters

Figure 5 shows the outcome of the K-mean analysis with prescribed 2 clusters and the corresponding Silhouette analysis which is the maximum value of SC. Two clusters are clearly separated with color code in the right sub-figure and the SC from each point is distributed in the left sub-figure. It is clear that a smaller number of points in cluster 1 (green color) have negative SC. The averaged SC from the entire cluster is shown as the red vertical dashed line in the left sub-figure, with the value of 0.29.

Figure 6 shows average driving speed distributions from each of the two clusters from the K-mean approach. In Figure 6, the blue distribution, which is labeled as 0 cluster, possesses relatively higher average driving speed distribution with the range from 40 to 70 mph with a peak at 60 mph. Considering the fact that the speed limit along the inter-state highway ranges from 65 to 75 mph in the most part of the U.S., this cluster may be identified *as a high-speed case*, which represents the circumstances that line-haul trucks drive on the highway in a cruise driving condition. The other cluster, labeled as 1 and colored in orange, ranges from 20 to 60 mph with peak at 48 mph. This cluster may be identified *as a low speed case*, which represents the situation that line-haul trucks driving in traffic along inter-state highway or through local routes.

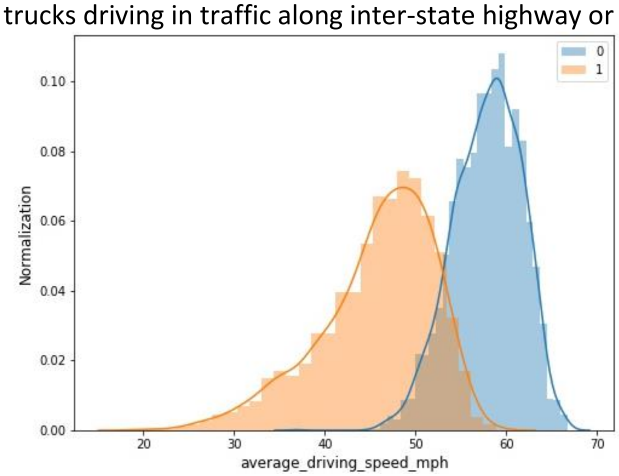


Figure 6. Average driving speed distribution of 2 clusters

2.1.2. Analysis of Two Clusters

It is widely believed that line-haul trucks typically drive in a cruise condition with high speed in rural areas, while operating at relatively lower speeds in urban areas due to the potential traffic environment. In order to evaluate the above assumption, each trip that was under consideration has been assigned a value to indicate whether it is in rural or urban area. This was done by comparing each trip's instantaneous GPS information with the adjusted urban area boundaries determined by Federal Highway Administration (US DOT FHWA, n.d).

Line-haul truck trips are often hundreds of miles and may cover both urban and rural areas. Rural distance fractions were calculated to show the distance fraction of each trip in rural areas. For example, if one trip has 40% of the distance within rural areas and 60% of the distance in urban areas, the value that was assigned to this trip is 0.4. The above calculation was employed for all the trips to achieve the bin distributions of rural distance fraction related to the two clusters, as shown in Figure 7.

From Figure 7, the majority of trips (above 80%) in the high-speed case have over 50% rural fraction. Specifically, 30% of the trips in high-speed case have over 90% trip distance within rural areas. However, for the low-speed case, the rural distance fraction has a relatively flat distribution, while almost all the bins account for 5-10% of trips (see yellow bins in Figure 7). The peak bin (accounting for 16% of trips) in low speed case is located around the urban area (very low rural distance fraction). This is intuitive since the line-haul truck operating in major urban areas may experience significant traffic which will reduce the average driving speed. However, even in rural areas (rural distance fraction is higher than 80%), some line-haul trips can still be categorized as a low-speed case. This may be due to traffic influences caused such as accidents or construction sites. Another factor is when the line-haul truck drives along a hilly road with relatively aggressive road grade profile. For safety or performance considerations, the line-haul truck has to reduce the driving speed in those conditions.

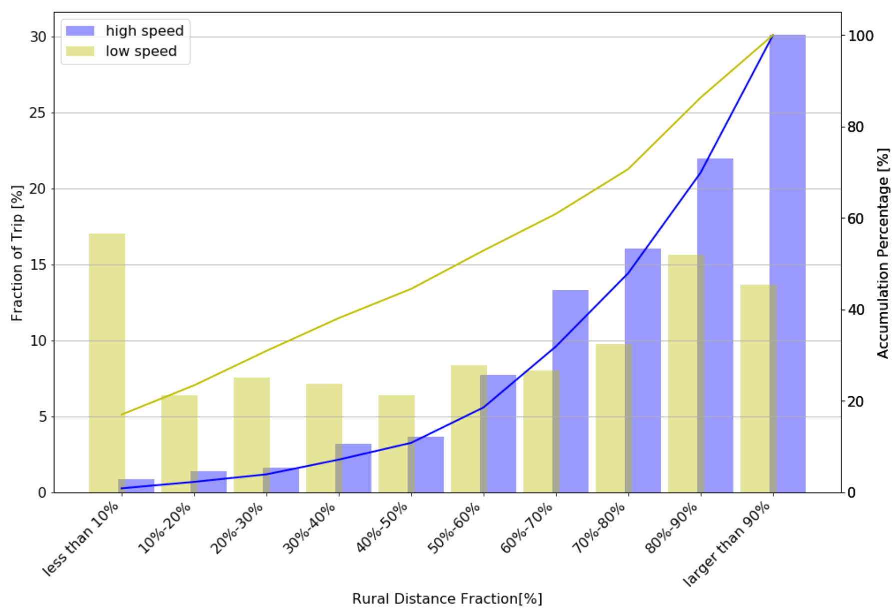


Figure 7. Rural Distance Distribution from two clusters

Given this observation, on-road testing of truck platooning must consider all the possible real-world driving scenarios, including high-speed cruise driving along the interstate highway and fluctuated speed profiles caused by either traffic influence around the urban area or the other factors in rural areas, such as road grade, construction and heavy traffic caused by accident.

2.2. Test route terrain and road grade

In a previous report (Wood et al., 2015), NREL has developed a specialized algorithm to search for nationally representative test routes that demonstrate road grade comparable to the national average. This algorithm has been leveraged in this current study to select test routes which have comparable national representative route terrain and road grade profile. The search criterion in this effort was focused within the state of Indiana to limit transport time from Cummins headquarters to the test site, with a target length of 100-200 mile highway stretches. Each candidate route was adjusted to a defined route by adjusting length and identifying available truck turnaround points at highway on/off ramps, as well as considering weigh stations and ports of entry that could impact test repeatability.

Two metrics were used to evaluate candidate drive cycles and assess the relevant attributes:

1. Distribution of grade. It is desirable to have a grade profile with an appropriate distribution of grades, representing highway miles driven by trucks correlated to actual customer usage. In addition to the cumulative grade distributions, rate of change of grade was also evaluated to ensure that a preference for shorter duration cycles (to reduce test time) does not result in non-representative conditions.
2. Hill length. Hills of differing duration will impact a vehicle's powertrain and platooning controls. Smaller hills cause more transient power requirements. Rolling hills might be the most favorable condition for certain powertrain configurations that recover downhill energy. Longer duration hills are inevitably encountered in the real world and the vehicle must have sufficient powertrain performance over these events. Hill length can also be evaluated by plotting a cumulative distribution of half-hill length (where "half-hill" is the portion of road between changes in sign (+/-) of the road's grade value).

The selected test route is shown in Figure 8. This route begins and ends in Columbus, IN at Cummins Machine Integration Center (CMIC) with a turnaround point in Evansville, IN. The round-trip length is 329 miles and consists of sections from I-65, I-265 and I-64, all within the state of Indiana.

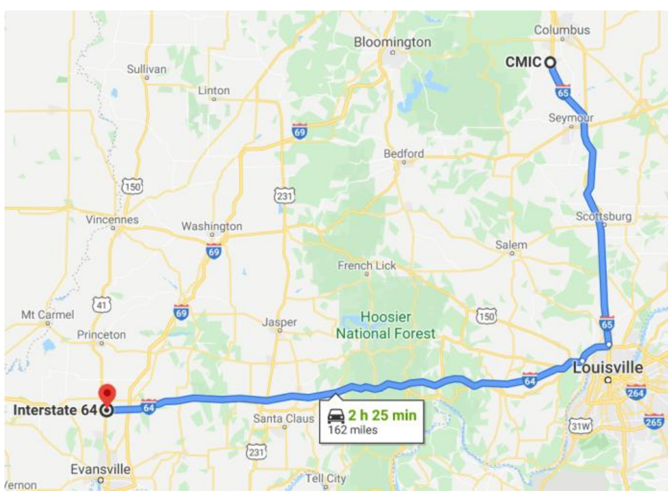


Figure 8. Selected Route for Fuel Economy Tests

Comparisons of this route with the nationally representative road grade profiles on absolute road grade and half hill distance are shown in Figure 9 and Figure 10. As mentioned above, half hill distance is defined as the length of a continuous stretch of roadway where grade does not change sign, so it is either a climb or a descent. As can be seen in Figure 9, the test route has a larger fraction of low road grade profiles (road grade < 1.2%) and a lower fraction of high road grade profiles (road grade > 1.2%) compared to the nationally representative road grade profiles. The average absolute error on road grade is around 4%. The half hill distance distribution shown in Figure 10 also reflects the similar trend, while almost 80% of half hill distance is less than 1.2 miles. The average absolute error on half hill distance is a little bit higher at 6%. The comparison reflects that the candidate route is a bit low in rolling and steeper hills fraction as would be expected in the state of Indiana. Both error levels were considered acceptable in the original work (Wood et al., 2015).

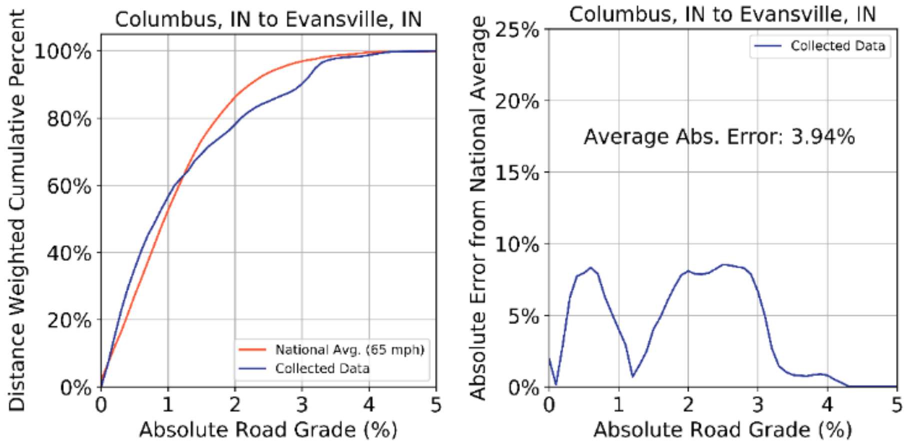


Figure 9. Comparison of the Indiana selected test route and the nationally representative profiles on absolute road grade (left plot) and absolute error between these two (right plot)

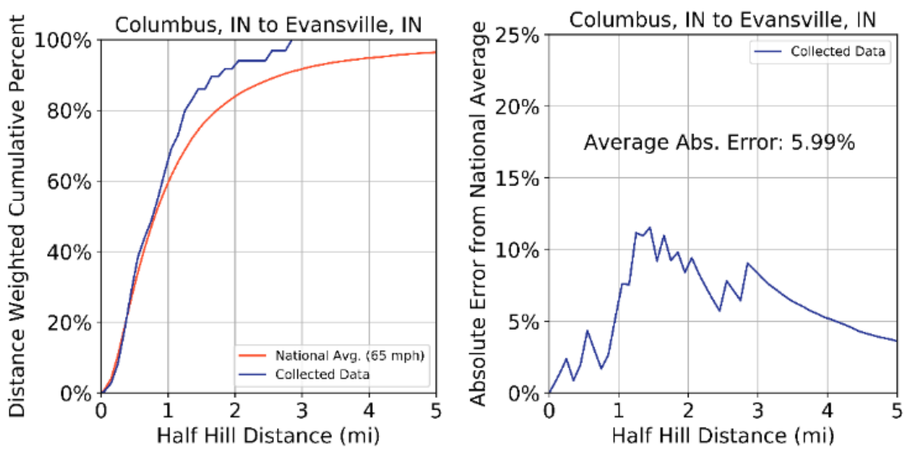


Figure 10. Comparison of the Indiana selected test route and the nationally representative profiles on half hill distance (left plot) and absolute error between these two (right plot)

3. Test Procedures

In this study, 4 different test phases were conducted as listed below, including both 2-truck and 3-truck platooning configurations:

1. Steady state (SS) CACC 0.6s (3-Truck 2021): CACC test at 0.6 sec headway time gap with lead truck in cruise operation at 65 mph (baseline: cruise operation at 65 mph without CACC)
2. On road CACC 0.6s with Cummins' Advanced Dynamic Efficient Powertrain Technology (ADEPT) (3-Truck 2021): CACC test at 0.6 sec headway time gap on Indiana route with lead truck in cruise at 64 mph with ADEPT features enabled (baseline: cruise at 64 mph or at speed limit if below 65 mph). Cummins ADEPT is a suite of powertrain fuel economy ADAS features available on engine software by Cummins (Cummins, n.d.). These features include predictive cruise control and neutral coasting.
3. On road CACC 0.6s with ADEPT (2-Truck 2020): CACC test at 0.6 Sec headway time gap on Indiana route with lead truck in cruise at 64 mph with ADEPT features enabled (baseline: cruise at 64 mph or at speed limit if below 65 mph)

4. On road CACC 0.6s without ADEPT (2-Truck 2020): CACC test at 0.6 Sec headway time gap on Indiana route with lead truck in cruise at 64 mph with ADEPT features disabled (baseline: cruise at 64 mph or at speed limit if below 65 mph)

The project team followed a modified SAE J1321 procedure when conducting all fuel economy tests on the test track and interstate highways. The main modification is to allow fuel economy assessment for the trucks in platooning operation. The settings of all test phases are highlighted below:

a. Steady state (SS) CACC 0.6s at Transportation Research Center (TRC) test track in East Liberty, OH (see Figure 11)
   - Test cycle: cruise operation at 65 mph speed target with 7 laps (total of 52.5 miles).
   - Baseline: all four trucks travelling individually without platooning in cruise at 65 mph speed target.
   - Control vehicle: Following SAE J1321.
   - Test vehicle: A test platoon was used to replace single test vehicle. Also, three test vehicles individually compared to one control vehicle simultaneously.

b. On road CACC 0.6s with and without ADEPT (see Figure 12)
   - Test cycle: Operation in cruise on Indiana on-highway route (see Figure 8). The route is further divided in 5 sections depending on road grade and traffic conditions as described in Figure 12 and Table 2. These sections are used later for further analysis to assess the impact of road grade variation.
   - Baseline: All trucks travelling individually without platooning on the same route in cruise.
   - Control vehicle: Following SAE J1321.
   - Test vehicle: A test platoon was used to replace single test vehicle. Also, three test vehicles individually compared to one control vehicle simultaneously.
   - Three test phases were completed with and without ADEPT features and through 2-truck or 3-truck platooning configuration.

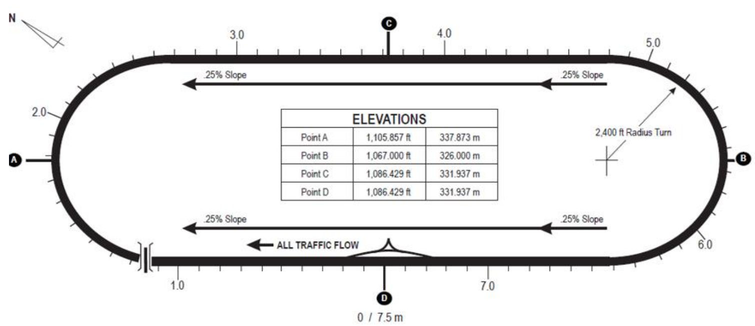


Figure 11. TRC High Speed Oval Track

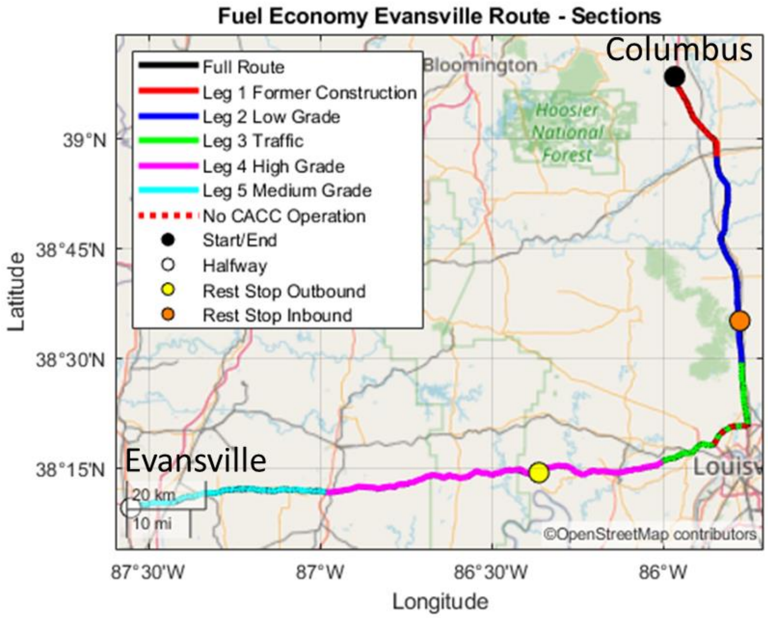


Figure 12. Indiana Linehaul Test Route with five sections

As can be seen in Figure 12, the test route is divided into 5 sections: construction, low grade, traffic, high grade, and medium grade, which reflect the essential traffic aspects obtained through traffic analysis in section 2.1. The blue, cyan, and magenta sections in Figure 12 correspond to the low, medium, and high road grade sections, respectively. The red and green sections are construction and traffic, respectively, both having speed limits that are below the normal 65 mph due to construction and traffic (merging situations and volume). However, when the 3-truck platoon test started, all the construction in the construction section had been completed – the naming of the section remains since it was used in the 2-truck platoon test. It should also be noted that there was a significant amount of construction in high-grade section of the route during the 3-truck platoon test. Table 2 shows the general route information. One other difference between 2-truck and 3-truck platoon testing is that for 3-truck testing, the trucks did not engage in CACC on I-265 due to high volumes of traffic and the complexity of forming the platoon.

Table 2. Selected Indiana Linehaul Route Key Metrics

Route Metrics	Construction	Low Grade	Traffic	High Grade	Medium Grade
One-way Distance [miles]	14	34	26	57	31
Percentage of Distance [%]	8.6	21.0	16.0	35.2	19.1
Change in Elevation (Outbound) [m]	-10	-23	98	-123	10
Average Grade [%]	0.66	0.53	1.04	1.63	0.87
Speed Limit [mph]	55-65	65	55-65	65	65

4. Test Vehicles

Four trucks were used for the 3-truck test phases. As shown in Table 3, all four trucks are the same except Lead, Middle and Trail trucks that have Michelin tires with telemetry. Figure 13 details the naming convention (truck labels) for two and three truck platoon configurations. When comparing the platoon of 3 trucks to the platoon of 2 truck, the comparison of the Middle truck of 3 truck platoon and Trail truck of 2 truck platoon becomes necessary, but the naming may cause confusion. Therefore, for this comparison the terms "T2" and "T3" will be used as seen in Figure 13, meaning "Truck in 2nd position" and "Truck in 3rd position". Also, a platoon consists of all the trucks in the platoon, regardless of the quantity. The Control truck was kept the same throughout all the tests. Test data was normalized against the control truck to minimize the impact from environmental effects.

Table 3. Vehicle Specification

	Control Truck	Lead/Middle/Trail Trucks
Truck Model	INTERNATIONAL 2020 LT625 6X4 (LT62F) - General Freight Long Haul Sleeper 	
GVW	68000 lb	
Engine	Cummins X15 Efficiency Series, EPA 2017, 430HP @ 1800 RPM, 1450/1650 lb-ft	
Transmission	Eaton Endurant 12-Speed Fully Automated Manual Overdrive	
Rear Axle Ratio	2.79	
Steer Tire	Bridgestone R283A ECOPIA 295/75R22.5	Michelin X Line Energy 275/80R22.5
Drive Tire	Bridgestone M710 ECOPIA 295/75R22.5	Michelin XDA Energy 275/80R22.5
Trailer Tire	Bridgestone R283A ECOPIA 295/75R22.5	Michelin X Line Energy 275/80R22.5
Trailer Model	2016 Hyundai 53' Van	2020 Great Dane 53' Van

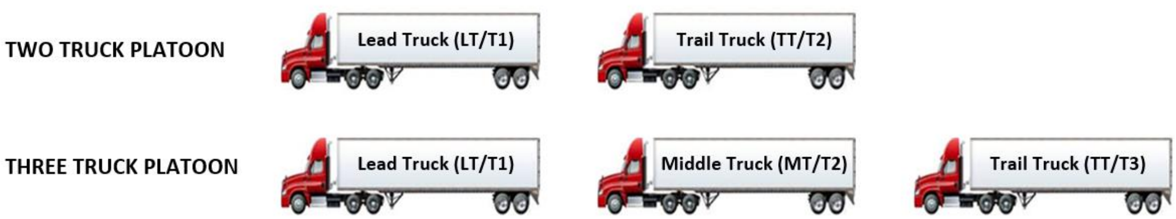


Figure 13. Truck Configuration and Label Disambiguation

5. Test Results

5.1. CACC Engagement

A summary of cruise control and CACC operation for the 3-truck on-road CACC test phase can be found in Figure 14. The vertical bars represent the % distance in cruise control for Control and Lead vehicles and % distance in CACC for Middle and Trail vehicles. The horizontal bars show the % distance when all platooning vehicles were engaged in CACC. Low grade section has the highest % CACC engaged followed by medium and high-grade sections. The reverse trend is true with number of disengagements, where the low-grade section had the fewest disengagements and high-grade section had the highest amount.

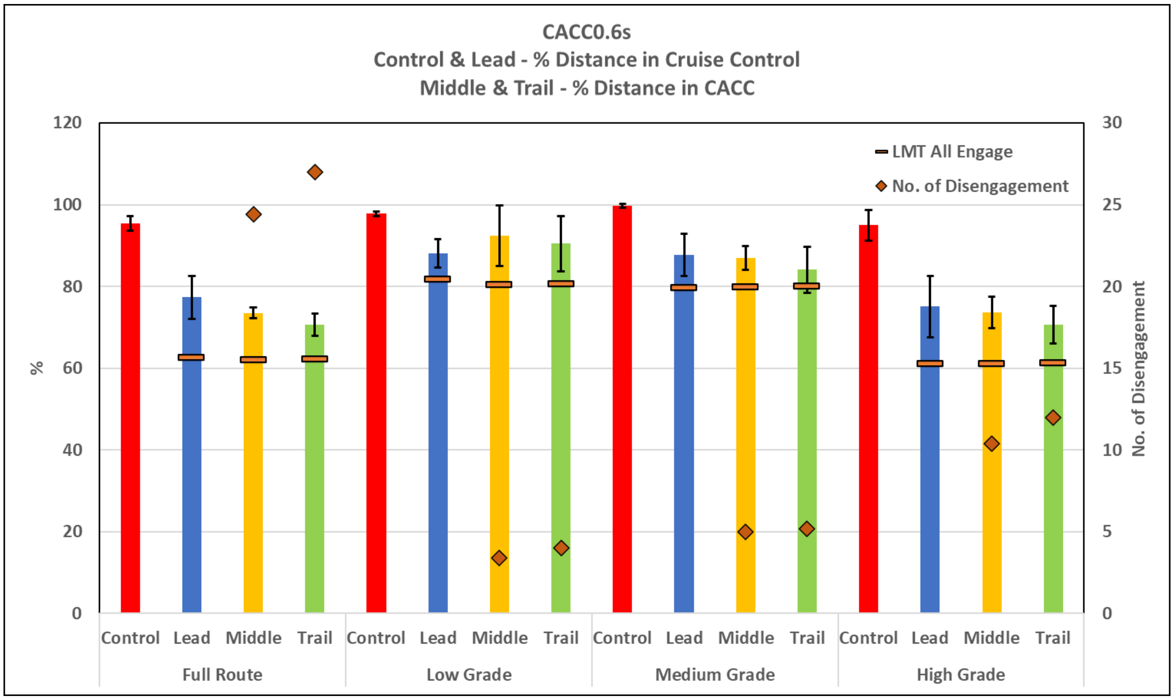


Figure 14. Summary of Cruise Control and CACC Engagement

It should be noted that a portion of the route did not provide conditions for platooning due to various reasons including construction, traffic, on/off ramps, and others. Figure 15 shows that between 25% and 30% of the route had conditions preventing the platoon from forming. The reasons for the distance not in CACC vary, but are mostly caused by outside factors, like traffic and construction. Traffic incidents include merging traffic and slow traffic that cause the platoon to change lanes (meaning the platoon dissolves and then reforms). It is important to note that less than 2% of all distance outside of CACC operation was due to the CACC system itself (e.g., radar loss of target, etc.). Combining Figure 15 with Figure 14 shows that the trucks stayed in the platoon for as much of the route as possible.

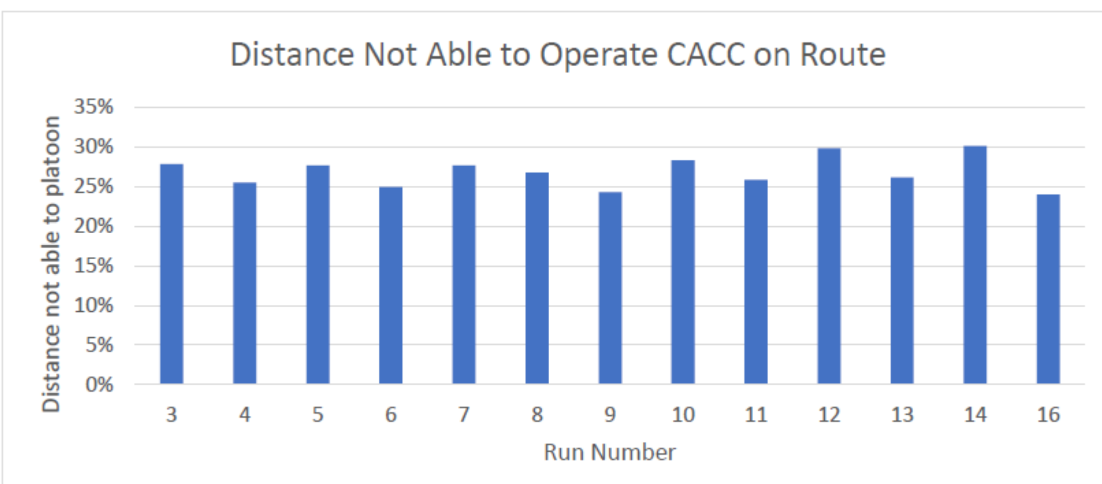
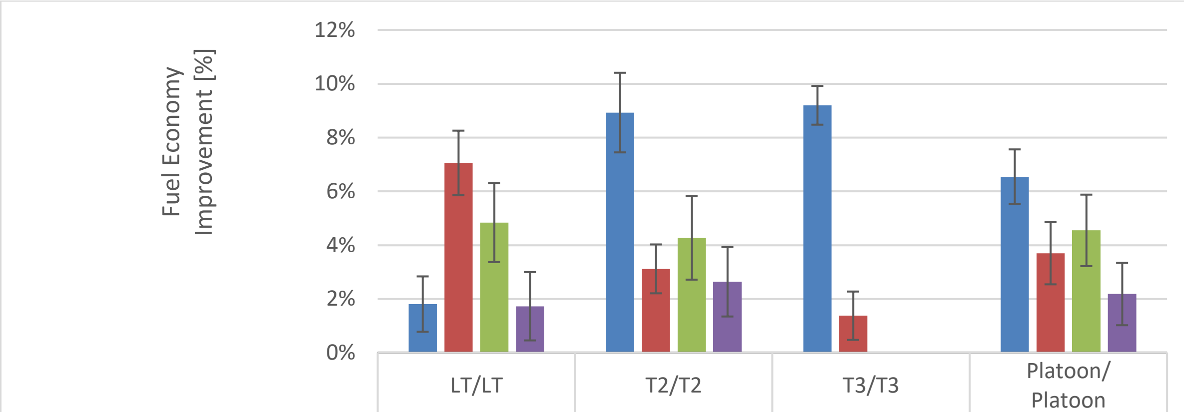


Figure 15. Distance Not Able to Operate CACC on Route

5.2. Fuel Economy Results

The comparison of the fuel economy test results is summarized in Figure 16. Each row of the table in Figure 16 represents one test phase. In addition, each column of the table in Figure 16 shows the corresponding percentage of fuel economy improvement achieved from Lead truck (LT), Middle/Trail truck (T2), Trail truck (T3), and the entire platoon.



	LT/LT	T2/T2	T3/T3	Platoon/ Platoon
3 Truck SS vs BL (Test Track)	1.81%	8.93%	9.20%	6.54%
3 Truck ADEPT vs BL	7.06%	3.12%	1.38%	3.70%
2 Truck ADEPT vs BL (2020)	4.84%	4.27%		4.55%
2 Truck No ADEPT vs BL (2020)	1.73%	2.64%		2.18%

Figure 16. Fuel Economy Results

A few observations to highlight include:

- Combined on-road platoon results show improvement for entire platoon in all configurations (3.70% for 3 trucks with ADEPT, 4.55% for 2 trucks with ADEPT, and 2.18% for 2 trucks without ADEPT), however the improvement seen in steady-state track tests was not achieved in on-road tests.
- There is a large improvement between baseline (BL) and CACC for LT (7.06%), but only a small improvement for T2 (3.12%) and T3 (1.38%) in 3-Truck configuration.
- LT and T2 improvements are similar between 3-truck and 2-truck tests, attributed to combined effects of ADEPT and Platooning.
- Comparing the results of both 2-truck platoon configurations, it is clear that employing advanced ADEPT control with platooning enables significant fuel economy gain (from 2.18% to 4.55%).

The fuel economy test results of 3-truck and 2-truck platoons are divided into sections per the route in Figure 12 and the results are presented in Figure 17 to further assess the impact of road grade variations.

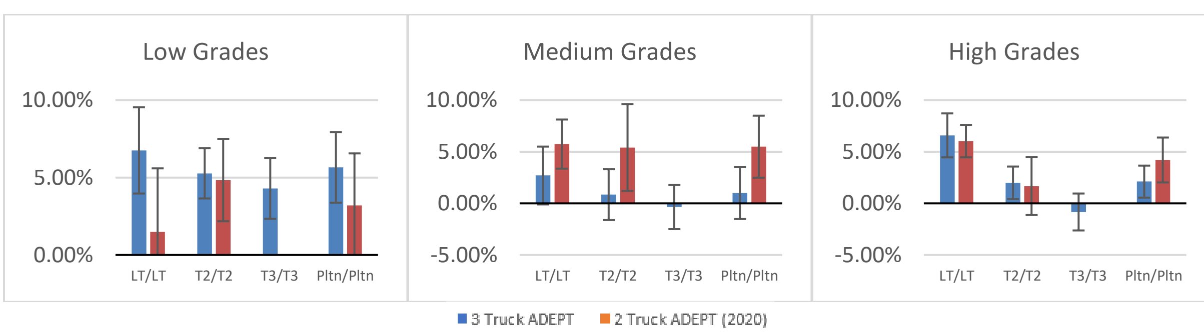


Figure 17. Fuel Economy Results – Sections

Similarly, a few observations can be obtained from this analysis:

- All sections show an improvement for platoons, but with mixed results for the individual trucks.

- Platooning with high grade shows significant reduction in fuel saving comparing to operation under low grade conditions.

The largest factor contributing to worse fuel economy was the inability for the trailing truck to remain at the target gap while traveling uphill. The gap increased consistently up the hills, causing an inherent increase in drag, which required the trail truck to either re-engage or catch the lead truck by increasing speed. In either scenario, the trail truck must accelerate to re-engage at the proper time gap.

5.3. Detailed Engine Operation

To further analyze the fuel economy results, an investigation into engine operation was done. The two fundamental contributors to fuel consumption are work done by the engine and efficiency of that work (assuming that the fuel energy density is constant). The primary contributor to the fuel economy differences in these tests was found to be engine cycle work – the total positive work provided by the engine (the work to propel the vehicle). Figure 18, Figure 19, Figure 21, and Figure 22 provide examples of duty cycles from valid test runs for the vehicles and show the differences between Baseline and CACC. The following section presents the observations between the two phases for all of the trucks.

Figure 18 and Figure 19 show few differences in the control truck duty cycles as we expected from an unchanged vehicle. In contrast, the Lead truck shows a major difference in the center of the plot, namely, the engine speed range has grown wider, and the torque range has shrunk. This change is primarily attributed to ADEPT control features since the same phenomenon occurs in Figure 20 where a duty cycle with ADEPT features is compared to one without the features. The more energy efficient vehicle speed with ADEPT features leads to the new duty cycle.

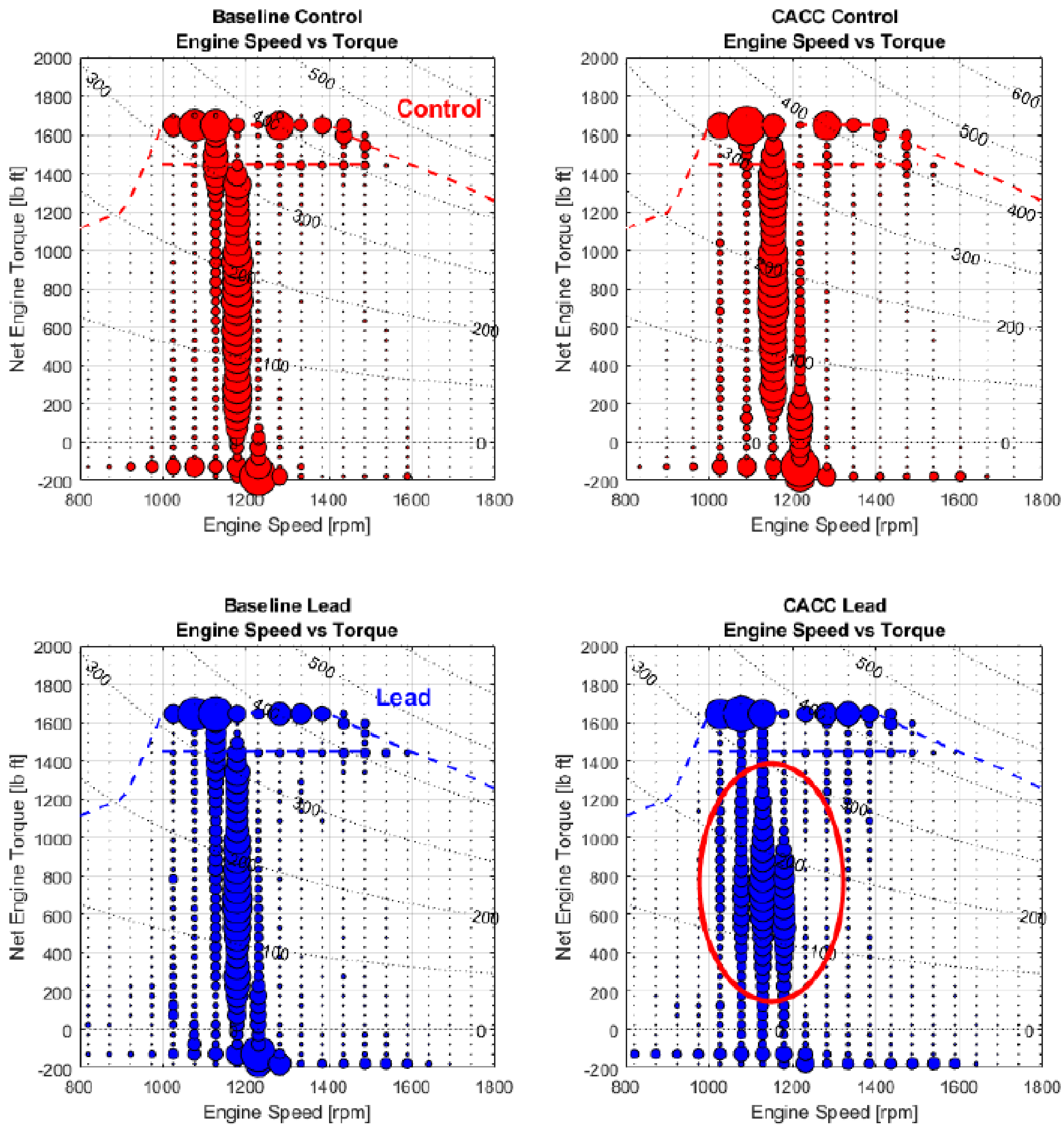


Figure 18. Positive Duty Cycles of Control and Lead Trucks Comparison

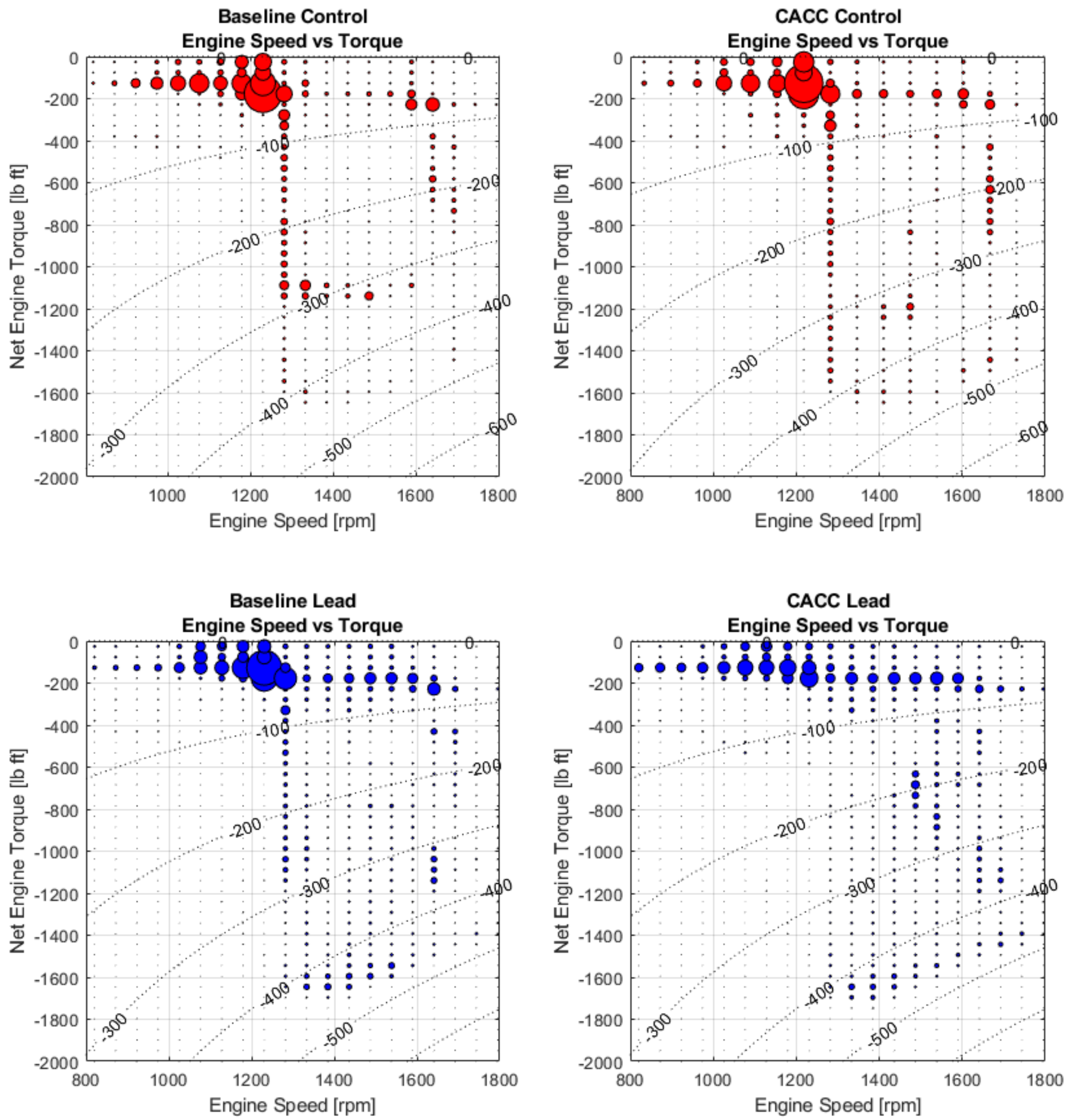


Figure 19. Negative Duty Cycles of Control and Lead Trucks Comparison

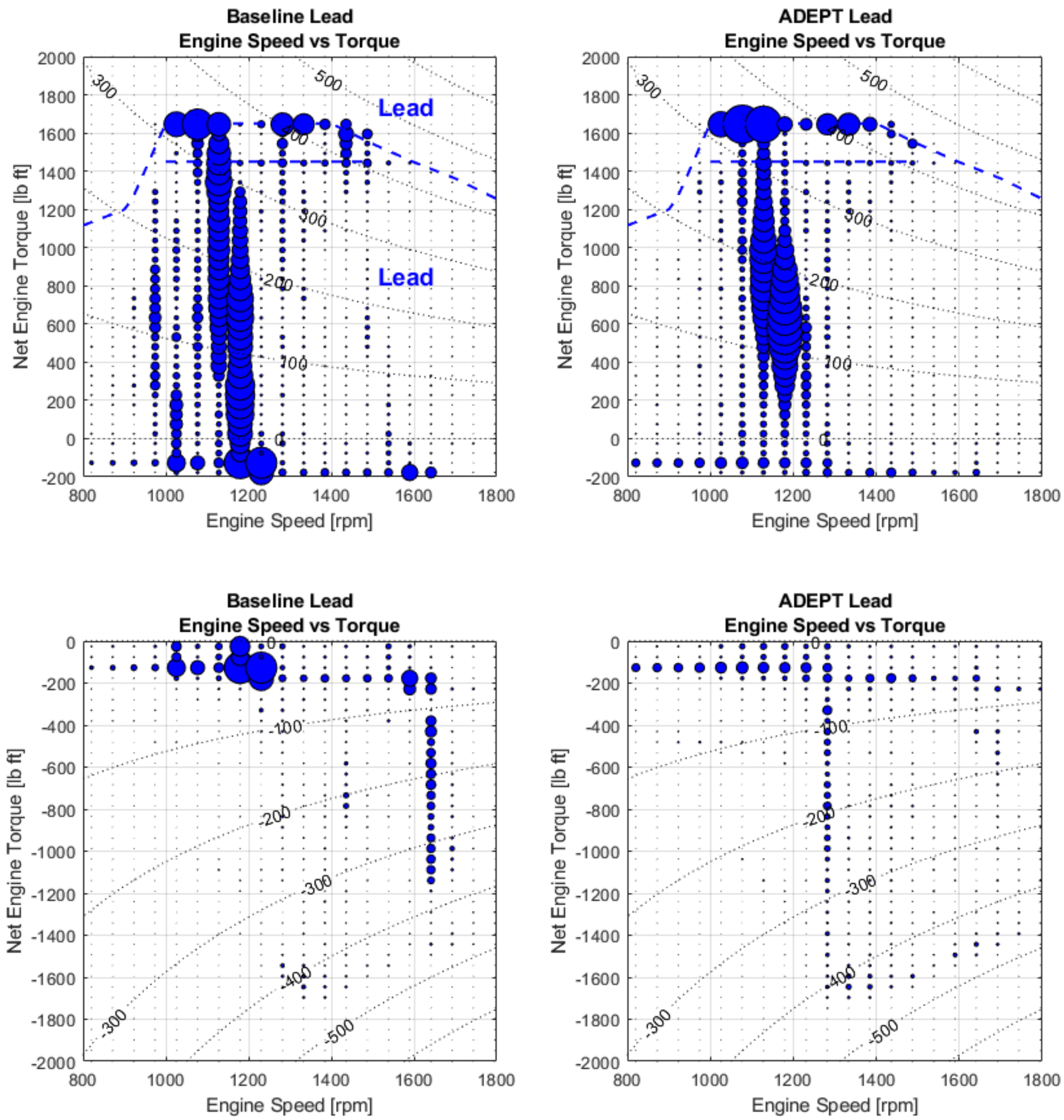


Figure 20. Duty Cycles of Lead Truck without ADEPT and with ADEPT Features Comparison

Figure 21 and Figure 22 show three major differences between the Baseline and CACC phases for both trucks. First, the amount of time in high torque areas (maximum torque curve) increased significantly – this is a result of higher demand from the engine. However, this is offset by an increase in motoring and engine braking, negative torque values that can be seen at the bottom of the figures. These two phenomena are effects of the aggressive distance tracking of the CACC system. Lastly, the propagated effects of ADEPT features in the Lead truck can be seen in the center of the duty cycles of the Middle and Trail trucks, such as wider engine speed range. The propagated effect of torque differences diminishes over the length of the platoon.

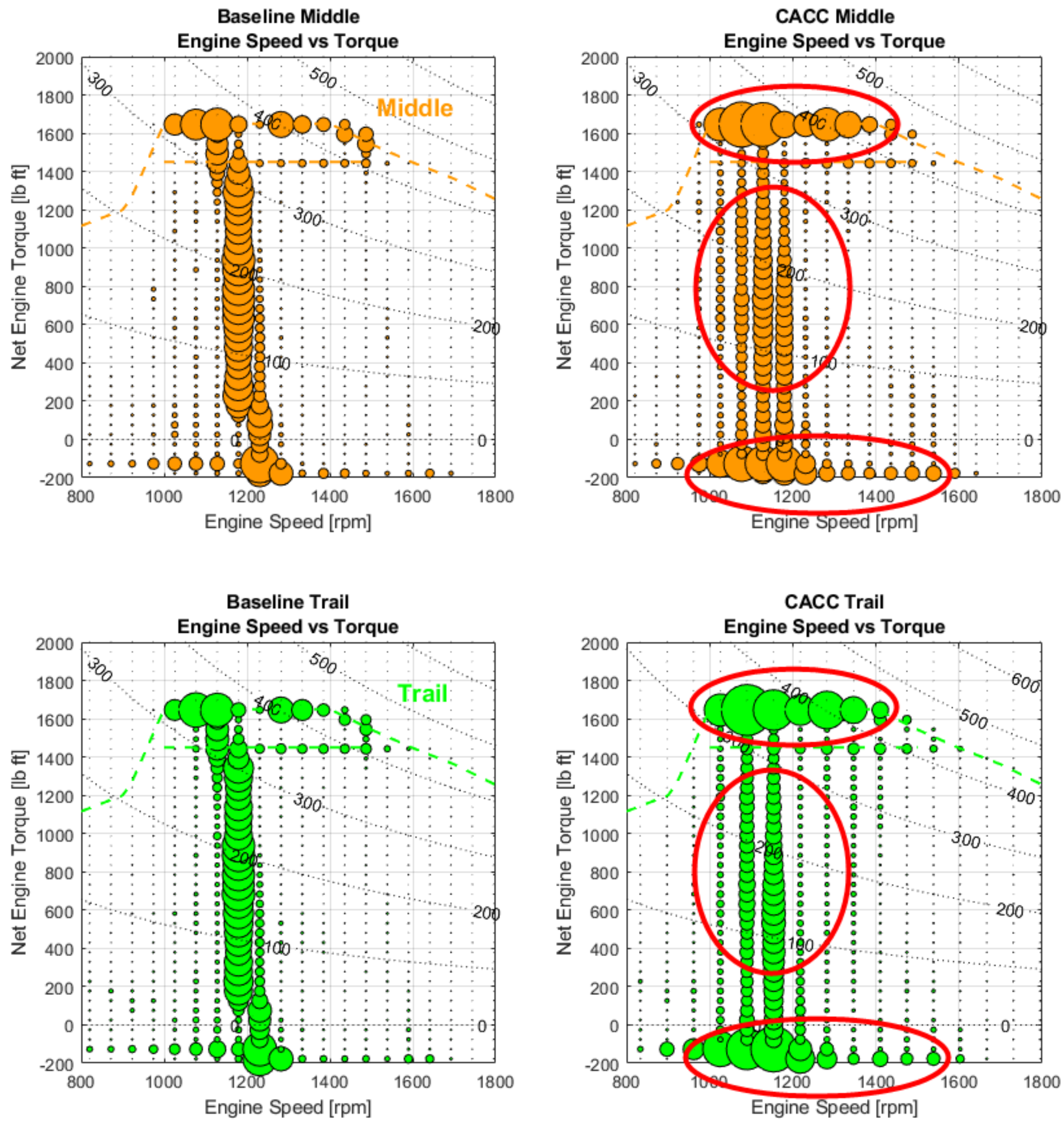


Figure 21. Positive Duty Cycles of Middle and Trail Trucks Comparison

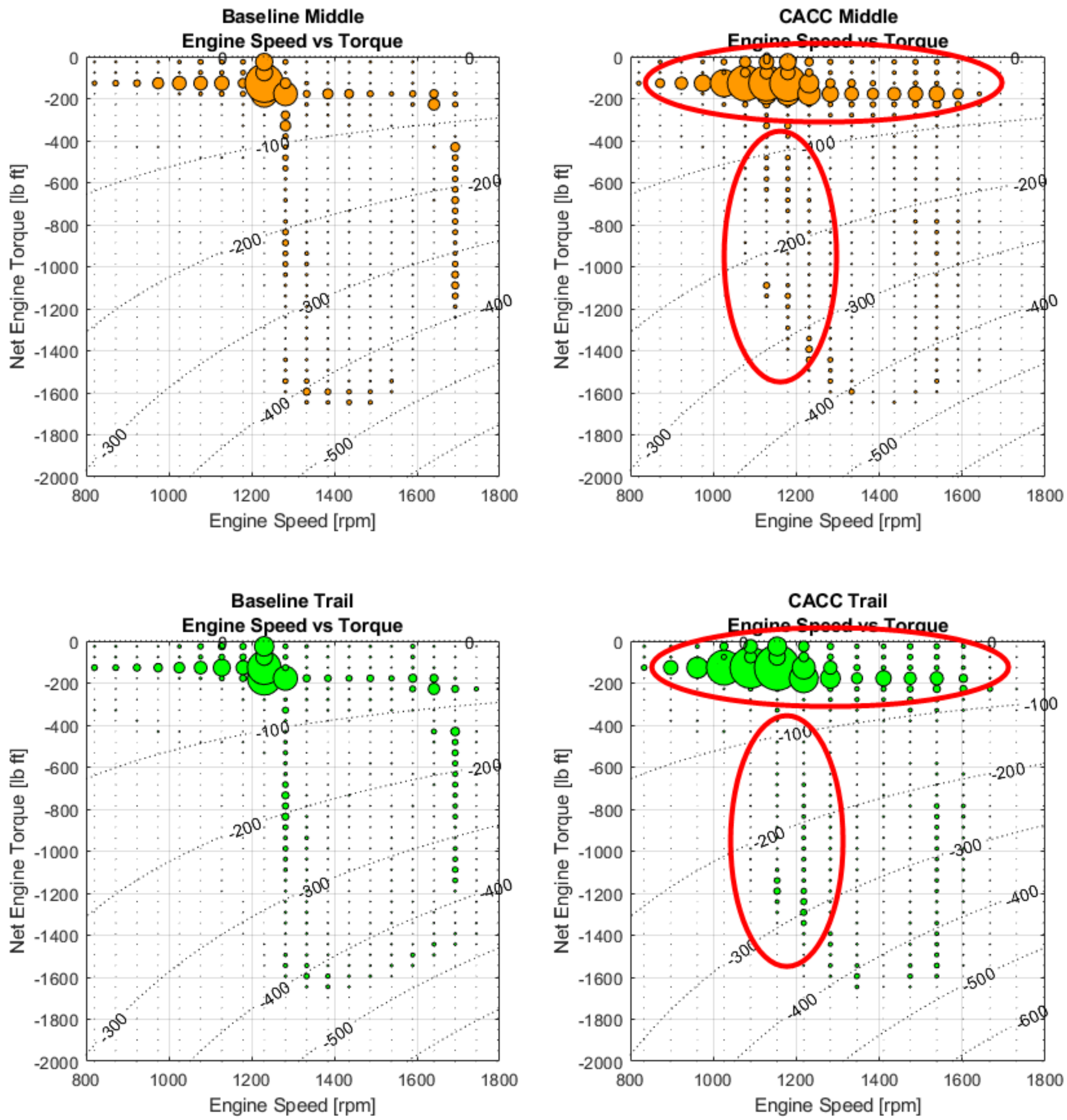


Figure 22. Negative Duty Cycles of Middle and Trail Trucks Comparison

The engine cycle work is closely correlated to the fuel used and reducing cycle work is a clear way to reduce fuel consumption. Reducing work could be accomplished by improving the vehicle dynamics (reduce engine motoring and engine braking), improving engine features (such as engine off coasting in place of motoring), or by adding an energy recovery system. Specific to this study, for the engine under investigation, lower torque values are less efficient and higher torque values are generally more efficient, thus having a higher positive torque has the beneficial effect of increasing efficiency.

After exploring the engine cycle work and corresponding efficiency, it is clear that engine cycle work is the reason behind fuel economy differences. In the low-grade section, the largest cycle work difference was observed, and therefore the largest fuel economy benefit was observed. Both Middle and Trail trucks did not show significant improvement on the medium and high grade.

6. Technology Barriers and Issues Related to Truck Platooning

- Safety concerns
  - There are many places where platoons cannot form or be maintained due to safety concerns, such as dense traffic, construction areas, or road junctions (e.g., on-ramps). Between 20% and 30% of the route was “non-platoonable” each day.
- Traffic
  - In places with on-ramps and off-ramps especially, vehicles frequently had no choice except to merge between the trucks in the platoon, thereby disconnecting the platoon. Much effort to reengage is sometimes needed, especially in dense traffic, reducing benefits of platooning in those conditions.
- Wasted energy
  - The project team found that a significant amount of energy was wasted through excessive braking and motoring events in an effort to maintain the desired distance gap under high grade or high traffic portions of the route, thus lowering fuel economy improvements. Reducing wasted energy or recovering energy will improve fuel economy.
- Grade variations
  - High variations in grade prevent the platoon from remaining at the ideal time gap, in large part due to characteristics of the selected platoon controller. A combination of delayed (reactive) acceleration uphill, low truck acceleration capability (due to engine torque limits), and aggressive distance tracking (due to safety requirements) lead to wasted energy (e.g., the trucks will unintentionally separate going uphill and then purposefully accelerate down the hill to return to the proper gap). In addition, the reduced drag will cause the trailing vehicles to require more engine braking (wasted energy) to prevent over-speeding. These phenomena are reduced when the lead vehicle has ADEPT eco-driving features enabled, but more could be done to efficiently use energy as a platoon.
- Driver behavior
  - Lead Truck (LT) driver behavior, in conjunction with platoon navigation through traffic, was a significant factor in the 3-truck test. It caused lower average speeds and increased transient activity. It is clear that the LT driver has significant influence on the outcome of the platoon, especially if the driver does not use automated systems like cruise control consistently and frequently.
- Differences in Gross Vehicle Weight (GVW)/heterogenous configurations
  - Different weights, powertrains, and vehicle specifications will complicate platooning control. For example, heavier/slower vehicles may lead a platoon at an unreasonably slow speed, or the slower vehicles may lose a platoon as they cannot retain the required average speed.
- Tire condition
  - Differences in stopping distance occur in situations where tire conditions vary among the trucks in the platoon. Weather conditions will further complicate this effect, making it challenging to safely platoon during non-ideal conditions.
- Changes in Vehicle to Vehicle (V2V) technologies
  - Advances in communication technologies have prompted a shift from decades-old DSRC (dedicated short-range communication) protocols toward C-V2X (cellular vehicle-to-everything). However, the infrastructure to support C-V2X is not yet widespread enough for high-volume implementation, and standards for these technologies continue to be developed.

7. Importance of Tire Connectivity

In 2021, through collaboration with Michelin North America, the project team studied the impact of steer tire (in the front axle position) and drive tire (in the drive axle position) constructions on the stopping distance performance of loaded and unloaded tractor-trailer Class 8 trucks running on dry asphalt road pavements. A first set of analytical tire tests that characterized tires individually indicated that the braking tire performance on dry asphalt is dependent on the tire construction. To quantify the effect on the vehicle braking performance, the project team conducted a second set of tests to measure the stopping distance of two groupings of steer and drive tires representing the extremes of these tires' individual braking performance on dry asphalt pavements. For these tests, these two steer and drive tire parings were mounted separately on a tractor pulling a semi-trailer fitted with common trailer tires. The tests indicated that the stopping distance between the two tire sets can vary by as much as 4.7% when the trailer is fully loaded and as much as 1.2% when the trailer is empty. The test data in 2020 show that this difference in stopping distance can increase to more than 20% under wet conditions.

The individual tire characterization with respect to braking performance was used to create tire models. The tire models were then coupled with vehicle simulation models to predict the stopping distances on dry pavements. The simulations predicted the correct tire set ranking, although the amplitude was higher than that obtained through vehicle tests. A subsequent slip histogram analysis showed that this discrepancy was probably due to a model versus actual vehicle difference in how the anti-lock brake system is tuned with the tire peak friction coefficient.

This project has shown that information in real time about the tire adherence capabilities can increase the fuel savings of vehicles running under platooning configurations. This improvement is because the tire characteristics have a considerable effect on the vehicle braking performance. Specifically, this work has shown that differences in tires can cause the stopping distance of a Class 8 vehicle to vary by as much as ~5% on a dry road and as much as ~20% on a wet road. In fact, these variations on wet surfaces placed the tire construction and wear state ahead of other variables such as the vehicle load. Furthermore, tests also showed that on dry asphalt pavements, differences in tire construction can lead to variations in vehicle stopping distance as high as 5%. Additional tests indicated that the variations noted were due to differences in the friction capabilities on wet and dry pavements provided by tires of different constructions. To capitalize on these findings, the project team developed tire models to determine in real time the friction coefficient generated between the tire and the road as a function of the tire construction, road pavement and vehicle usage conditions. The project team then used these friction coefficients in vehicle models to predict the optimum platooning distance between Class 8 vehicles running different duty cycles. The simulations indicated that knowing the tire friction capabilities in real time allows the platooning distance to be further optimized by advanced predictive and optimal platooning control, thus increasing the vehicle fuel savings. For the trail platooning vehicle, these gains are predicted to be between 2% for low traffic and low road grade conditions and 5% for duty cycles that include road grade variations.

8. Advanced Platooning Solutions: Connected and Cooperative Eco Driving

Platoons consisting of automated convoys of heavy-duty trucks are designed to maintain close gaps between trucks to exploit drafting benefits and improve fuel economy, and have traditionally been handled with classically-designed connected and adaptive cruise control (CACC). Classical methods that enforce a gap can reduce energy use in steady-state uninterrupted operation. During transients induced by traffic or road grade, however, maintaining a desired gap may require application of brakes, thus wasting energy, or may lead to platoon disengagement when the trail truck falls behind.

The Clemson University (CU) partners addressed the above challenges of classical CACC by devising optimization-based control algorithms that are predictive in nature rather than reactive. These methods provide the capability to optimize the balance between gap tracking and powertrain efficient operation to minimize energy use. The team focused on devising variants of a Model Predictive Controller (MPC) that optimized the longitudinal motion and lane decisions of each truck over a receding horizon and showed considerable improvement in fuel economy compared to traditional methods in high fidelity simulations. The benefits were higher when V2V connectivity allowed communication of future intentions by the preceding trucks to the following trucks. In heterogenous platoons, road tests showed that in hilly roads and during gear shifts, the platoon may still split due to a truck falling behind. To address this experimentally observed issue, CU introduced a considerate MPC variant that enables the leading trucks to accommodate those behind them by slowing down for them when necessary. The project team demonstrated the performance of the considerate strategy in a real-world driving scenario against a similar non-considerate control strategy. Overall, the team found that the considerate strategy significantly improved harmonization between the platooned trucks and prevented platoon disengagement.

While a constant target speed for the platoon is energy efficient on relatively flat roads, in hilly scenarios where maintaining a constant speed requires brake actuation, a variable target speed is more energy efficient. Test data showed that for truck platooning in situations with high grade variation, when the Cummins ADEPT eco-driving features were integrated on the LT, significant fuel savings resulted.

An important analytical contribution by the team is the successful formulation of target speed optimization over the remaining route to the destination as a Linear Program that is solved an order of magnitude faster than previously proposed methods in the literature. Therefore, the proposed method has considerable energy saving potential for commercial implementation, not only in platooning but also in long-haul trucking.

The team also identified opportunities for energy savings by more systematic and optimized lane change decisions. The team proposed an optimal lane change algorithm, tailored for the complex geometry of a class-8 tractor-trailer, and successfully simulated realistic scenarios in dense traffic microsimulations. The proposed algorithm allows a single truck or a truck convoy to safely initiate and complete a lane change or take-over maneuver with energy efficiency consideration at its core.

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Participants and Other Collaborating Organizations

a) Key team members:

- Hoseinali (Ali) Borhan, Principal Investigator, Technical Research Manager, Columbus, IN
- Tracey Yarbrough, Project Manager, Admin. Associate, Cummins Inc., Columbus, IN
- Nathan T Brady, Fuel Economy and Vehicle Performance Team Engineer, Cummins Inc., Columbus, IN
- David Yu, Global Machine Integration Technical Specialist, Cummins Inc., Columbus, IN
- Gayatri Adi, Sr. Technical Specialist, Systems and Control, Cummins Inc., Columbus, IN
- Karla CS Fuhs, Sr. Technical Specialist, Systems and Control, Cummins Inc., Columbus, IN
- Roopak Ingole, Manager-Advanced Embedded Software, Cummins Inc., Columbus, IN
- Bibin Pattel, Software Engineer and Technical Lead, Cummins Inc., Columbus, IN
- Ardalan Vahidi, Professor of Mechanical Engineering, Clemson University, Clemson, SC
- Tyler Ard, Graduate Student, Clemson University, Clemson, SC
- Robert Austin Dollar, Graduate Student, Clemson University, Clemson, SC
- Robert Radulescu, Executive Fellow, Michelin North America, Greenville, SC
- Gurkan Erdogan, Sr. Tire Performance Research Engineer, Michelin North America, Greenville, SC
- Kenneth J. Kelly, Team Leader, Commercial Vehicle Technologies, National Renewable Energy Laboratory, Golden, CO
- Michael P. Lammert, Senior Commercial Vehicle Technologies Engineer, National Renewable Energy Laboratory, Golden, CO
- Chen Zhang, Commercial Vehicle Technologies Engineer, National Renewable Energy Laboratory, Golden, CO
- Kerri Garvin, Executive Director, Greater Indiana Clean Cities Coalition, Fort Wayne, IN

b) Other organizations involved as partners:

- Organization Name: Michelin North America, Greenville, SC 29615
  - Contribution to the project: Michelin team worked on tire connectivity related tasks and milestone to demonstrate the importance of tire monitoring through connectivity to platooning/CACC performance.
- Organization Name: Clemson University, Clemson, SC 29634
  - Contribution to the project: Develop modeling and advanced control algorithms to develop prototype solutions for the identified barriers.
- Organization Name: National Renewable Energy Laboratory (NREL), Golden, CO 80401
  - Contribution to the project: to collaborate with the technical team to provide data and data analysis of line-haul truck operations and platooning scenarios to inform modeling and design, field evaluation test plan design and assistance with all truck level field evaluations including data analysis and reporting.
- Organization Name: Greater Indiana Clean Cities Coalition, Fort Wayne, IN 46802
  - Contribution to the project: Greater Indiana Clean Cities advances alternative, domestic fueled transportation including energy efficient technologies across all sectors in Indiana. The coalition is a liaison between end-users of the technology and all government and/or private entities.