Correlations of Platooning Track Test and Wind Tunnel Data

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List of Acronyms

CFD	computational fluid dynamics
DOE	U.S. Department of Energy
FY	fiscal year
HD	heavy duty
LBNL	Lawrence Berkeley National Laboratory
LLNL	Lawrence Livermore National Laboratory
NO_x	nitrogen oxides or oxides of nitrogen
NRC	National Research Council
NREL	National Renewable Energy Laboratory
SAE	SAE International

Table of Contents

List of Figures

Executive Summary

The National Renewable Energy Laboratory (NREL) analyzed results from several independent truck platooning projects to compare and contrast reported results under similar test conditions to wind tunnel test results conducted by Lawrence Livermore National Laboratory (LLNL). By combining track tests, wind tunnel, and computational fluid dynamics (CFD) results from several organizations, we show where there is broad consensus on results, and highlight areas where additional testing, research, and development is needed. NREL compiled data from vehicle track testing studies conducted by the North American Council for Freight Efficiency (2013), NREL (2014), Auburn University (2015), and National Research Council (NRC) Canada/Lawrence Berkeley National Laboratory (2016), along with wind tunnel test results from LLNL, and CFD simulations from Denso. We found significant correlations between multiple track studies, wind tunnel tests, and CFD, but showed that there is more to learn regarding close formation and longer-distance effects. All platooning scenarios being considered today offer significant opportunity for fuel and emissions savings in the near term, but there are still unanswered questions and clear opportunities for system optimization. Comparing oxides of nitrogen (NO_x) data from the NREL 2014 track tests and the 2015 Auburn track tests, we showed that Peloton appears to have refined its system to address the NO_x increases that were first identified by NREL in 2014. In the longer term, platooning fuel savings can be significantly enhanced by addressing barriers to closer platoon formation and more vehicles in platoon. Other potential areas for research and development include aerodynamic packages optimized for platooning, measurement of platoon system performance in traffic conditions, impact of vehicle lateral offsets, and characterization of the national potential for platooning based on fleet operational characteristics. NREL continues to coordinate with industry and government stakeholders under programs such as the Connected and Automated Vehicles pillar of the U.S. Department of Energy Systems and Modeling for Accelerated Research in Transportation (SMART), the U.S. Department of Transportation Automated Vehicle Research, California Partners for Advanced Transportation Technologies (PATH), and NRC Canada to address those areas of improvement.

Introduction

The primary objective of this study is to correlate multiple independent platooning test results to establish where there is widespread agreement, to help validate and inform Lawrence Livermore National Laboratory (LLNL) wind tunnel testing, and identify areas where further research is needed. The National Renewable Energy Laboratory (NREL) focused on the evaluation of full-scale platooning of long-haul tractor trailers using both track testing and in-service evaluations in collaboration with LLNL wind tunnel testing and computational fluid dynamics (CFD) modeling as called for in the U.S. Department of Energy's (DOE's) Vehicle Technologies Office Annual Operating Plan Lab Call—Topic 9D "Vehicle Systems Efficiency Improvements." The project also ties in with the Connected and Automated Vehicles pillar of the DOE Systems and Modeling for Accelerated Research in Transportation (SMART) work in that platooning is a soon-to-be-adopted, connected, and partially automated vehicle technology intended to save fuel and increase safety. This project will provide unbiased heavy-duty (HD) platooning test results and detailed analysis to industry, fleets, government agencies, and the research community. Data, analysis, and reports are shared with DOE, national laboratory partners, and industry to help:

- Define intelligent usage of platooning technology
- Guide research and development for platooning.

Platooning technology is an early application that supports development of autonomous vehicle technology. Truck platooning is gaining significant attention from industry with public investments in the technology by Volvo, UPS, Nokia, Intel, Lockheed Martin, and others. However, all the variables impacting possible fuel savings from following distances and the number of vehicles in platoon, to the impact of fleet logistics on the percent of miles that can be platooned still remain significant unknowns. In fiscal year (FY) 2014, NREL showed the technology has the potential to reduce fuel use by 3% – 6% (tandem average). Analysis of the results indicated a potential opportunity to further optimize the system performance. (Lammert et al. 2014)

Technical Discussion

Background

This activity supports DOE's mission of improving our energy security and supporting the U.S. economy while providing valuable data and information to DOE research partners. Long-haul commercial vehicles are a critical part of U.S. trade, commerce, and economic growth. Vehicle automation is a promising petroleum-reduction technology for HD highway trucking applications. Platooning systems for HD vehicles are likely to be an early commercial application of vehicle automation technology. These systems may employ existing technologies, such as radar or laser range finders, global positioning systems, dedicated vehicle-to-vehicle communications, and braking and engine torque authority to enable vehicles to follow closely safely with the goal of reducing fuel consumption through improved aerodynamics, as well as reducing traffic congestion and possibly collisions. Figure 1 illustrates how platooning is intended to make two trucks appear more like one object to the airflow, resulting in reduced turbulence behind the lead truck and reduced forebody drag on the trailing truck.

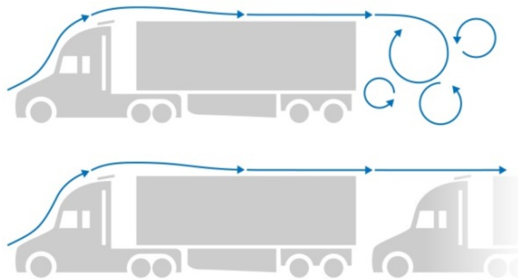

Figure 1. Truck platooning air flow

In FY 2014, NREL teamed with Intertek and Peloton to evaluate the fuel efficiency of line-haul trucks operating in platooned pairs under controlled track testing. The first round of track testing of the Peloton system was completed in March 2014. The technology showed the potential to improve fuel use by 3%–6% (tandem average). Figure 2 shows the actual FY2014 test vehicles in platoon formation. (Lammert et al. 2014)

Figure 2. Trucks in platoon formation during testing. *NREL #31237*

Approach

NREL has developed a process for conducting accurate and objective track evaluations of tractor-trailer platooning using controller area network-based data loggers, along with accurate gravimetric fuel use measurements, and SAE Type II J1321 fuel consumption test and data analysis procedures. These methods were supplemented with NREL's long-standing method for testing vehicle technologies in commercial use versus conventional counterparts.

This research project, which was funded by DOE, intended to increase understanding around the dynamic interactions between platooning vehicles that impact fuel savings to determine the best application scenarios. Activities were undertaken to corroborate the LLNL wind tunnel findings on platooning envelope parameters, evaluate the performance of platooned tractor-trailers in real-world conditions, and provide unbiased HD platooning test results and detailed analysis to industry, fleets, government agencies, and the research community. NREL is leveraging existing published studies and data for meta-analysis that refines our understanding of questions from FY 2014 and planning studies to increase understanding around the dynamic interactions between platooning vehicles that impact fuel use. This project answers questions raised by results from an FY 2014 series of 10 modified SAE Type II J1321 fuel consumption track tests that were performed to document the fuel consumption of two platooned vehicles and a control vehicle at varying steady-state speeds, following distances, and gross vehicle weights.

A partnership was created with LLNL and other participants to increase understanding of the aerodynamic envelope governing truck platooning, and to investigate some of the questions raised in the FY14 track tests about close following conditions, long following distances, alignment sensitivity, and three-truck platoons.

Six independent platooning evaluations were reviewed and compared. All consider platooning impacts to tractor-trailers with conventional “aero” sleeper cab shapes, 53-ft. van trailers, 65,000-lbs. load, and travelling at 65 mph:

1. SAE J1321 road testing —conducted in 2013 in Utah [North American Council for Freight Efficiency (NACFE)] (Roeth 2013)
2. SAE J1321 track testing—conducted in 2014 in Uvalde, Texas [NREL] (Lammert et al. 2014)
3. SAE J1321 track testing—conducted in 2015 in Ohio [Auburn University, Transportation Research Center] (Bevly et al. 2017)
4. 1/50th scale wind tunnel testing—conducted in 2015 [LLNL]
5. Denso CFD modeling—presented to 21st Century Truck Partnership in 2015
6. SAE J1321 track testing—conducted in 2016 in Quebec, Canada [Transport Canada, National Research Council (NRC), Lawrence Berkeley National Laboratory (LBNL) (McAuliffe et al.2017)

Results

Fuel Savings from Platooning Aerodynamics

Significant agreement was observed pertaining to trends and magnitude between track testing and wind tunnel testing, as well as CFD modeling. Both of NREL’s most interesting findings from 2014 were corroborated—the following vehicle experiences a benefit at longer distances than anticipated, and the following vehicle experiences a reduction in savings at distances closer than 50 ft. Figure 3 shows the comparison of track, road, and wind tunnel tests and the general trend agreements across all six studies. Track test results changing from solid to dotted lines indicate results that were not statistically significant. While we attempted to compare like tests to the greatest extent possible, some differences in the test equipment were inevitable in these independent studies. NREL, Auburn, NACFE, and LLNL tests included trailer skirts but no trailer tails. NRC/LBNL conducted a round of testing on vehicles without trailer aerodynamic devices (“std”), and another round of testing with both side skirts and trailer tails (“aero”); additionally, the NRC/LBNL tests were conducted on a three-vehicle platoon, and as such, they have lead-, mid-, and tail-vehicle results with the tail vehicle experiencing the greatest savings. Given these variations, it is not a surprise that their findings for following vehicles approximately straddle those of NREL, Auburn, and LLNL at the following distances where they overlap. Note that for all test series, the lead vehicles group together and the following vehicles group together. Also note that dotted lines for track test results indicate findings that are not statistically significant.

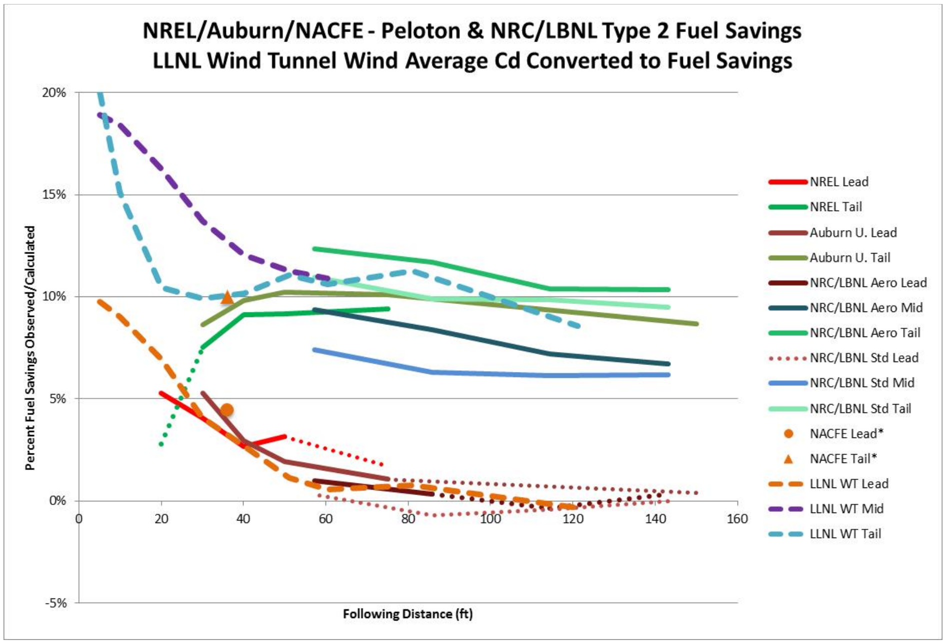

Figure 3. Platooning evaluations comparison

Figure 4 shows only the lead vehicles' fuel saving trends for clarity. All test campaigns were in agreement that, for following distances greater than 50 ft., savings for the lead vehicle in a platoon were negligible. When the vehicles were closer than 50 ft., the lead vehicle experienced increased savings with shortened following distances. The NRC/LBNL standard trailer lead vehicle actually had a fuel consumption increase that was not statistically significant, hence the negative savings dotted line. The NRC/LBNL test series did not include test conditions for vehicles closer than 50 ft., and as such, the observed behavior only correlates with the negligible savings of the lead vehicles from other studies with vehicles farther apart than 50 ft.

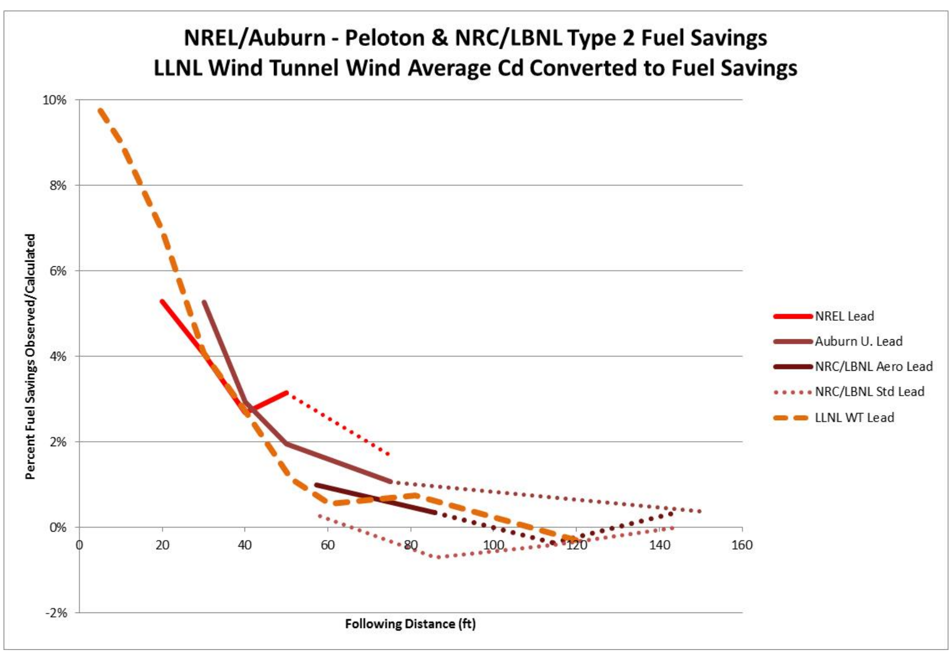

Figure 4. Platooning evaluations comparison: Fuel savings for lead vehicle

Figure 5 shows only the following vehicles' fuel saving trends for clarity. While the NRC/LBNL study did not test in the close-following region (less than 50 ft), the NREL track tests, Auburn track tests, and the LLNL wind tunnel studies all show a reduction in savings at following distances from less than 50 ft. to about 30 ft. The slope of this reduction is similar among all tests. The NREL test showed significant engine fan engagement at 20 ft., which appeared to affect the fuel consumption numbers and so is left out of the trend analysis. The LLNL wind tunnel test series show 30 ft. as the point of lowest savings at which point the savings goes up dramatically at following distances of less than 20 ft.—an indication that much greater savings are available if barriers such as engine cooling impacts, and driver & public acceptance to very close formation can be overcome. At longer following distances, all studies found significant savings, and the degradation slopes were all approximate to each other. More study is required to confirm if the variation observed is dependent on trailer aerodynamic packages and platoon following position as the early results seem to indicate. The NRC/LBNL study consistently found the aero-equipped trailers had higher savings than standard trailers, and the third vehicle in the platoon saved more than the second vehicle in both trailer configurations. The NRC/LBNL study found that position in the platoon had greater influence than trailer aerodynamics with the third position favored.

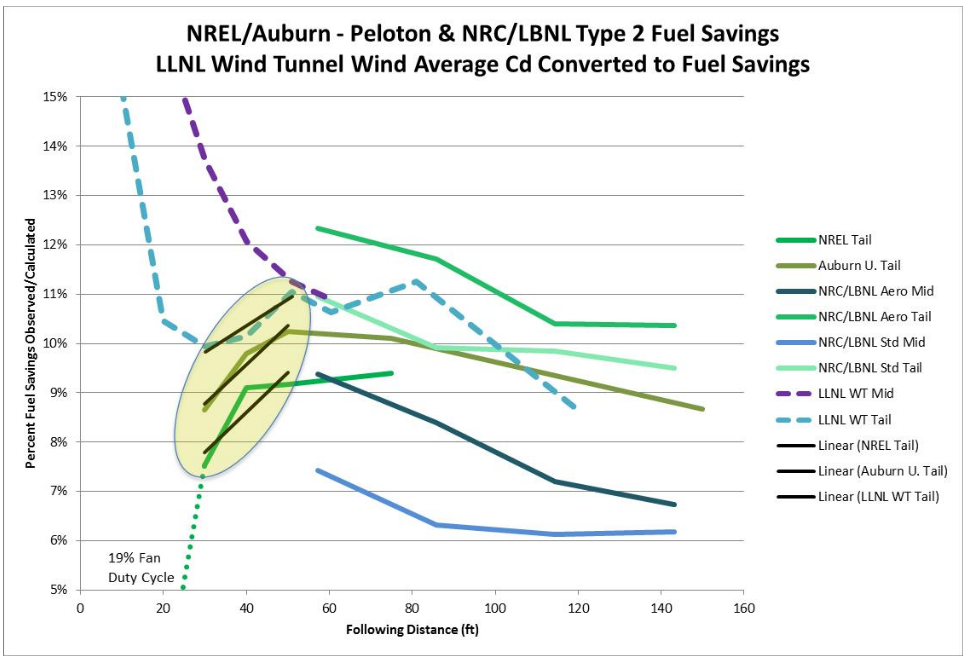

Figure 5. Platooning evaluations comparison: Fuel savings decrease for following vehicle from 50 ft. to 30 ft.

In wind tunnel testing, the wind average stagnation pressure (from pressure probes at the radiator) matches well with Denso CFD of radiator flow during platooning, including the change in slope beginning at approximately 50 ft. following distance. Figure 6 shows the wind tunnel model pressure probe installation. Figure 7 shows the correlated data from CFD and wind tunnel pressure measurements. The following vehicle experiences a reduction in airflow and pressure at the radiator that correlates with the reduction in fuel savings for following vehicles, and an increase in savings for lead vehicle (bend in curve at 40–50 ft.) observed in the NREL, Auburn, and LLNL track tests shown in Figures 3–5. It is important to note that current testing shows cooling packages are adequate at all distances, but engine fan engagement may be needed at very close distances.

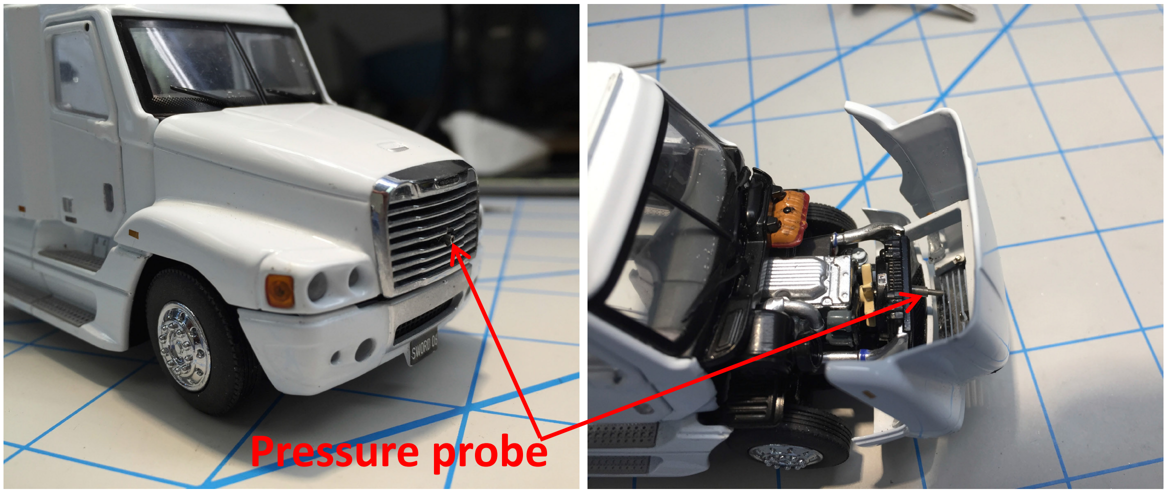

Figure 6. Wind tunnel platooning model pressure probe location

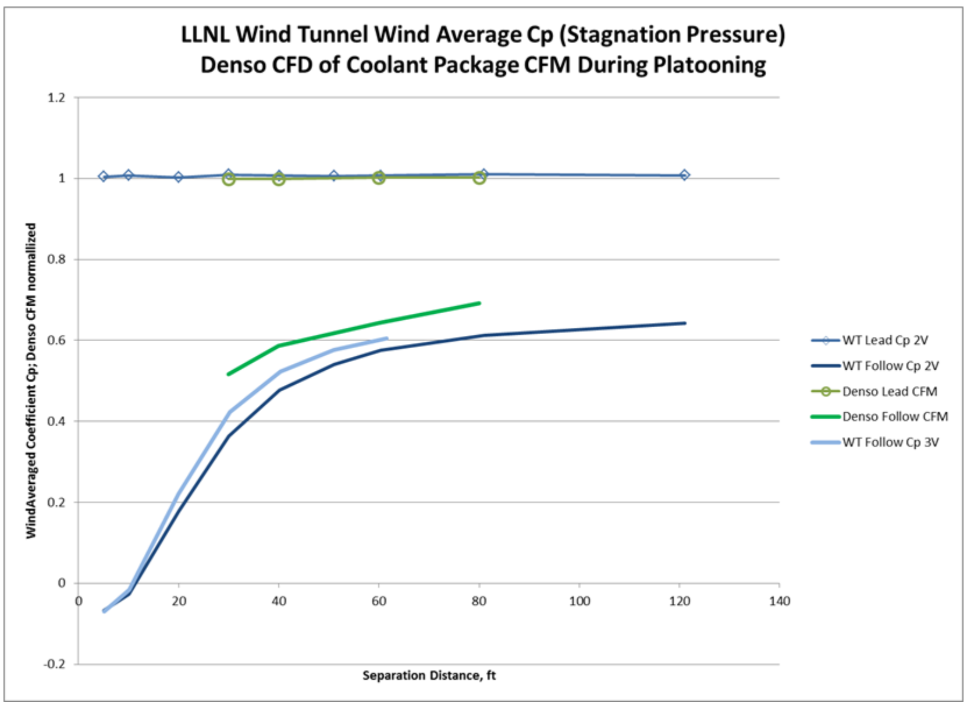

Figure 7. Platooning evaluations comparison: Wind tunnel results vs. CFD results

NO_x Emissions While Platooning

During the 2014 NREL track testing, an increase in NO_x emissions for the following vehicle during platooning was identified. Engine temperatures (intake air, coolant, exhaust) and engine map explanations were ruled out as the cause. However, the frequency and amplitude of commanded torque changes correlated with the magnitude of NO_x increase. This command “dither” was suspected to be “confusing” the engine controller and causing the NO_x increase.

Peloton was informed of this and chose to address the control issue. During the 2015 Auburn testing, NREL installed data-logging devices to observe NO_x emissions issues and found:

- Control "dither" was significantly reduced.
- Raw grams of NO_x were reduced compared to baseline during 2015 tests while 2014 tests had shown an increase in raw grams of NO_x
- Brake-specific grams per brake horsepower-hour (g/bhp-hr) NO_x emissions were lower than baseline at 50 ft. and 75 ft., and there were still slight increases at 30 ft. and 40 ft., but greatly reduced from 2014.

Figure 8 shows the increase in total NO_x during 2014 testing and the reduction during 2015 testing. Figure 9 shows the increase in brake-specific NO_x during 2014 testing and the results from 2015 testing. Figure 10 shows the torque control dither during 2014 testing, increasing at shorter following distances, which roughly correlates with the increase in brake-specific NO_x and the fairly constant and lower dither rate present during 2015 testing.

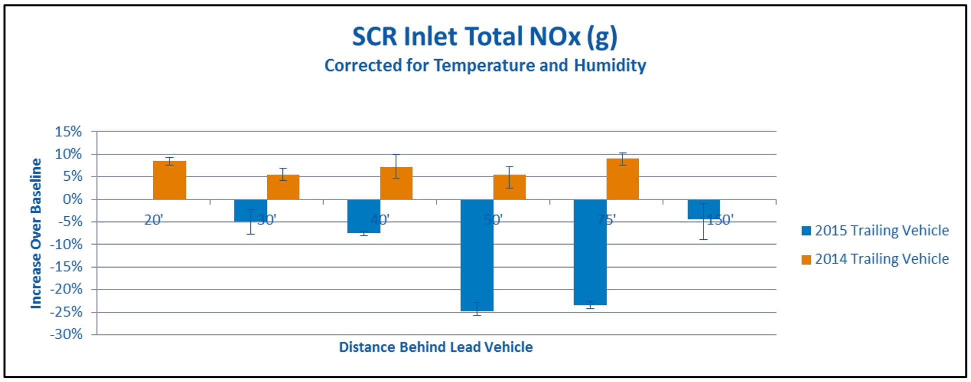

Figure 8. SCR inlet total NO_x comparison

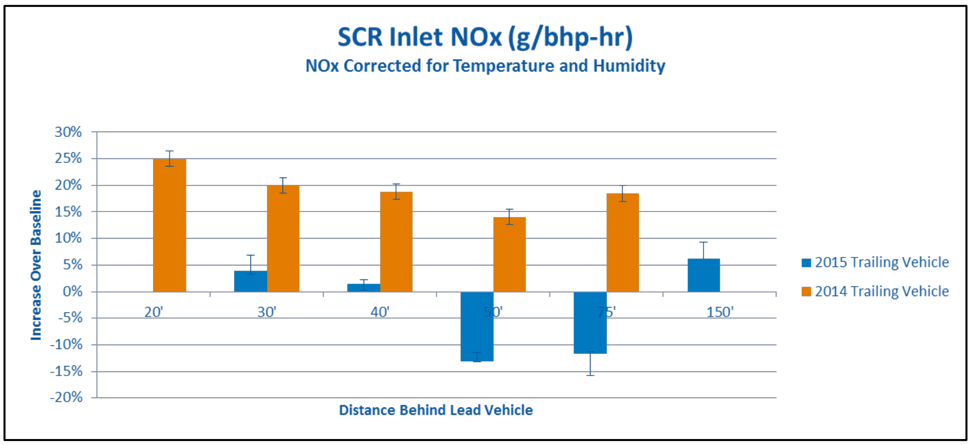

Figure 9. SCR inlet brake-specific NO_x comparison

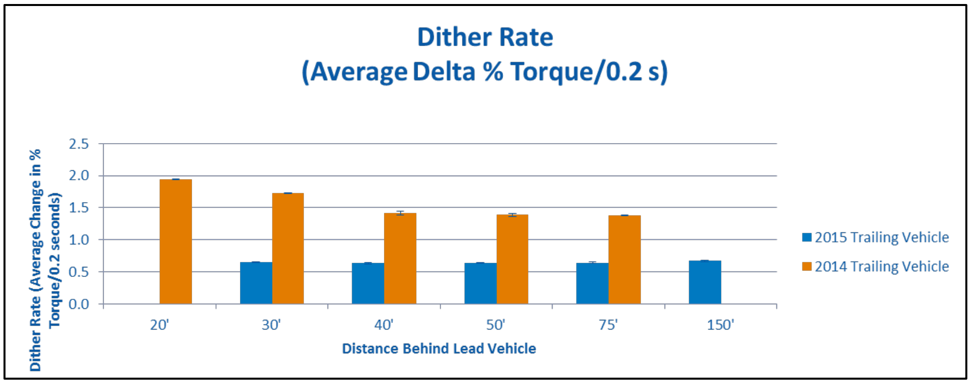

Figure 10. Dither rate comparison

Accounting for Natural "Background Platooning"

NREL worked with Volpe National Transportation Center to adapt the data within its 2016 *Naturalistic Study of Truck Following Behavior Final Report* (Nodine et al. 2016) to develop an understanding of the amount of time trucks at highway speeds follow one another at proximities that would yield platooning savings. This information was used to help answer the question of whether trucks are already drafting and getting platooning savings without semi-autonomous platooning technology. The answer from this analysis is "no." During lower-speed operations, trucks operate close together more frequently, but above 60 mph only 2.2% of driving time had a lead vehicle within 90 meters (295 ft.). Using a degradation curve for estimating savings of the rear vehicle beyond the tested distances, an estimated savings of less than 0.2% background "savings" is possible within this data set. Additionally, video-validated samples of the following encounters estimate that 57% of the events had a light-duty vehicle ahead of the test truck, which would reduce the aerodynamic savings compared to following directly behind another truck. Figure 11 shows following durations in different speed bins from the study compared to average predicted savings for the following vehicle of a platooning pair. The area shaded in red represents the time spent above 60 mph with a target vehicle detected. This Volpe study was a limited set of in use tractors and as such an analysis of a broader population of in service tractors is needed to validate these findings.

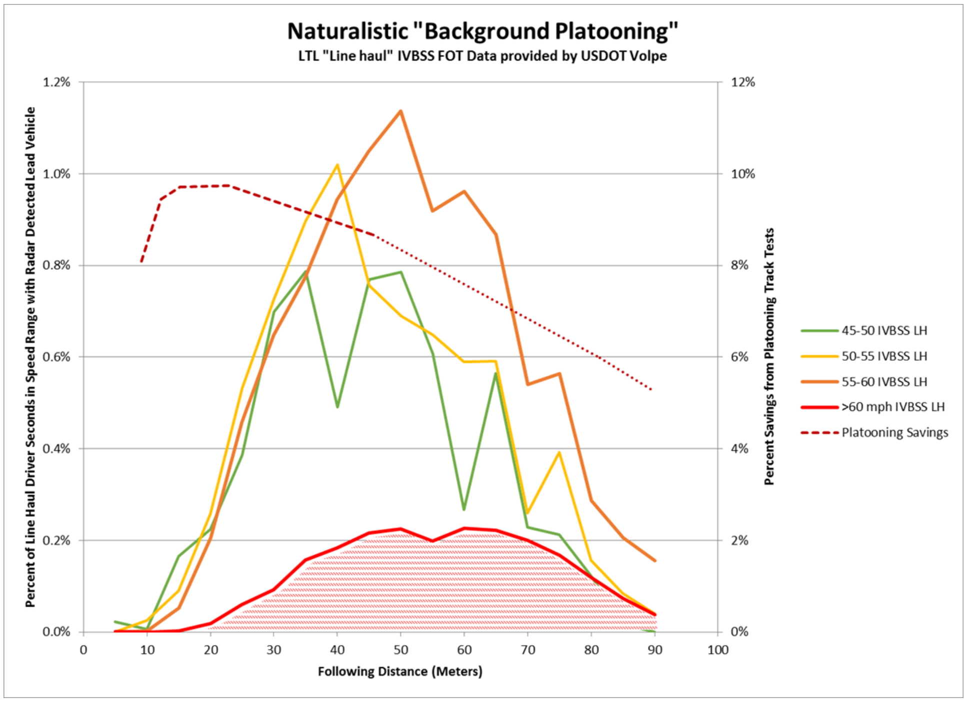

Figure 11. Naturalistic "background platooning"

Remaining Questions

There are several remaining important questions to answer with additional future testing:

1. What is the full-scale airflow behavior during close-following situations?
   - Track and wind tunnel results both indicate an unexpected drop in fuel savings for the following truck in the 20 ft. –50 ft. following range
   - NREL plans to incorporate vehicle-mounted anemometers and pressure sensors during track study August 2017 in conjunction with LBNL/NRC/Transport Canada to validate wind tunnel findings (stagnation pressure and particle image velocimetry) to help explain/correct this phenomenon.
2. What is the validation of long-following distance behavior?
   - The savings degradation curve needs to be validated at long distances to what was observed in recent LLNL wind tunnel tests.
   - Savings at long distances could impact realized fuel savings from platooning if current traffic conditions have trucks in this range.
3. What is the importance of vehicle alignment to savings—impact of offset-following vehicle?
   - The impact of vehicle offset to what was observed in wind tunnel needs to be validated.
   - What is a possible alternate explanation for the unexpected drop in savings for rear truck in 20 ft. –50 ft. range.

4. What investigation of savings from other vehicle configurations should be performed?
    - Day cabs with double/triple 28 ft. trailers: this configuration is common with less-than-truckload (LTL) operators and UPS/FedEx carriers who may be likely early adopters.
        - Higher single-vehicle aerodynamic Coefficient of Drag may mean larger percent savings from platooning, especially during empty trailer return trips (product movement isn't equal in all directions).
    - Three or more truck platoons, does the center vehicle realize savings for both lead and following vehicles?
5. What is the "Big Picture" impact?
    - NREL is seeking fleet/OEM partners to acquire telematics data for thousands of vehicles to study how many miles would be "platoonable" with minimal disruption to operations of large fleets, i.e., how often are vehicles in close enough proximity and direction?
    - The answer will shed light on true fuel savings and congestion mitigation that can be realized by platooning.
    - Platooning is a unique technology given that it requires a compatible partner vehicle available on the same road at the same time; a savings analysis only considering test conditions does not apply directly to savings in operation.
6. What is the real-world fuel savings of platooning in revenue use?
    - Measured with Fleet Evaluation with first-fleet deployments.
    - NREL is planning to be involved with first-fleet demonstrations/deployments of platooning in freight service.
    - This will give a window into real-world savings and percent of miles conducive to platooning.

Conclusions

The primary conclusion is that all platooning scenarios being considered today offer significant opportunity for fuel and emissions savings in the near term, but there are still unanswered questions and clear opportunities for greater savings. In the longer term, platooning fuel savings can be significantly enhanced by addressing barriers to closer platoon formation and adding more vehicles to a platoon. Additionally:

- Significant correlation between multiple unaffiliated track studies, wind tunnel, and CFD work was observed, but there is more to learn regarding close formation and long-distance effects as well as the impact of aerodynamic packages and three-vehicle platoons.
- Background platooning is probably minimal and as such will not significantly impact realized savings, however a study with a larger sample size is needed
- Criteria pollutant emissions can be negatively affected by platooning control and must be monitored, but NO_x benefits can be realized with proper platooning interaction with the engine and emissions controls systems.

Future Plans

Future plans include:

- Incorporating direct aerodynamic study into track testing (truck-mounted anemometer, pressure transducers, thermocouples, smoke trails, etc.) to confirm wind tunnel and CFD findings
- Undertaking a Big Data geospatial & temporal analysis of telematics data to estimate the fraction of platoonable miles traveled by class 8 tractor trailers.

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