# *IMMEDIATE DECARBONIZATION OF CLASS 8 TRUCKING*

A 1.3 Million Mile Evaluation of 100% Biodiesel


Unlocking nature.
Enriching life.
ADM
ADM Trucking Inc

# SUMMARY

**Background**

To facilitate dramatic reductions in scope 1 carbon emissions, ADM Trucking undertook a 16-month biodiesel field trial covering nearly 1.3 million miles of on-road operation with 10 Class 8 Mack trucks (see Table A.1). This trial compared the operation of five trucks upgraded with Optimus Technologies' Vector System and fueled with 100% biodiesel (B100) against a control group of five unmodified trucks operating on 11% biodiesel (B11), ADM's conventional diesel fuel in Illinois. All 10 trucks operated on similar routes with like duty cycles, consumed similar amounts of fuel and were equipped with New Technology Diesel Engines (NTDEs) which employ diesel oxidation catalyst (DOC), diesel particulate filter (DPF), and selective catalytic reduction (SCR) aftertreatment technologies. A comparison of fuel economy, operations, maintenance, and emissions data between the trucks equipped with the Vector System operating on B100 (the "Vector System trucks") and the B11 base case was performed.

“Protecting our planet and its natural resources is core to our purpose as an organization," said Steve Finn, ADM Vice President of Transportation, and due to use of the Vector System and the biogenic nature of biodiesel, the five upgraded trucks provided a reduction in ADM Trucking’s scope 1 carbon emissions of over 940 metric tons during the 16-month field trial.[1]

**Vector System B100 Results**

The Vector System trucks saw an increase of 1.3% in fuel economy, a 32% reduction in the ash accumulated in the DPF, a 22% reduction in time spent actively regenerating the DPF, and an overall reduction of over 50% in the total number of active DPF regenerations. Engine oil drain intervals were maintained at the same interval for the Vector System and the base case B11 trucks. This interval was consistent with ADM trucking’s standard interval and no negative engine oil impacts from operation with the Vector System were observed.

**~1.3 million miles in testing**

**102% improvement in regen intervals**

**943 metric tons of carbon reduced**

1. As compared to ADM's conventional diesel fuel B11 (11% biodiesel).

# SUMMARY CONT.

In fact, the Vector System trucks resulted in oil sample oxidation and soot/nitration levels that were substantially improved compared to the B11 trucks, and viscosity differences across all crankcase oil samples were not statistically different. No variation in maintenance costs related to the engine, fuel system, or exhaust components were observed. Over the course of the field trial there were no impacts reported on the commercial operations of ADM Trucking, and the drivers surveyed reported positive experiences with the deployment of Optimus' Vector System and B100.

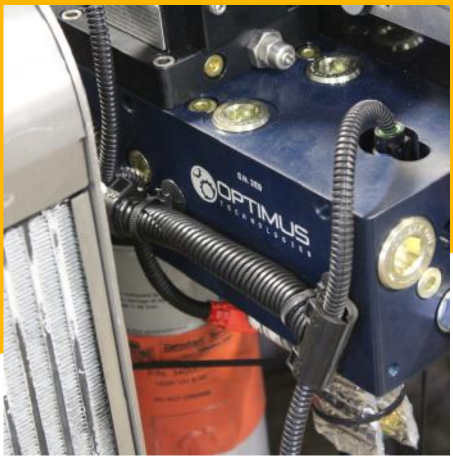
**Conclusion**

Over the project period the five Vector System trucks consumed 77,424 gallons of B100 and mitigated an additional 993 gallons of diesel fuel offsetting carbon emissions by approximately 943 metric tons. The data collected and analyzed demonstrates the positive operational, performance, and sustainability benefits that can be achieved with the deployment of Optimus' Vector System and the use of 100% biodiesel in modern heavy-duty NTDEs.

Class 8 ADM B100 Truck in Sub-Zero Temperatures

# PROJECT OVERVIEW

Class 8 ADM B100 Truck in Sub-Zero Temperatures



Optimus Technologies Vector System Manifold

Biodiesel Dispenser Cabinnet

**The Importance of Climate Resilience**
The drive for sustainable solutions has transitioned from a notion of convenience to a cry for immediate action. Climate induced disasters are increasing in scope and severity, and all data indicates these events to be the beginning of a looming catastrophe.

While carbon reductions are being made in multiple sectors, an enormous gap exists between the performance, reliability, and availability of carbon reduction solutions for medium- and heavy-duty fleet applications. Class 8 trucks often run long routes, extended hours, or both, that make current battery electric and hydrogen fuel cell solutions unsuitable or prohibitively expensive to purchase and operate. For this reason, ultra-low carbon fuels such as biodiesel play an important role in mitigating climate impacts.

A recent study conducted by the American Transportation Research Institute (ATRI) analyzed the life-cycle $CO_2$ emissions for the production, operation, and disposal of Class 8 trucks.

The study evaluated traditional diesel, battery electric, and fuel cell electric trucks; data analyzed was derived from the U.S. Department of Energy, Argonne National Laboratory's GREET life-cycle analysis tool. When evaluating the production and disposal lifecycle $CO_2$ emissions of a Class 8 truck, diesel, battery electric, and hydrogen fuel cell trucks are estimated to generate approximately 77,000 lbs of $CO_2$ , 528,500 lbs of $CO_2$ , and 118,500 lbs. of $CO_2$ emissions respectively.[2] Due to the substantial reduction in carbon emissions from truck operations that can be achieved from use of the Vector System and B100, and the substantially lower manufacturing and disposal emissions generated, a diesel Class 8 truck upgraded with the Vector System operating on 100% biodiesel achieves the lowest total lifecycle $CO_2$ emissions when compared to battery electric and hydrogen fuel cell trucks. In addition to being the lowest carbon option, the Vector System and B100 provide the lowest total cost of implementation and lowest total operating costs when analyzing weight- and range-limited operating scenarios of battery electric trucks.[3]

2. Short, Jeffery, and Danielle Crownover. 2022. Review of Understanding the $CO_2$ Impacts of Zero-Emission Trucks. American Transportation Research Institute.
3. Frank, Jenny, Tristan Brown, Martin Haverly, Dave Slade, and Robert Malmsheimer. 2021. "Quantifying the Comparative Value of Carbon Abatement Scenarios over Different Investment Timing Scenarios." Fuel Communications 8 (September): 100017. https://doi.org/10.1016/j.jfueco.2021.100017.

# PROJECT OVERVIEW CONT.

**Total Life-Cycle $CO_2$ Production/Disposal of a Class 8 Truck**

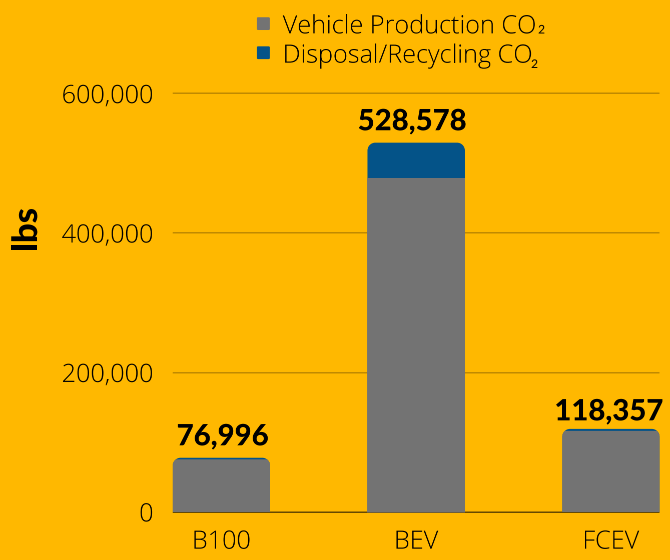


Figure 1 Total Life Cycle $CO_2$ Production/Disposal Comparison of a Class 8 Truck

A diesel Class 8 truck upgraded with the Vector System operating on **100% biodiesel achieves the lowest total lifecycle $CO_2$** emissions when compared to battery electric and hydrogen fuel cell trucks.

**Strive 35 Sustainability Commitments**

ADM has committed to aggressive environmental sustainability goals, called "Strive 35" – an ambitious plan to, by 2035 [over the 2019 baseline], reduce absolute greenhouse gas (GHG) emissions by 25%, reduce energy intensity by 15%, reduce water intensity by 10%, and achieve a 90% landfill diversion rate."[4] ADM's 2020 Sustainability Report indicates corporate scope 1 and 2 carbon emissions were 15.7 million metric tons globally with 13.9 million metric tons from ADM's North American operations. 623,000 metric tons of carbon emissions were attributed to mobile combustion sources including ADM's operations from trucking, rail, and marine. The ADM Trucking fleet operations include 680 trucks throughout the United States utilized in regional haul delivery operations. These trucks emit approximately 126,000 metric tons of scope 1 carbon emissions when using an average case 5% biodiesel (B5) fuel.

4. Review of Local Action Global Impact. 2020. ADM. https://assets.adm.com/Sustainability/2020-Corporate-Sustainability-Report_210521_121113.pdf.

# PROJECT OVERVIEW CONT.

### The Project

In February of 2020, ADM began a 16-month on-road test of Optimus Technologies' Vector System technology, an advanced fuel system technology that upgrades diesel engines to operate on 100% biodiesel. The five ADM fleet trucks were upgraded with the Vector System to operate primarily on 100% biodiesel with the goal of reducing scope 1 carbon emissions. The objective of the study was to validate the scope 1 carbon emission reductions and determine the operational impact of the Vector System on ADM's fleet of high mileage regional haul NTDE trucks operating out of ADM's Decatur, Illinois facility.

### Data Collection

The data monitored and analyzed for this field trial includes biodiesel utilization, fuel quality, fuel economy, carbon reductions achieved, DPF operation, engine oil analysis, and overall maintenance impacts on the engine's fuel and exhaust system components over the 16-month period. The trucks selected to participate were identified due to their similar yearly maintenance activities, utilization, accumulated mileage, and expected duty cycles. Five trucks were selected as diesel (B11) control trucks and five trucks were selected to be upgraded with Optimus' Vector System to operate on 100% biodiesel. All biodiesel utilized for the project was derived from soybean oil feedstock and sourced from ADM's BQ-9000 certified Mexico, Missouri facility.

# ON-ROAD FIELD TRIAL OVERVIEW

The on-road field trial commenced at the end of February 2020 and concluded at the end of June 2021. The 10 trucks in the field trial were 2014 Mack CXU613 models equipped with a 10.8L MP7 engine that utilized a diesel oxidation catalyst/diesel particulate filter and selective catalyst reduction system. The field trial covered nearly 1.3 million miles, a total of approximately 650,000 miles of operation for each of the Vector System trucks and the B11 trucks. The mileage was recorded at the start of the field trial from a direct odometer reading and the miles at the end of the field trial were values provided by ADM, pulled from their fleet management software. Statistical analysis conducted throughout this report was performed using a two-sample t-test (assuming unequal variances) with a confidence interval of 95%, $\alpha=0.05$.

# VECTOR SYSTEM OVERVIEW

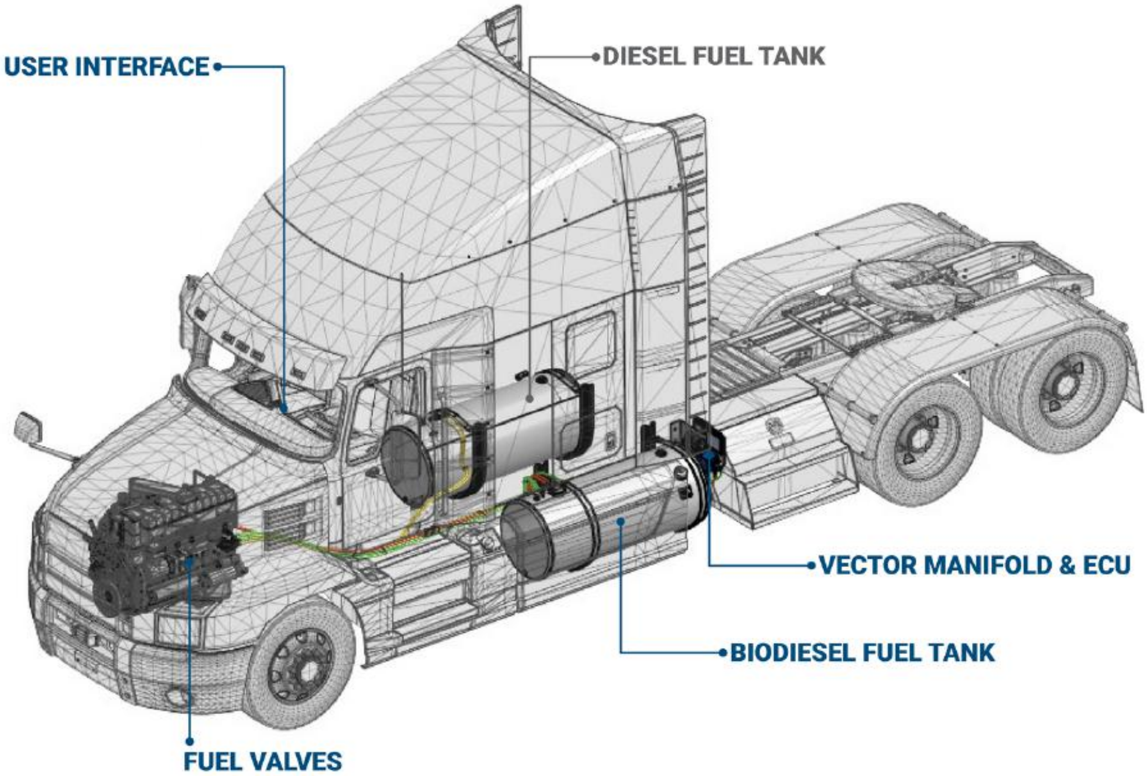



Figure 2 Overview of Vector System Primary Components

## Vector System Principles of Operation

The Vector System upgrades any medium- or heavy-duty diesel engine to operate on 100% biodiesel year-round, regardless of ambient temperatures. The system is an advanced dual fuel supply system that retains a diesel fuel tank and the use of diesel fuel for engine startup, shutdown, active DPF regenerations, and any conditions not meeting suitable operating requirements for use of 100% biodiesel. During this field trial, ADM's Vector System upgraded trucks achieved operational runtimes of up to 87% on B100. By eliminating “range anxiety” and reducing potential operational impacts, the retention of diesel fuel on-board provides critical fleet operations the necessary risk mitigation for the transition to a low carbon future, without requiring a leap of faith step change in emerging technologies.

The Vector System is fully automated, employs bi-directional communication with the engine’s control system, and utilizes software and control algorithms to ensure seamless integration into fleet operations without requiring any input or change in behavior from drivers.

# VECTOR SYSTEM OVERVIEW CONT.

Optimus' Vector System technology tracks and analyzes carbon reductions, cost-savings, and petroleum offsets. The system automatically optimizes the use of biodiesel when all suitable operating conditions are met, and concurrently monitors over 150 key fuel system and engine parameters. All real-time data is reported by embedded telematics and available for monitoring and access by the fleet's team via an online dashboard.

The Vector System can be integrated into new truck production or as a retrofit, as was the case in this project, installed in existing trucks in as little as 20 hours.

Through the use of waste engine heat and a series of heat exchangers, engines upgraded with the Vector System are able to operate on 100% biodiesel in harsh environments and sub-zero temperatures overcoming traditional cold flow challenges associated with the use of biodiesel.

**The lowest operational ambient temperature while operating on 100% biodiesel was -10°F.** Even at these extreme temperatures, the Vector System trucks performed without operational challenges.

"The computer shifts from diesel to the biodiesel quickly after the engine heats up to temperature, so you don't have to do anything."
- R. Merriman, ADM Trucking Driver


Optimus Technologies Vector System Dashboard Display

Gelled B100 In Fuel Tank Prior to Vector System Conditioning

# SCOPE 1 CARBON EMISSIONS

**An Overview of Scope Emissions**

One of the primary benefits of fuel switching to B100 is the steep reduction in scope 1 carbon emissions that can be achieved. Scope 1 emissions are direct GHG emissions that occur from sources that are controlled or owned by an organization (e.g., emissions associated with fuel combustion in vehicles, boilers, furnaces). [5]

**Scope 1 Emission Comparison B100 vs. Diesel**

Direct reductions of scope 1 carbon emissions can be achieved by operating on B100 when compared to petroleum diesel. Due to the biogenic nature of the carbon emissions of biodiesel, nearly all carbon produced by combustion of B100 is sequestered by the natural carbon cycle.

This circular loop in which the carbon contained in the fuel is directly sequestered by the next generation of new plants and animals, enables B100 to achieve a net-zero carbon contribution. Fossil fuels are derived from crude oil reserves extracted from the ground comprised of carbon that has been sequestered for millions of years. The combustion of each unit of fossil fuel results in a transfer of carbon from underground reserves into the atmosphere as carbon dioxide. Carbon emissions from fossil fuels represent carbon that was not present in the modern atmosphere but is introduced due to human activity; this is defined as anthropogenic carbon. Combustion of anthropogenic carbon provides a net addition to atmospheric GHG's and is one of the largest factors driving climate change. In our industrialized world, net addition of carbon emissions is occurring at a rate far beyond the earth’s natural processes to remove carbon dioxide from the atmosphere directly resulting in, and accelerating, climate change.

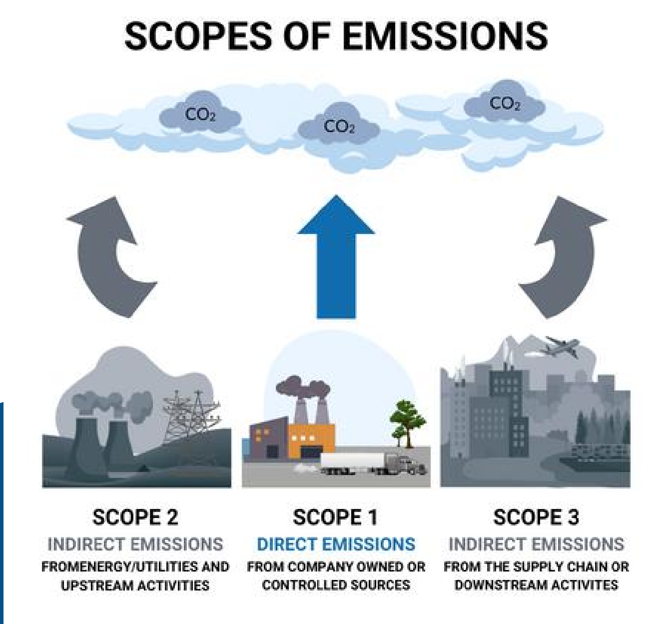



Figure 3 Scope Classifications of Carbon Emissions

5. US EPA, OAR. 2015. “GHG Inventory Development Process and Guidance.” Www.epa.gov. July 17, 2015. https://www.epa.gov/climateleadership/ghg-inventory-development-process-and-guidance.

# SCOPE 1 CARBON EMISSIONS CONT.

Biodiesel is produced from natural oils or fats through a biorefining process called transesterification. In the case of ADM's Mexico, Missouri soybean oil biodiesel production, atmospheric carbon is sequestered by the soybean plant as it grows. After harvested, soybeans are crushed to produce approximately 80% high-quality protein soybean meal and 20% soybean oil. The resulting soybean oil is then refined into biodiesel which is then used to directly replace fossil fuels. In contrast to the combustion of fossil fuels which result in a net addition of carbon emissions to the atmosphere, the closed loop cycle of sequestration and combustion of biogenic carbon from biodiesel does not have a contributing effect to climate change. Recognizing the benefits of the biogenic carbon cycle of biodiesel is a key aspect of how scope 1 carbon emissions are accounted.

### Third-Party Verifications of Scope 1 Emissions

In applications such as long-haul trucking that are extremely difficult and expensive to electrify, the Vector System provides an immediate cost-effective pathway to reduce scope 1 carbon emissions. During the duration of this project the five Vector System trucks consumed 77,424 gallons of B100, eliminating approximately 931 metric tons of carbon (see Table A.2). ADM tracks and documents GHG emissions from operations in accordance with the ADM Greenhouse Gas Protocol and the emission results are verified annually by a third-party reviewer. ADM utilizes the Global Reporting Initiative (GRI) Sustainability Reporting Standards to report this information in their annually published Sustainability Report issued by the Global Sustainability Standards Board (GSSB).

GRI states that the reporting of "biogenic emissions of $CO_2$ from the combustion or biodegradation of biomass shall be reported separately from the gross direct (scope 1) emissions,"[6] because they do not have a net climate impact.

### Fuel Economy

Due to the increase in fuel economy of the Vector System trucks, 993 gallons of diesel fuel consumption was mitigated resulting in an additional 12 metric tons of carbon offset. If applied fleet wide, the Optimus Vector System using B100 could reduce scope 1 carbon emissions from the ADM Trucking fleet operations by 117,000 metric tons, resulting in a reduction of approximately 19% of ADM's total mobile combustion emissions.


Class 8 ADM B100 Truck

Over the project period **the five Vector System trucks consumed 77,424 gallons of B100** and mitigated an additional 993 gallons of diesel fuel **offsetting carbon emissions by approximately 943 metric tons**.

6. GRI is an independent international organization helping businesses measure and take accountability for the impact of their operations. GRI protocol 305-1 defines the required disclosure methods that pertain to scope 1 GHG emissions that result from the mobile combustion of fuels such as those from the ADM Trucking operations.

# FUEL ECONOMY

### Biodiesel Overview

Biodiesel is a mono-alkyl ester of the long chain fatty acid hydrocarbons found in natural fats and oils. The long chain hydrocarbons in biodiesel provide a relatively high energy density, high cetane fuel, and high flash point while the oxygen in the ester provides superior lubricity, biodegradability, and reduces emissions from engines optimized for conventional diesel fuel. 100% biodiesel has a 5-9% deficit in energy content (BTUs) relative to diesel fuel but has a higher cetane value.[7] The weighted average cetane value for the biodiesel utilized in the field trial was 48 (see Table A.3).

### Biodiesel Fuel Economy

Studies on the fuel economy impact of biodiesel to date have typically been with 20% (B20) or lower biodiesel blends. While biodiesel is a high energy density fuel, B100 energy content is generally less than most #2 diesel fuels. The lower energy content, and the corresponding theoretical calculation is often extrapolated to a resulting direct relationship on reduced fuel economy; however, existing fuel economy data on biodiesel blends up to B20 generally shows no impact on fuel economy, a divergence from the theoretical result.[8] Due to the historical focus on B20 in the U.S., very little fuel economy data is available on B100 and no fuel economy data from real-world operations using 100% biodiesel in modern diesel engines (NTDEs) had been collected until this project.

> "The mileage was better under the biodiesel... It was very noticeable that I was able to go much further before refueling than usual."
> - R. Merriman, ADM Trucking Driver

ADM Trucking Service Laptop with Optimus Analytical Software

> "This study helped to give us and other fleets the data they need to feel secure in implementing the Vector System with B100 to enhance sustainability efforts without sacrificing efficiencies."
> - Steve Finn, ADM Vice President of Transportation

7. Jung, H, D Kittelson, and M Zachariah. 2006. Review of Characteristics of SME Biodiesel-Fueled Diesel Particle Emissions and the Kinetics of Oxidation. Environmental Science & Technology 40 (16).
8. C. R. McKinley, and J. H. Lumkes Jr. 2009. "Quantitative Evaluation of an On-Highway Trucking Fleet to Compare #2ULSD and B20 Fuels and Their Impact on Overall Fleet Performance." Applied Engineering in Agriculture 25 (3): 335–46. https://doi.org/10.13031/2013.26884.

# FUEL ECONOMY CONT.

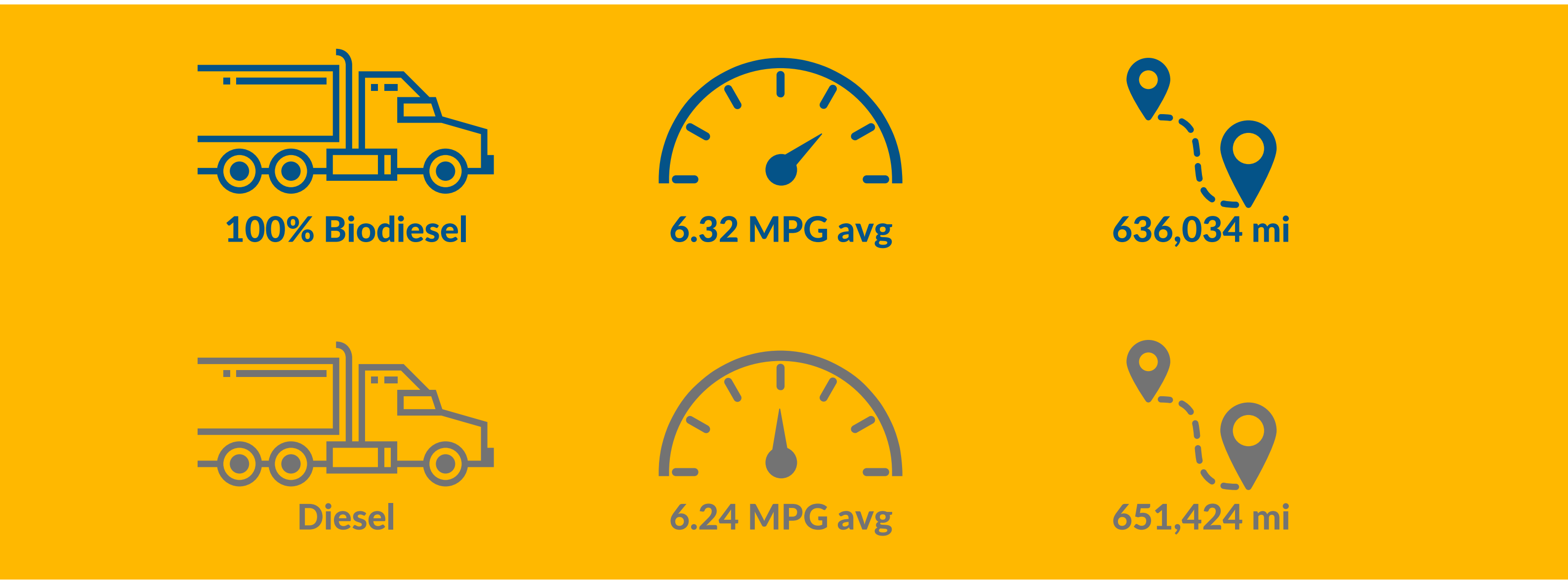



Figure 4 Fuel Economy Comparison

**Particulate Matter Reductions with B100**

It has been well established that the use of 100% biodiesel results in approximately 58% less combustion generated particulate matter.[9] Also well documented is the fact that soot particulates generated with biodiesel blends burn off faster and at a lower temperature in the DOC/DPF than those of conventional petroleum-based diesel.[10] Fewer particulates, either from initial generation or from a more accelerated burn-off of soot, accumulating in the DPF results in lowering the back-pressure on the exhaust system. This back-pressure reduction requires less work to be performed by the engine to expel exhaust gases through the particulate filter when compared to a corresponding diesel unit. Therefore, the efficiency gains provided by the improved aftertreatment operations of the Vector System trucks can overcome the theoretical result in fuel economy of use of 100% biodiesel calculated based solely on energy content.

**Vector System B100 Miles Per Gallon**

The Vector System trucks in this field trial averaged 6.32 miles per gallon over the project period with a total distance of 636,034, while the base case B11 trucks averaged 6.24 miles per gallon over the project period with a total distance traveled of 651,424 (see Table A.4/A.5). The result is better than the theoretical value expected when extrapolating and comparing based solely on the BTU content of the #2 diesel and biodiesel fuels. Typically, fleet fuel economy testing has been performed according to SAE J1321 which utilizes a 40-mile test route or controlled track environment, and the results are interpreted more broadly to be representative of long-haul operations. The results, further detailed in the Impact of B100 On Diesel Particulate Filters section, demonstrates the improvement of fuel economy of the Vector System trucks is due to the substantial particulate matter reductions associated with B100.

9. Multimedia Working Group. 2015. Review of Multimedia Evaluation of Biodiesel. State of California California Environmental Protection Agency. https://ww2.arb.ca.gov/sites/default/files/2018-08/Biodiesel_Multimedia_Evaluation_5-21-15.pdf.
10. Williams, Aaron, Jon Luecke, Robert L. McCormick, Rasto Brezny, Andreas Geisselmann, Ken Voss, Kevin Hallstrom, Matthew Leustek, Jared Parsons, and Hind Abi-Akar. 2011. Review of Impact of Biodiesel Impurities on the Performance and Durability of DOC, DPF and SCR Technologies. Alliance for Sustainable Energy, LLC. https://www.nrel.gov/docs/fy11osti/50297.pdf.

# FUEL ECONOMY CONT.

These reductions result in lower soot loading of the DPF, less backpressure in the exhaust aftertreatment system, and reduced the need for active DPF regeneration events by over 50%. When compared to the SAE J1321 40-mile track test, the data collected in this controlled, real-world field trial is much more insightful in understanding the impact of the Vector System and B100 use as compared to that of an unmodified NTDE using conventional B11 diesel fuel. The trucks in this field trial averaged 25% idle time for the diesel control group and 17% for the Vector System group; these ranges are typical across the ADM Trucking fleet and considered within industry averages.

The North American Council for Freight Efficiency's Confidence Report on Idle Reduction Technologies indicates that a 10% reduction in idling generally has approximately 1% total impact on fuel economy.[11] When adjusting for variation in idle times, an 8% delta for the two groups, the field trial results still indicate an improvement in fuel economy for the Vector System trucks with a theoretical idle-adjusted value of 6.27 miles per gallon. Therefore, the dramatic reduction in engine out particulate matter and ease of soot burn off associated with B100 appears to be the main reason for the increase in fuel economy with the Vector System compared to the base B11 case and theoretical calculations based solely on BTU content differentials.

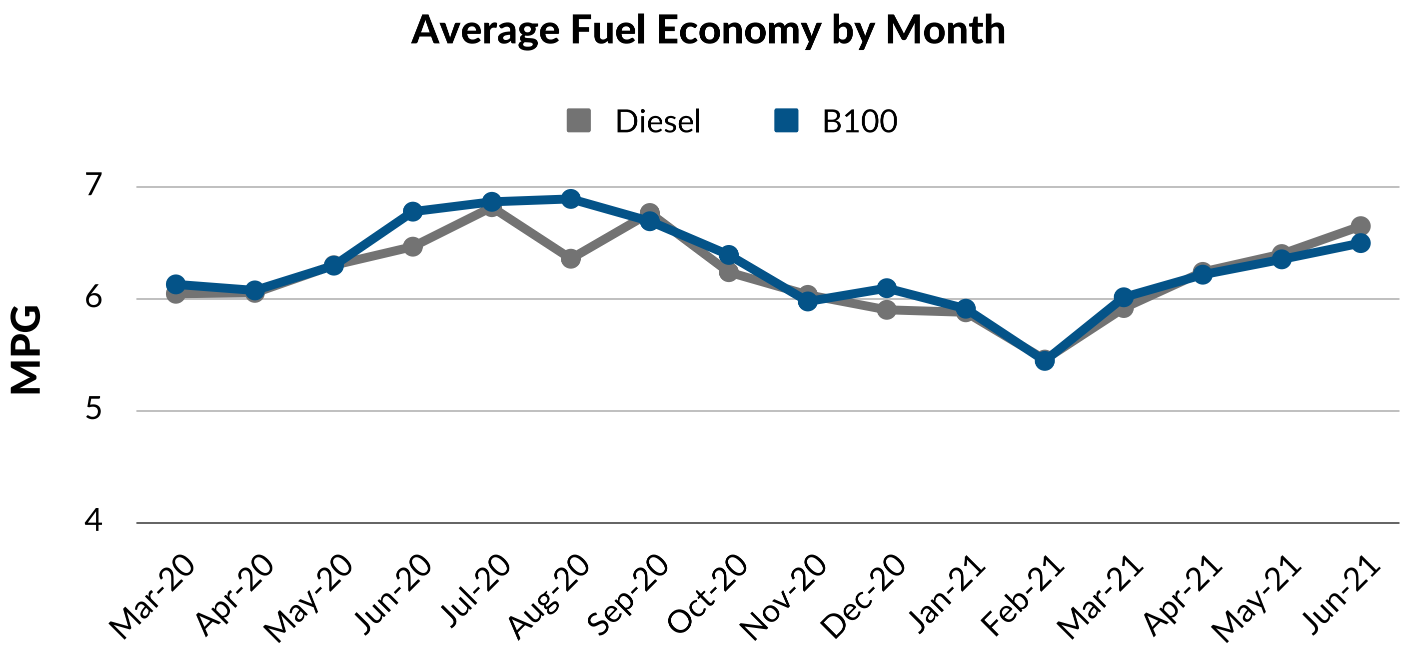



Figure 5 Average Fuel Economy by Month

11. Otto, Kevin, Denise Rondini, and Mike Roeth. 2019. Review of CONFIDENCE REPORT: Idle-Reduction Technologies. NACFE. https://nacfe.org/wp-content/uploads/2019/08/Idle_Reduction_Full_Report_08082918.pdf

# IMPACT OF B100 ON DIESEL PARTICULATE FILTERS

**Overview of Diesel Particulate Filters**

Diesel particulate filters most commonly consist of a diesel oxidation catalyst in combination with a catalyst-coated filter substrate designed to collect essentially all diesel soot, engine oil related ash, and other byproducts that make up particulate matter emissions from diesel engine combustion. These particulate compounds accumulate and increase exhaust back-pressure which can reduce the overall efficiency of the engine by requiring additional work to be performed for the exhaust gases to be expelled through the DPF and out the exhaust system. DPFs are a requirement for any on-road diesel engine produced after 2007 in the U.S., and they are extremely efficient in eliminating over 90% of the particulate matter emissions of diesel engines.

**Managing Long-Term DPF Operation**

While DPFs used in NTDEs do an excellent job of reducing particulate matter emission that is typically associated with older diesel engines, eventually this accumulated material must be removed or reduced. Soot and unburned hydrocarbons collected by a DPF can be removed by elevating the exhaust gas and DPF temperatures to the ignition temperature of these materials so that they can be oxidized; this process is called 'regeneration' of the DPF.

Diesel Particulate Filter Element Pre- and Post-Project

# IMPACT OF B100 ON DIESEL PARTICULATE FILTERS CONT.

Mack Trucks Bulldog Hood Ornament


Optimus Technologies Vector System Manifold

Regeneration of a DPF can reduce the carbonaceous materials but it does not remove metallic ash compounds which are primarily the result of engine oil wear additives or, to a lesser extent, may be found in the fuel. Eventually, it is necessary to remove the unburned ash compounds from the DPF through a cleaning process that involves physically removing the DPF and using a pneumatic or wet rinsing machine to remove the accumulated ash. Original equipment manufacturers (OEMs) design DPFs to minimize the ash cleaning requirements over the life of the system.

Currently there is no testing required for metal compounds in #2 diesel fuel specification (ASTM D975).

The specifications for B100 (ASTM D6751), however, do have requirements on metals such as sodium (Na), potassium (K), calcium (Ca) and magnesium (Mg). Nearly all values of B100 in today's market are extremely low (less than 1 ppm average total Na+K+Ca+Mg).[12]

One of the objectives of this field trial was to determine if there were any potential impacts of biodiesel metals on DPF operations in the field compared to those of the base B11 case. The B100 (commercially available biodiesel fuel from ADM's Mexico, Missouri facility) utilized in the project had near-zero levels (<1ppm) of detectable metals (Na, Ca, Mg and K - see Table A.3).

12. Alleman, Teresa L. 2021. Assessment of BQ-9000 Biodiesel Properties for 2020. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5400-79815. https://www.nrel.gov/docs/fy21osti/79815.pdf.

# IMPACT OF B100 ON DIESEL PARTICULATE FILTERS *CONT.*

## Regeneration of DPFs

Removal of the carbonaceous materials collected by diesel particulate filters happens through two primary means. First, some materials oxidize during normal operation of the engine when the exhaust gas temperatures are hot enough for long enough periods of time; this is most often referred to as passive regeneration. The second method is through a temporary addition of fuel through the injectors in-cylinder during the exhaust stroke or use of an additional fuel dosing injector in the exhaust stream located just prior to the DOC/DPF. In either active regeneration case, unburned fuel starts combusting in the DOC and creates enough heat to elevate the DOC/DPF to the ignition point of the soot and oxidizes the carbonaceous material. The additional fuel injected into the cylinder or doser for active regeneration of the DPF results in a direct reduction in overall fuel economy as this fuel is used only for the regeneration process and is not used to create engine power.

## Vector System Design for DPF Systems

The Mack MP7 engines in this field trial deploy a dosing injector design strategy for active regeneration of the DPF. Although this strategy works well when used with #2 diesel fuel, and biodiesel blends up to B20, B100 has a very high flash point which falls outside of the system's design parameters and can present issues. Additionally, the increased viscosity of B100 can result in a deviation of doser spray pattern atomization. This variation of doser spray atomization, in combination with the increased flashpoint, can result in reduced performance and possible degradation of the DOC/DPF during the active regeneration process. It should be noted that generally, the higher flashpoint of biodiesel is a desired attribute as it makes the handling and storage of biodiesel much safer than conventional diesel fuel.[13]

Diesel Particulate Filter Equipped with Monitoring Sensor


Interior of Mack Truck

13. "Biodiesel Benefits and Considerations." Alternative Fuels Data Center: Biodiesel Benefits, https://afdc.energy.gov/fuels/biodiesel_benefits.html.

# IMPACT OF B100 ON DIESEL PARTICULATE FILTERS CONT.

A statistically significant **increase in regeneration interval of 121.3 hours was found on the Vector System trucks** when compared to the diesel trucks (see Table A.6).

DPF units from the **Vector System trucks averaged a 13% improvement in ash clean out** (55% vs. 42%) when compared to the diesel control group.

The Vector System overcomes the challenges associated with higher biodiesel blend use for active regenerations by isolating the dosing injector fuel lines so that they are only supplied with #2 diesel fuel and the Vector System automatically defaults the engine to diesel only operation during active regeneration.

## Diesel Particulate Filter Evaluations

At the onset of the field trial, all trucks were equipped with new DOC and DPF units so that an accurate comparison could be made between the Vector System trucks and the base B11 trucks. The DPFs were weighed and analyzed by an independent laboratory prior to installation and then removed at the conclusion of the test for a more detailed evaluation. The total ash accumulation was determined by comparing the recorded baseline mass values to the completed post-test mass values. Both the baseline and post-test values were measured after the DPF was heated in a controlled laboratory oven to remove any carbonaceous material and moisture so that an accurate value of the metallic ash compounds could be determined.

FSX Trap Blaster 7 DPF Cleaning Machine

# IMPACT OF B100 ON DIESEL PARTICULATE FILTERS *CONT.*

**Ash Clean Out**

At the conclusion of the test, the DPF units underwent a typical ash removal cleaning process. The cleaning process was conducted on a Mack approved FSX TRAPBLASTER™ Pneumatic DPF Cleaner according to manufacturer recommendations. The mass value of the DPF was recorded at the conclusion of the test; following the ash clean out, the DPFs were again weighed, and the percentage of ash removed was calculated (clean out efficiency). The DPF units from the Vector System B100 trucks had an average ash removal of 54.8%, while DPF's from the base B11 control trucks showed an average of 41.9%, a 12.9% improvement in ash clean out efficiency (see Table A.7).

**Results**

The base B11 case control trucks had an average normalized mass accumulation of 1.36 x $10^{-3}$g/mile of ash while the Vector System trucks accumulated 0.93 x $10^{-3}$g/mile of ash. This represents a 32% reduction in the grams of ash accumulated per mile for the Vector System trucks when compared to the B11 control group. The Mack recommended maintenance clean out interval for the DPF on the project trucks is 400,000 miles. Calculating the grams of ash accumulation for operation of the B11 trucks based on the field trial results (assuming a linear correlation) suggests a clean out threshold of approximately 550 grams of ash. By comparing that to the results of the ash loading found with the Vector System trucks, the same 550 grams of ash loading would occur over a 580,000 mile interval, a theoretical improvement in the clean out interval of the DPFs for the Vector System trucks of 180,000 miles as compared to the base B11 trucks (see Table A.8).

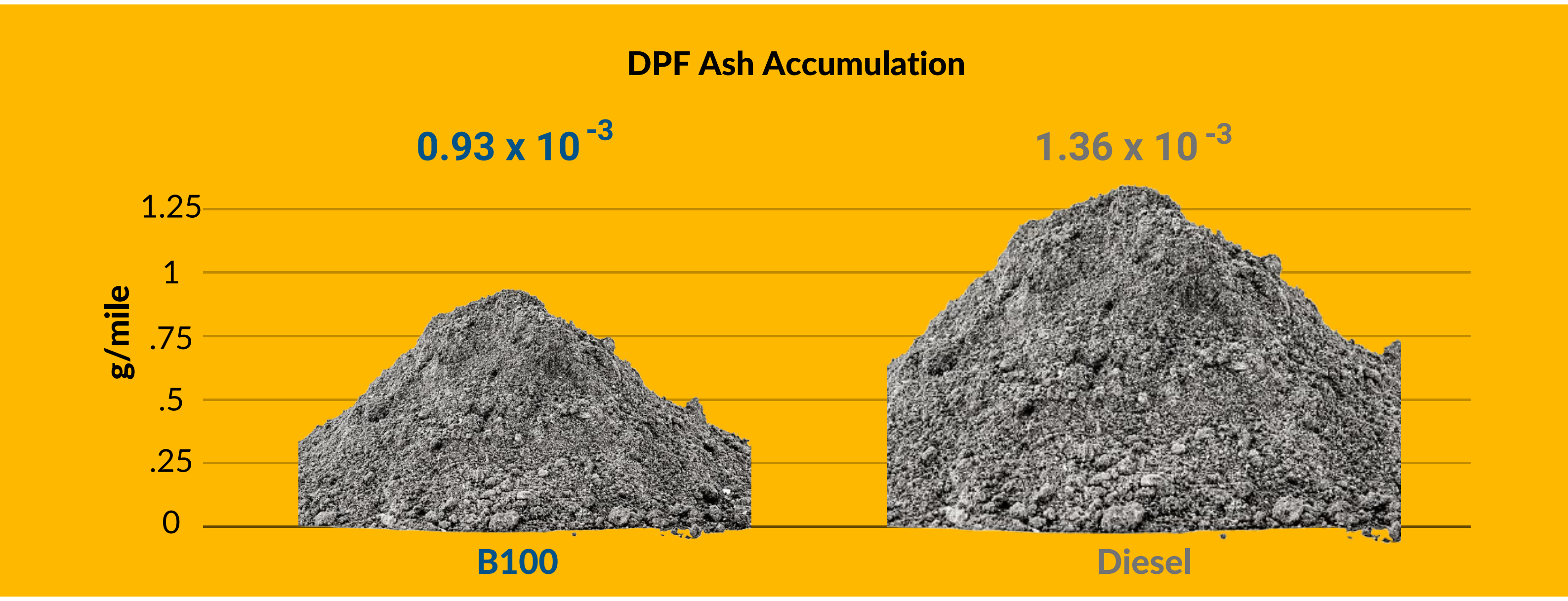



Figure 6 DPF Ash Accumulation (g/mile) Comparison

# IMPACT OF B100 ON DIESEL PARTICULATE FILTERS CONT.

**Additional Parameters Monitored**
Two additional key parameters that were monitored over the course of the project were the accumulated time the engine spent in the “active regeneration” state (when the dosing injector was actively injecting fuel into the exhaust stream to elevate exhaust gases for thermal management) and the time intervals between these active regeneration states (a measure of the rate of soot loading on the DPF which triggers an increase in exhaust backpressure and ultimately engages the active regeneration).[14]

These parameters were tracked by monitoring and recording the engine control module (ECM) signals for the engine’s state via onboard CAN bus signals for J1939 PGN 64892 (the ECM’s signal for diesel particulate filter control).

When comparing the groups, there was an average of 118.8 operating hours between active regeneration events for the base B11 trucks and an average interval of 240.1 operational hours between regeneration events for the Vector System trucks (see Table A.8). The number of active regenerations of the Vector System trucks was over 50% less than those needed for the base B11 case.

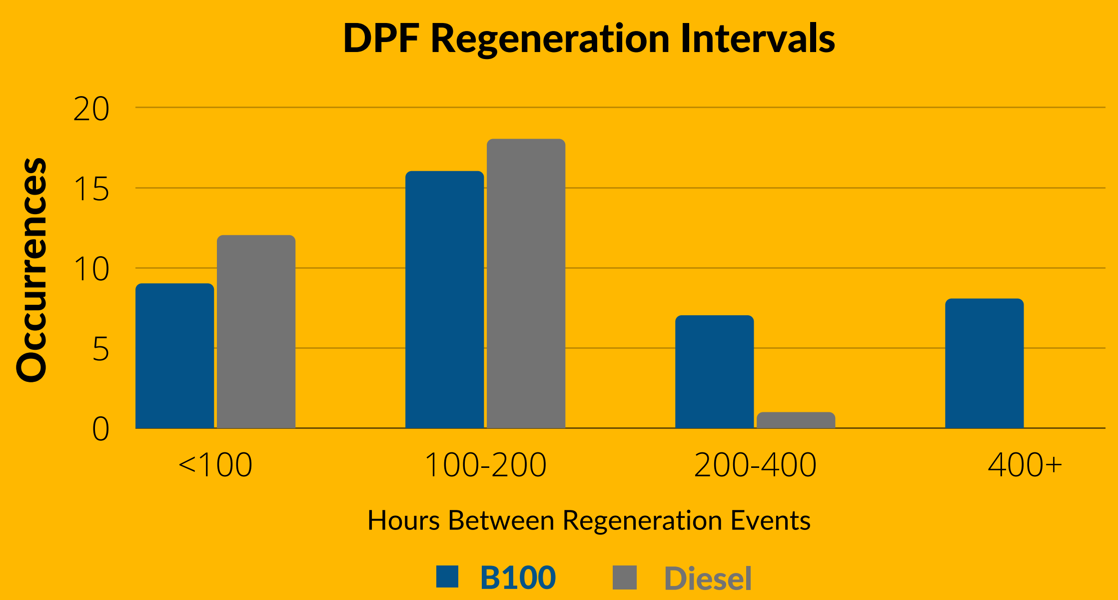



Figure 7 DPF Regeneration Intervals

14. In comparing the time between regeneration events, intervals less than 14 hours were considered part of the same event and not included in the calculation of the mean interval length; this 14-hour threshold was chosen to align with a period of one shift (the maximum daily hours of on-duty time allowable for a driver).

# OIL ANALYSIS

### Spectrographic Engine Oil Analysis

"By far the most popular technique to predict current internal condition and impending failures [of an engine] is spectrographic oil analysis." … "Almost anything happening in the engine will eventually show up in the oil." [15]

One of the objectives of this field trial was to evaluate any differences in engine oil impacts with the use of B100 in the Vector System trucks vs. the base B11 case. Fuel oil dilution in diesel engines typically occurs as a result of a few primary factors including fuel blow-by of the piston rings (commonly occurs prior to ring sealing and due to excessive ring wear), leaking fuel injectors, and incomplete combustion. With the introduction of active DPF regenerations being accomplished through the use of in-cylinder post-injection of fuel on the exhaust stroke (versus a dedicated dosing injector strategy) there has been increased interest in monitoring engine oil dilution as a result of the post-injection strategy; however, the Mack engines used for this test do not utilize in-cylinder post-injection for active DPF regenerations, so any impact due to this factor is minimized for this field trial.

### Vector System Oil Dilution Mitigation Principle

Biodiesel use helps to overcome two of the three primary causes of engine oil dilution, leaking fuel injectors and incomplete combustion, due to the improved cetane rating and oxygenation of the fuel which results in improved combustion and lower particulate matter formation when compared to #2 diesel. The third primary cause is overcome by one of the key operating principles of the Vector System; biodiesel is not injected into the combustion chamber until the engine has stabilized at operating temperature enabling the piston rings to expand, sealing the combustion chamber, and minimizing the opportunity for fuel dilution occurrences from blow-by. By starting the engine on diesel fuel, the Vector System eliminates the cold-start period of the engine's operation most at risk for fuel dilution of biodiesel in the engine oil.

### Oil Change Interval

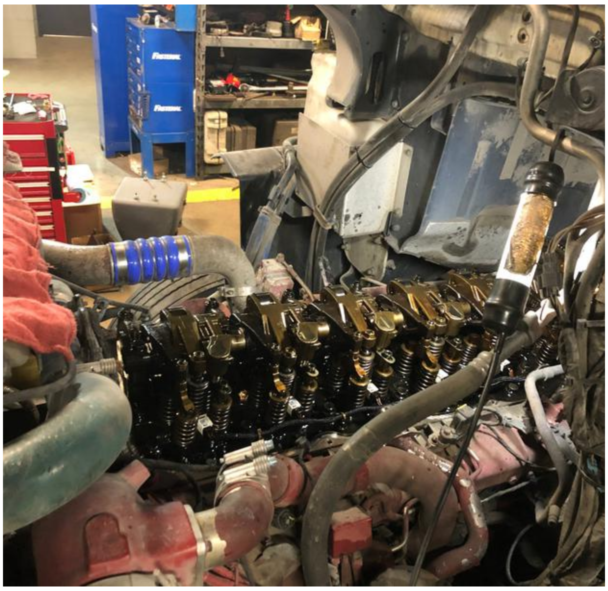
Variance in engine oil quality can be detected through implementation of a rigorous oil analysis and monitoring program. These monitoring activities are beneficial regardless of the fuel type; ADM Trucking performs oil analyses on all trucks within the fleet and has done so from the time each asset was put into service. Over the duration of the test, no changes were made to oil change intervals and routine oil monitoring was in place prior to the beginning of the B100 field trial and remained unchanged throughout the test.

Over the project period there were 21 engine oil samples for the B11 control trucks and 20 samples for the Vector System trucks that were analyzed. The average interval between engine oil changes for the group was approximately 47,400 miles.

15. Levitt, Joel. 2010. Basics of Fleet Maintenance. Reliabilityweb.com.

# OIL ANALYSIS CONT.

The overall analysis showed no negative impacts from the Vector System trucks and, in fact, **statistically significant improvements were found in the Vector System truck samples** for several parameters including the values of oil oxidation and soot/nitration levels.



MP7 Engine with Valve Cover Removed

**Oxidation Levels**

Higher oxidation levels of the lubricating oils can have a negative impact on the wear and tear of the engine and can increase the chances of catastrophic failure. The oxidation values of the oil are presented as a percentage of oxidation, with 100% indicating a completely oxidized oil sample. The oxidation values for the Vector System engine oil samples averaged 43% compared to the baseline B11 engine oil samples which averaged 48% (see Table A.9).


FTC Compliant B100 Biodiesel Dispenser Labeling

The results of this field trial conclude, with statistical significance, that **the oxidation levels of the oil from the engines upgraded with the Vector Systems improved by 5%** compared to the diesel engine oil samples.

# OIL ANALYSIS CONT.

Optimus Technologies Vector System Manifolds


B100 Fuel Sample

**Soot/Nitration Levels:**

A statistically significant reduction in the measured soot/nitration levels of the Vector System engine oil samples were found as compared to the B11 control group. This result is expected as biodiesel is well understood to reduce in cylinder particulate matter (soot) formation during combustion by approximately 58%.[16] The biodiesel utilized in these field trials had an average cetane number of 48 which is 20% higher than 40 as required in the ASTM D975 specification for diesel fuel. It aligns with expectation that the dramatic reduction in soot from biodiesel combustion provides a net benefit via reduction in overall wear and tear on the engine and a lower soot level in the engine crankcase oil. Soot/nitration levels reported indicate the percentage of contamination of the oil; target values are below 1.5%. The B11 samples averaged 1.32% contamination compared to the Vector System samples which averaged 1.21% (see Table A.9).

**Viscosity**

Viscosity is a key indicator of engine oil health and can be a barometer for detection of fuel dilution, oxidation, and other degradation parameters. The viscosity average across all samples was within an acceptable range and had a difference of only 0.02 cSt between the Vector System and B11 control trucks (see Table A.9).

**Fuel Dilution**

Fuel dilution in engine oil can be a concern when operating an engine on biodiesel blends due to biodiesel's higher flashpoint. None of the oil samples from this test showed any detectable level of fuel in the engine oil.

16. Multimedia Working Group. 2015. Review of Multimedia Evaluation of Biodiesel. State of California California Environmental Protection Agency. https://ww2.arb.ca.gov/sites/default/files/2018-08/Biodiesel_Multimedia_Evaluation_5-21-15.pdf.

# MAINTENANCE & OPERATIONAL IMPACTS

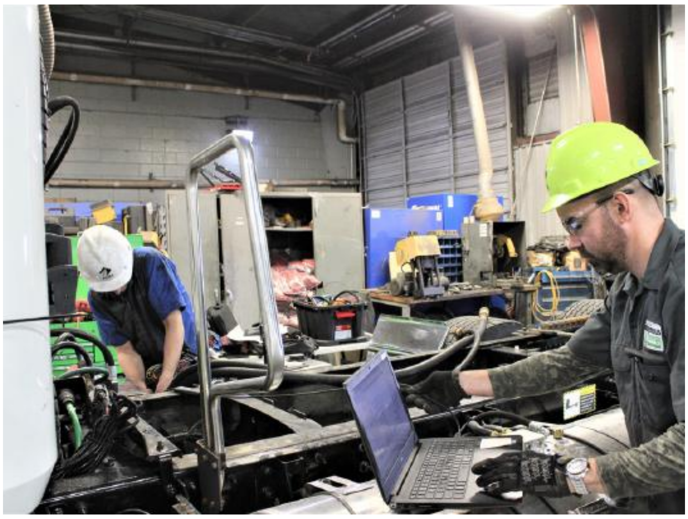
## Fleet Maintenance

"The bulk of the effort in fleet maintenance is to control maintenance costs. These costs are complicated, and changing them (and the activity they represent) can have severe consequences."[17] Trucking operations represent critical activities within a business unit, and any disruptions can have wide-ranging implications. Fleet operations tend to be conservative in their approach toward changes in fundamental operations, such as switching fuels. Although studies have been done on the operational and maintenance impacts of lower biodiesel blends of 20% and below,[18] no data has been publicly reported for use of B100.

## Cost Analysis

This field trial was groundbreaking in yet another aspect, enabling monitoring and tracking of the long-term cost implications the Vector System and the use of B100 has on the maintenance operations of the fleet. Service orders were analyzed across all ten trucks comparing preventative maintenance service, repair, and replacement on all fuel wetted and exhaust or aftertreatment components where fuel composition could possibly affect wear, function, or lifespan. No differences in the cost per mile of maintenance was observed between the two groups.

ADM Trucking reported **no additional truck downtime** as a result of the Optimus Vector System and the use of the 100% biodiesel fuel.



Technicians Installing The Optimus Vector System

17. Levitt, Joel. 2010. Basics of Fleet Maintenance. Reliabilityweb.com.
18. C. R. McKinley, and J. H. Lumkes Jr. 2009. "Quantitative Evaluation of an On-Highway Trucking Fleet to Compare #2ULSD and B20 Fuels and Their Impact on Overall Fleet Performance." Applied Engineering in Agriculture 25 (3): 335–46. https://doi.org/10.13031/2013.26884.

# MAINTENANCE & OPERATIONAL IMPACTS CONT.

**Operational Impact**

Over the course of the project none of the drivers assigned to the Vector System trucks encountered any diminished power or performance of the trucks, nor did they report any experiences of negative impacts on day-to-day operations.

**Driver Feedback**

Upon conclusion of the project, ADM's communications team conducted interviews with each of the six drivers of the Vector System trucks, providing an opportunity for them to share feedback about their participation in the project. Unanimous positive feedback was gathered during these interviews; drivers were incredibly supportive of the project, their ability to participate in helping ADM reduce carbon emissions, the seamless transition that occurred upgrading the trucks with the Vector System, and the transition to B100 without any impact on their day-to-day operations.

Driver Operating B100 Equipped Vehicle


Optimus Technologies SMARTFuel Dispensing Management System Interface

"If you borrowed my truck... you'd never know any difference between the biodiesel and the diesel fuel."
- R. Merriman, ADM Trucking Driver

"As companies look to reduce their carbon footprint, clean fuels like biodiesel and renewable diesel offer an immediate, seamless solution to lower greenhouse gas emissions."
- Donnell Rehagen, CEO of Clean Fuels Alliance America

# PARTNERS

**This field trial was made possible through a wide-ranging collaboration among many partners, immense gratitude is owed for the following organizations for facilitating this project.**

ADM unlocks the power of nature and transform crops into ingredients and solutions for foods, beverages and supplements for people all around the world, and we provide a complete range of solutions and services for livestock, aquaculture and pets.

adm.com

The American Lung Association's mission is to save lives by improving lung health and preventing lung disease. We do this through education, advocacy, and research.

cleanairchoice.org

Clean Fuels serves as the industry's central coordinating entity for technical, environmental, and quality assurance programs and will be the strongest voice for its advocacy, communications, and market development.

cleanfuels.org

Decatur Mack is Mack Truck's multiple award-winning central region dealer of the year, consistently striving for customer service second to none.

decaturmack.com

ESW America is a leading CARB / EPA recognized independent emissions testing facility operating a variety of engine and light & heavy-duty chassis dynamometers. ESWA is focused on diesel OBD validation, manufacturer self-testing, certification and emission control system validation. In addition, ESWA offers accelerated aging of catalysts / DPFs as well as component modification services.

eswgroup.com

The Illinois Soybean Association (ISA) is a statewide organization that strives to enable Illinois soybean producers to be the most knowledgeable and profitable soybean producers in the world. The project is funded by the Illinois Soybean Association Checkoff Program.

ilsoy.org

Mid Continent Testing is built on the commitment to prompt, accurate results by utilizing state-of-the-art equipment in a highly automated lab. MCT provides clients with rapid, reliable data and ensures the integrity of data by actively participating in lab certification programs to keep standards high.

thechemistrylab.com

The Missouri Soybean Merchandising Council is a statewide, farmer-led organization working to improve opportunities for Missouri soybean farmers through a combination of research, outreach, education and market development efforts supported by the soy checkoff.

mosoy.org

Optimus Technologies is a clean energy technology company based in Pittsburgh, Pennsylvania. Optimus manufactures the Vector System, an advanced fuel system technology that enables diesel engines to operate on 100% biodiesel.

optimustec.com

To accomplish its farmer profit mission, the soy checkoff is dedicated to growing the preference for U.S. Soy. Setting market-focused objectives with a clear plan of action is how we get there.

unitedsoybean.org

*None of the partners associated with this report specifically endorse any product, device, or service mentioned in this document.

# APPENDIX

**Table A.1 Truck Data**

| Truck ID # | 4683-B | 4753-B | 4760-B | 4761-B | 4762-B | 4719-D | 4749-D | 4757-D | 4759-D | 4763-D |
|---|---|---|---|---|---|---|---|---|---|---|
| Fuel Type | B100 | B100 | B100 | B100 | B100 | B11 | B11 | B11 | B11 | B11 |
| Model Year | 2014 | 2014 | 2014 | 2014 | 2014 | 2014 | 2014 | 2014 | 2014 | 2014 |
| Manufacturer | Mack | Mack | Mack | Mack | Mack | Mack | Mack | Mack | Mack | Mack |
| Model | CXU613 | CXU613 | CXU613 | CXU613 | CXU613 | CXU613 | CXU613 | CXU613 | CXU613 | CXU613 |
| Engine Model | MP7 | MP7 | MP7 | MP7 | MP7 | MP7 | MP7 | MP7 | MP7 | MP7 |
| Engine Displacement | 10.8L | 10.8L | 10.8L | 10.8L | 10.8L | 10.8L | 10.8L | 10.8L | 10.8L | 10.8L |
| # of Cylinders | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 |
| Horsepower Rating | 335 | 335 | 335 | 335 | 335 | 335 | 335 | 335 | 335 | 335 |
| Transmission | 10 Speed Manual | 10 Speed Manual | 10 Speed Manual | 10 Speed Manual | 10 Speed Manual | 10 Speed Manual | 10 Speed Manual | 10 Speed Manual | 10 Speed Manual | 10 Speed Manual |
| GVW (lbs) | 80,000 | 80,000 | 80,000 | 80,000 | 80,000 | 80,000 | 80,000 | 80,000 | 80,000 | 80,000 |
| Axle Configuration | 6x4 | 6x4 | 6x4 | 6x4 | 6x4 | 6x4 | 6x4 | 6x4 | 6x4 | 6x4 |
| Starting Mileage | 671,208 | 572,390 | 707,967 | 535,841 | 645,849 | 607,878 | 646,220 | 587,216 | 558,614 | 646,499 |
| Ending Mileage | 798,087 | 706,379 | 818,971 | 639,991 | 805,868 | 753,714 | 751,885 | 693,473 | 715,679 | 783,132 |

# APPENDIX CONT.

**Table A.2 Fuel Loads COA - Key Properties**

| ANALYSIS | UNITS | RESULTS | | | | | |
|---|---|---|---|---|---|---|---|
| **Load Number** | Load # | 543222 | 722022 | 847723 | 109373 | 441361 | 737893 |
| **Volume** | Gallons | 6,450 | 6,426 | 6,456 | 6,673 | 6,882 | 6,855 |
| Cetane Number (ASTM D613) | --- | 50 | 48 | 48 | 48 | 48 | 48 |
| Water & Sediment (ASTM D2709) | % Volume | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Water "Karl Fischer" (ASTM D6304) | mg/kg | 207 | 238 | 271 | 335 | 249 | 290 |
| Sulfur (ASTM D5453) | mg/kg | 0.4 | 0.4 | 0.5 | 0.4 | 0.5 | 0.6 |
| Acid Number (ASTM D664) | mgKOH/g | 0.35 | 0.32 | 0.36 | 0.32 | 0.44 | 0.43 |
| Oxidation Stability @110°C (EN14112) | Hours | 8.8 | 7.9 | 6.7 | 8 | 8.8 | 7.8 |
| Calcium & Magnesium (EN14538) | mg/kg | < 1 | < 1 | < 1 | < 1 | < 1 | < 1 |
| Sodium & Potassium (EN14538) | mg/kg | < 1.00 | < 1.00 | < 1.00 | < 1.00 | < 1.00 | < 1.00 |
| Phosphorus (ASTM D4951) | mg/kg | 0.001 | 0.000 | 0.000 | 0.001 | 0.001 | 0.001 |

| ANALYSIS | UNITS | RESULTS | | | | | |
|---|---|---|---|---|---|---|---|
| **Load Number** | Load # | 878118 | 168812 | 454955 | 454956 | 985600 | 242554 |
| **Volume** | Gallons | 3,004 | 6,955 | 6,938 | 6,919 | 6,979 | 6,887 |
| Cetane Number (ASTM D613) | --- | 48 | 48 | 48 | 47 | 47 | 47 |
| Water & Sediment (ASTM D2709) | % Volume | 0.00 | 0.00 | 0.00 | 0.02 | 0.00 | 0.00 |
| Water "Karl Fischer" (ASTM D6304) | mg/kg | 244 | 227 | 219 | 214 | 296 | 293 |
| Sulfur (ASTM D5453) | mg/kg | 0.3 | 0.2 | 0.2 | 0.2 | 0.1 | 0.1 |
| Acid Number (ASTM D664) | mgKOH/g | 0.37 | 0.44 | 0.42 | 0.36 | 0.32 | 0.37 |
| Oxidation Stability @110°C (EN14112) | Hours | 9.4 | 7.4 | 7.1 | 7.5 | 7.7 | 7.2 |
| Calcium & Magnesium (EN14538) | mg/kg | < 1 | < 1 | < 1 | < 1 | < 1 | < 1 |
| Sodium & Potassium (EN14538) | mg/kg | < 1.00 | 1.37 | < 1.00 | < 1.00 | < 1.00 | < 1.00 |
| Phosphorus (ASTM D4951) | mg/kg | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 |

**Table A.3 Fuel Loads COA Weighted Averages (77,424 Gallons)**

| Cetane Number (ASTM D613) | Water & Sediment (ASTM D2709) | Water "Karl Fischer" (ASTM D6304) | Sulfur (ASTM D5453) | Acid Number (ASTM D664) | Oxidation Stability @110°C (EN14112) | Calcium & Magnesium (EN14538) | Sodium & Potassium (EN14538) | Phosphorus (ASTM D4951) |
|---|---|---|---|---|---|---|---|---|
| **48** | **0.00 % Volume** | **258 mg/kg** | **0.3 mg/kg** | **0.38 mgKOH/g** | **7.8 Hours** | **<1 mg/kg** | **<1.00 mg/kg** | **0.001 mg/kg** |

# APPENDIX CONT.

Table A.4 Fuel Economy 16-Month Project Averages

| Truck ID # | Efficiency (MPG) |
|---|---|
| 4719-D | 6.47 |
| 4749-D | 6.49 |
| 4757-D | 5.90 |
| 4759-D | 6.39 |
| 4763-D | 5.97 |
| 4683-B | 6.50 |
| 4753-B | 6.16 |
| 4760-B | 6.64 |
| 4761-B | 6.33 |
| 4762-B | 5.95 |

**Notes: Table A.4 is the average fuel economy per truck over the course of the 16-month project.**

**Table A.5 is the average fuel economy based on the aggregate monthly averages of each fuel type.**

**All fuel economy numbers are based on Samsara fleet telematics data provided by ADM Trucking. Any fuel economy data points reported below 3mpg were omitted as these data points occurred due to the vehicle being out of service or otherwise not utilized during the period.**

Table A.5 Fuel Economy Monthly Averages (MPG)

| Fuel Type | Mar-20 | Apr-20 | May-20 | Jun-20 | Jul-20 | Aug-20 | Sep-20 | Oct-20 |
|---|---|---|---|---|---|---|---|---|
| B11 | 6.04 | 6.05 | 6.30 | 6.47 | 6.82 | 6.36 | 6.77 | 6.24 |
| B100 | 6.13 | 6.07 | 6.30 | 6.78 | 6.87 | 6.89 | 6.69 | 6.39 |

| Fuel Type | Nov-20 | Dec-20 | Jan-21 | Feb-21 | Mar-21 | Apr-21 | May-21 | Jun-21 |
|---|---|---|---|---|---|---|---|---|
| B11 | 6.03 | 5.90 | 5.88 | 5.45 | 5.92 | 6.24 | 6.40 | 6.65 |
| B100 | 5.98 | 6.09 | 5.91 | 5.44 | 6.01 | 6.22 | 6.35 | 6.50 |

# APPENDIX CONT.

**Table A.6 DPF Interval Statistical Analysis**

| DPF Regen Intervals (hours between events) | | |
|---|---|---|
| Fuel Type | B100 | B11 |
| Average | 240.1 | 118.8 |
| P-Value | 0.0044 | |
| Statistical significance based on two sample t-test (assuming unequal variances) CI =0.95 | | |

**Table A.7 DPF Ash Loading and Cleaning Analysis**

| Truck ID # | Fuel Type | Total Project Miles | Pre-Test DPF Mass (kg) | Post-Test DPF Mass (kg) | Ash Accumulation on DPF During Test (g) | Normalized Ash Values (g/mile) | Post-Test DPF Mass After Pneumatic Clean Out (kg) | Ash Removed From Pneumatic Clean Out (g) | % of Accumulated Ash Removed by Pneumatic Clean Out |
|---|---|---|---|---|---|---|---|---|---|
| 4683-B | B100 | 126879 | 17.049 | 17.220 | 171 | $1.35x10^{-03}$ | 17.115 | 105 | 61.4% |
| 4760-B | B100 | 111004 | 17.179 | 17.274 | 95 | $8.56x10^{-04}$ | 17.220 | 54 | 56.8% |
| 4761-B | B100 | 104150 | 17.279 | 17.324 | 45 | $4.32x10^{-04}$ | 17.311 | 13 | 28.9% |
| 4753-B | B100 | 133989 | 17.152 | 17.276 | 124 | $9.25x10^{-04}$ | 17.189 | 87 | 70.2% |
| 4762-B | B100 | 160019 | 17.101 | 17.279 | 178 | $1.11x10^{-03}$ | 17.178 | 101 | 56.7% |
| 4757-D | B11 | 106257 | 17.025 | 17.184 | 159 | $1.50x10^{-03}$ | 17.100 | 84 | 52.8% |
| 4763-D | B11 | 136633 | 17.114 | 17.288 | 174 | $1.27x10^{-03}$ | 17.227 | 61 | 35.1% |
| 4719-D | B11 | 145837 | 17.054 | 17.206 | 152 | $1.04x10^{-03}$ | 17.152 | 54 | 35.5% |
| 4759-D | B11 | 157065 | 17.147 | 17.403 | 256 | $1.63x10^{-03}$ | 17.290 | 113 | 44.1% |

Note: Truck 4749-D experienced a catastrophic DPF failure requiring replacement mid-test, therefore, the data for this truck has been omitted.

**Table A.8 Theoretical Ash Cleanout Improvement Calculations**

| | |
|---|---|
| Mack recommended cleanout interval: | 400,000 mi |
| Normalized baseline (B11) ash accumulation: | 0.00136 g/mi |
| Normalized Vector System (B100) ash accumulation: | 0.00093 g/mi |
| Total extrapolated ash accumulation of baseline (B11) vehicles at 400,000 miles: | 544 g |
| Total miles to achieve 544 g ash loading based on ash accumulation rate of Vector System (B100) equipped trucks: | 584,946 mi |

# APPENDIX CONT.

**Table A.9 Spectrographic Oil Analysis Results**

| | Viscosity (cSt) | | Soot/Nitration | | Oxidation | |
|---|---|---|---|---|---|---|
| Fuel Type | B100 | B11 | B100 | B11 | B100 | B11 |
| Average | 13.84 | 13.82 | 1.21 | 1.32 | 42.70 | 48.10 |
| Variance | 0.673 | 1.036 | 0.023 | 0.028 | 72.747 | 66.490 |
| P-Value | **0.942** | | **0.021** | | **0.045** | |
| | Statistical significance based on two sample t-test (assuming unequal variances) CI = 0.95 | | | | | |