SAND2024-12983R

The Case for Reducing Emissions from Heavy-Duty Off-Road Applications via Ducted Fuel Injection

Kayla Graybill-Justiniano

Date: May-August 2024

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

ABSTRACT

Designers of heavy-duty diesel engines use a variety of techniques to improve efficiency and reduce pollutant emissions. Ducted fuel injection (DFI), high fuel injection pressures, optimized injection orifices, multiple injection sites, and oxygenated fuels are a few techniques used by designers to improve fuel/charge-gas mixtures within the combustion chamber to improve efficiency and emissions results. Ducted fuel injection (DFI) has been proven to substantially reduce soot for low- and mid-load conditions in heavy duty engines, without significantly increasing nitrogen oxides (NO_x). This study investigates the performance of DFI utilizing conventional diesel fuel and the potential the technique has for future research utilizing varieties of test fuels and operating-parameter values. Optimization for high engine efficiency and low emissions will help facilitate DFI deployment for substantial environmental benefits in heavy-duty sectors where electrification and/or carbon-free fuels aren't feasible.

INTRODUCTION

The dramatic industrial growth and technological advancements visible around the world today have depleted fossil fuels and led to significant environmental problems due to climate change. The United States is currently taking action to resolve our current climate crisis and address fossil fuel depletion by instating several strict decarbonization goals in the hopes of curtailing greenhouse gas emissions within the next two decades. One of these goals is to achieve a net-zero emissions economy by 2050 [1]. This aspiration, along with stringent emissions regulations and competition with electric vehicles, has drawn public concern regarding the feasibility and potential cost of achieving this goal. One major concern that calls for attention is the feasibility of reaching this goal with the current technologies available, specifically within the transportation sector. The largest source of greenhouse gas emissions in the United States, the transportation sector, contributed over 28% of U.S. emissions in 2022 [2]. Medium- and heavy-duty vehicles are the second largest source of hazardous emissions within the transportation sector and produce more greenhouse gases than the aircraft, rail, and shipping industries combined [2]. This has spurred a great deal of interest, as researchers test alternative diesel fuels and advanced combustion technologies to be used in diesel engines and search for methods to inform the public of their findings.

The decarbonization of the transportation sector is imperative in achieving emission reduction targets; specifically, reductions are needed from medium- and heavy-duty vehicles, as they contribute to 26% of the total greenhouse gas emissions in the U.S. transportation sector, in 2020 [2]. One proposed solution is the implementation of alternative fuels. Research and development seeks to find fuels that are renewably sourced, reduce life-cycle greenhouse gas emissions, minimize environmental impact, and are cost-effective for the consumer [3]. Biodiesel is a competitive alternative to fossil fuels as it can be used in existing internal combustion engines, either in pure mixtures or in blends with other fuels [4]. Biodiesel derived from palm oil is being investigated due to the similarities in physiochemical properties to petroleum diesel [5]. The chemical composition of biodiesel derived from palm oil results in reductions in carbon monoxide, carbon dioxide, hydrocarbons, and soot emissions, making the biodiesel an incredibly attractive fuel alternative [6]. However, using edible vegetable oils, like palm oil, as a fuel source has its own environmental drawbacks, such as deforestation, soil destruction, and consumption of arable land [7]. The economic feasibility of feedstock usage as a fuel source is also questioned as the use of food crops could potentially cause competition between food and fuel companies [7].

Fuel and engine innovations can improve vehicle performance, fuel economy, and aftertreatment systems for the benefit of emissions reductions. Soot and nitrogen oxides (NO_x) are examples of harmful emissions that need to be reduced but are a problem that cannot be solved easily with alternative fuels [8]. Various aftertreatment systems are currently being researched and developed such as diesel particulate filters and selective catalytic reduction. In addition to aftertreatment approaches, engine modifications can be used to reduce emissions. Ducted fuel injection (DFI) is an example of an engine modification that can help reduce diesel engine-out soot [9]. Such technologies are in demand as they have the potential to improve internal combustion vehicle emissions to within the U.S. emissions regulations without significant cost increases. Furthermore, the implementation of low-lifecycle-CO_2 fuels with technologies such as DFI has been proven to reduce soot and NO_x without compromising engine performance or increasing other emissions. In fact, a study conducted by a project sponsored by the US Department of Energy found that when DFI is used in tandem with oxygenated low-lifecycle-CO_2 fuels, soot and NO_x could simultaneously be reduced by as much as 93% and 82% respectively, relative to conventional diesel combustion [12]. Oxygenated fuels are fuels containing one or more oxygen atoms bonded into one or more chemical species in the fuel. Examples of oxygenated fuels include ethers, esters, and alcohols. Biodiesel derived ethers and esters have some of the greatest percent greenhouse gas reduction due to their sustainable sources. When lifecycle-CO_2 analysis is conducted on renewable diesel in a diesel engine and battery electric vehicles (BEVs), renewable diesels showed significant lifecycle-CO_2 reductions when compared to petroleum diesel, and emissions reductions that are comparable to battery electric vehicles (BEVs) [13].

Educating people on common misconceptions surrounding climate change, lifecycle greenhouse gas emissions, vehicle electrification, and spreading awareness of existing approaches to combat climate change, such as DFI, is necessary to empower people to not only make changes in their own lives but undertake beneficial changes within communities. Programs such as the Climate Change Education for Sustainable Development Programme aim to educate people on the impacts of global climate change and increase "climate literacy" [10]. Such programs and initiatives aim to motivate change through increasing knowledge of the matter rather than using scare tactics. These educational programs emphasize the importance of reducing fear for greater effectiveness in bringing about lasting improvements in society [10].

One commonly misunderstood topic within society is vehicular emissions. Vehicular emissions can be categorized in three ways: a tailpipe basis, a well-to-wheel basis, and a cradle-to-grave basis. Fully electric vehicles do not produce tailpipe emissions as the vehicle itself is not directly powered by fuel combustion. On the other hand, conventional vehicles produce tailpipe emissions through exhaust pollutants, as well as evaporation from the vehicle's fuel system during operation and refueling. Well-to-wheel emissions refer to all emissions related to fuel production, processing, distribution, as well as use. For internal combustion engines, this includes all emissions related to the extraction, refining, distribution to stations, and the combustion of said fuel in vehicles. For electric vehicles on the other hand, well-to-wheel emissions refer to the emissions related to energy production, which includes emissions related to the extraction, processing, and distribution of the primary energy sources used to make electricity.

In total, 60% of the U.S.'s electricity generation is sourced from the combustion of fossil fuels [15]. Thus, each electric vehicle, although producing zero emissions at the tailpipe, still produces significant emissions. The final emissions quantification category is the cradle-to-grave method, which considers all emissions from well-to-wheel, as well as emissions associated with vehicle and powertrain manufacturing, recycling, and disposal. Lifecycle analysis of greenhouse gases takes all three of these methods into consideration and even explores the quantity of greenhouse gases being removed from the carbon cycle through carbon sequestration, planting trees, or displacement credits. Even so, the most common emission analysis is the tailpipe method, meaning the production, fuel sourcing, and disposal emissions are neglected. This method may be the most common, but it does not accurately portray the emissions produced by electric vehicles, since the electricity supplied by the energy sector, which is used to power EVs, is the largest greenhouse gas producing sector in the world.

On top of this there are several applications where electrification or switching to carbon-free fuels simply isn't feasible due to lack of infrastructure, lack of time for recharging, and the additional cost, weight, and volume of the propulsion system relative to current liquid-fueled systems. Examples of this include the heavy-duty transportation, construction, military, agriculture, marine, and railway industries, where propulsion systems powering these vehicles must be powerful enough to propel such large machinery and include energy storage capabilities to accommodate for the long distances these vehicles must travel, two characteristics where electric powertrains face serious challenges. For this reason, new alternative fuels and emissions reduction technologies must be developed and assessed.

1 LITERATURE REVIEW

1.1 AFTERTREATMENT TECHNIQUES

Carbonaceous particulate matter, better known as soot, is a climate forcing species formed during the combustion of carbon-based fuels when insufficient oxygen is present for complete combustion [14]. Even when enough oxygen is present within the combustion chamber, zones where the reactants are not thoroughly mixed can still occur, causing incomplete combustion and soot production [11]. Fuel oxygenation, high injection pressures, and injector orifice configurations are all techniques that have been researched and employed to achieve increased levels of local fuel/charge-gas premixing prior to the autoignition zone [11]. These modifications, while effectively reducing soot emissions, often cause resulting increases in NO_x emissions. This inverse relationship between soot and NO_x is called the "soot/NO_x trade-off."

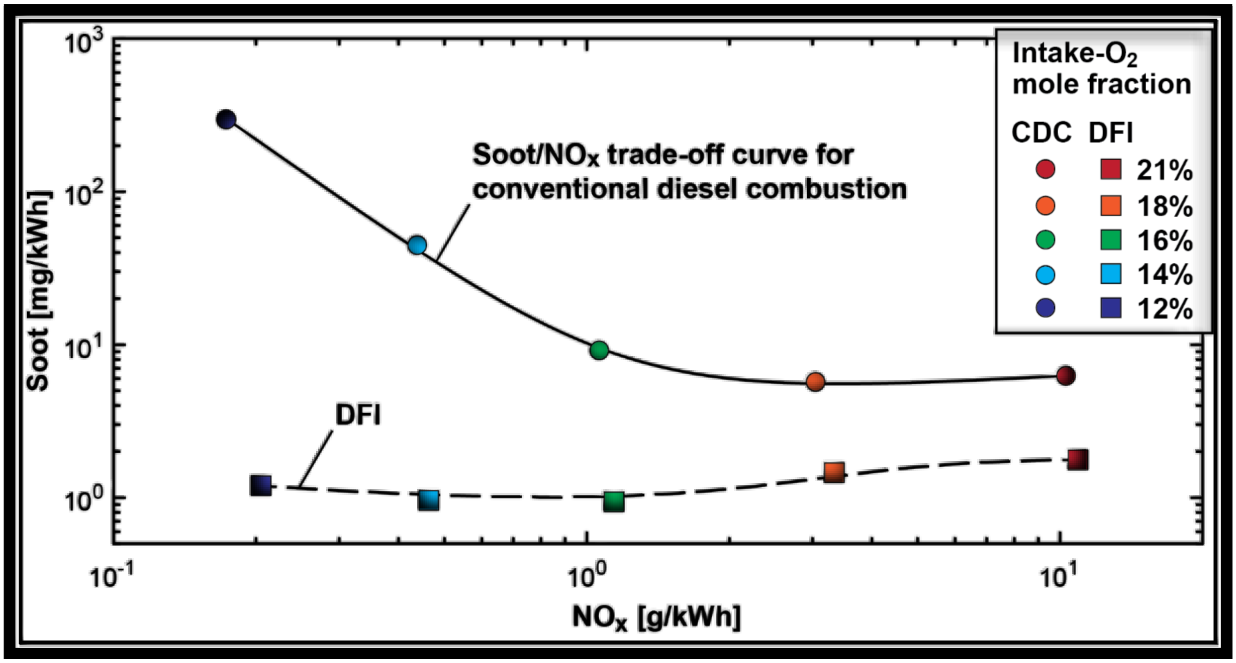

Figure 1. Measured engine-out soot vs. NO_x emissions for conventional diesel combustion (CDC) and DFI. The scales of both axes are logarithmic. For CDC, soot emissions increase dramatically as engine-out NOx emissions are reduced via intake charge gas dilution. In contrast, DFI enables a NO_x reduction of approximately 50X at constant engine-out soot.

NO_x is a general term for NO and NO_2 [17]. NO_x emissions are toxic and are formed during combustion when high temperatures break triple bonds within the nitrogen molecules and react with oxygen, generating thermal NO [17]. Historically the soot/ NO_x trade-off was believed to be an insurmountable drawback to diesel engines, but with DFI, the inverse relationship between the two can be broken, making it possible to reduce the production of soot by several orders of magnitude without increasing NO_x emissions. With soot emissions mitigated by DFI, NO_x emissions can be tackled through cost-effective, established techniques, such as intake charge-gas dilution and selective catalytic reduction.

1.2 DUCTED FUEL INJECTION (DFI) AND ELECTRIFICATION

One proposed solution for meeting emissions standards is the use of DFI with low-lifecycle-CO_2 fuels. DFI refers to the technique of injecting fuel along the axis of a small cylindrical duct within the combustion chamber of a diesel engine to achieve a more-complete mixture of air and fuel prior to autoignition.

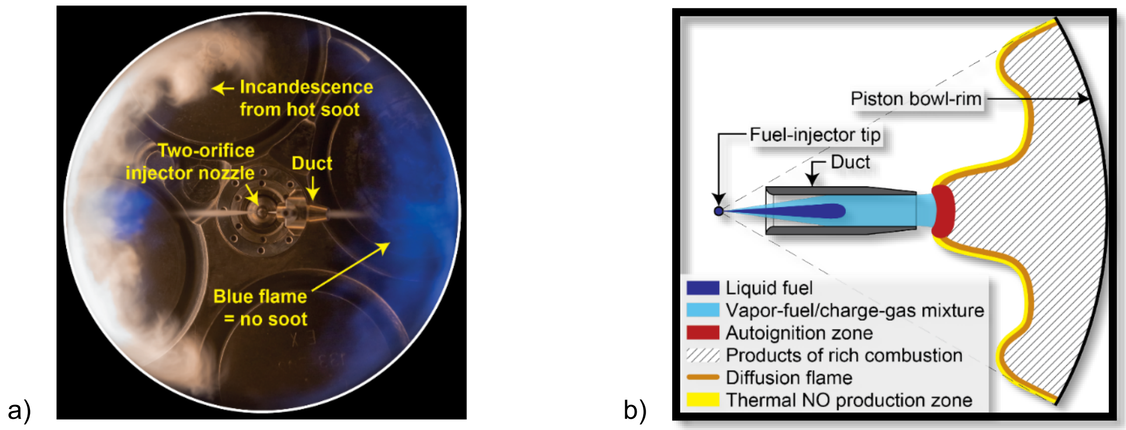

Figure 2. **a) An image showing a conventional diesel combustion spray (on the left) and DFI (on the right). b) A schematic depicting DFI as applied to a single fuel spray in a diesel engine.**

DFI can enable significant reductions in soot, typically 50-90%. These advancements in diesel emissions reduction are revolutionary because they break the rigid soot/ NO_x trade-off. DFI has proven to provide clean, reliable, low-lifecycle-CO_2 power for applications where electrification or the use of carbon-free fuels is currently impractical. DFI can be implemented in any type of diesel engine, and it can be retrofitted for current models on the market. It can also reduce the total cost of owning and operating a diesel vehicle by eliminating expensive aftertreatment requirements, lowering exhaust fluid consumption rates, and extending oil-change intervals. DFI has substantial economic benefits along with the sustainability benefits of using low-lifecycle-CO_2 fuels, providing a viable alternative path to a more sustainable future.

2 RESULTS AND DISCUSSION

2.1 FUELS WITH TESTING POTENTIAL

Emissions reductions are important; however, feasibility, economics, warming potential of the greenhouse gas, and life span of the greenhouse gas are also important factors in choosing alternative fuel sources [16]. Reducing the impacts of medium- and heavy-duty transportation can be achieved through advanced engine technologies combined with low-lifecycle-CO_2 fuels. DFI is currently being tested in tandem with such emission reducing technologies and fuels to reduce emissions, with the goal of enabling diesel propulsion systems to provide environmental and economic benefits in sectors where electrification and/or the use of carbon-free fuels are not currently viable.

Table 1 **Renewable and biodiesel fuels with appealing lifecycle greenhouse gas reductions and potential for future testing with DFI.**

Fuel Name	Percent GHG Reduction Compared to Petroleum Diesel
Fatty Alkyl Esters	57–75%
Alkoxyalkanoates (Derived from Lactate Esters)	65%
Soybean	42-67%**
Canola	40% to 69%
Carinata	40% to 69%
Oilseed	63-77%
Used cooking oil UCO	79-86%
Distillers' corn oil DCO	79-86%
Tallow	79-86%
Waste feedstocks	63-77%
Vegetable oil RD	67.30%
BEVs	60-68%

2.2 EDUCATIONAL VIDEO

A significant fraction of the effort during this internship was the production of an informational video. The objective of this video is to educate people regarding common misconceptions surrounding climate change, lifecycle greenhouse gas emissions, vehicle electrification, and alternative approaches to emissions reduction, specifically DFI. Educational videos are one of the most effective strategies to reach many different people, of all ages, quickly and cheaply. Please see the SULI final presentation for this project for an overview of the content of the video.

3 CONCLUSION AND AREAS FOR FUTURE RESEARCH

Much remains to be learned about how different fuel types and operating conditions affect DFI performance, such as efficiency, torque, and emissions. Future research utilizing varieties of test fuels and operating-parameter values, and optimizing for high engine efficiency and low emissions will help facilitate DFI deployment for substantial environmental benefits in heavy-duty sectors where electrification and/or carbon-free fuels aren't feasible.

ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy, Office of Science, Office of Workforce Development for Teachers and Scientists (WDTS) under the Science Undergraduate Laboratory Internships Program (SULI) and in part by Cooperative Research and Development Agreement #2043. The work was conducted at Sandia National Laboratories' Combustion Research Facility in Livermore, California. The author would like to thank Dr. Chuck Mueller of Sandia's Applied Combustion Research Department for his help and suggestions.

APPENDIX A. REFERENCES

[1]
https://www.whitehouse.gov/climate/#:~:text=Reducing%20U.S.%20greenhouse%20gas%20emissions,clean%20energy%20to%20disadvantaged%20communities
[2] https://www.epa.gov/greenvehicles/fast-facts-transportation-greenhouse-gas-emissions
[3] https://www.mdpi.com/2076-3417/10/3/907
[4] https://www.sciencedirect.com/science/article/pii/S001623611400492X?via%3Dihub
[5] https://www.mdpi.com/1996-1073/11/8/2132
[6] https://www.sciencedirect.com/science/article/pii/S1364032113000300
[7] https://www.sciencedirect.com/science/article/pii/S1364032116301459
[8] https://saemobilus.sae.org/papers/development-oxidation-catalyst-diesel-engine-940240#view
[9] https://pubs.rsc.org/en/content/articlelanding/2023/se/d3se00381g
[10] https://www.un.org/en/climatechange/climate-solutions/education-key-addressing-climate-change
[11] https://agupubs.onlinelibrary.wiley.com/doi/10.1002/jgrd.50171
[12] https://www.sciencedirect.com/science/article/pii/S0016236122039916#b0200
[13] https://truckingresearch.org/2024/04/renewable-diesel-a-catalyst-for-decarbonization/
[14] https://www.sciencedirect.com/science/article/pii/S0306261917308644?via%3Dihub
[15] https://www.eia.gov/tools/faqs/faq.php?id=427&t=3
[16] https://scied.ucar.edu/learning-zone/how-climate-works/some-greenhouse-gases-are-stronger-others#:~:text=Compared%20with%20carbon%20dioxide%2C%20sulfur,28%20times%20as%20much%20warming.
[17] https://www.sciencedirect.com/science/article/pii/S1364032112005874