Laser-based in-exhaust gas sensor for on-road vehicles

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Abstract

A novel laser-absorption gas sensing apparatus capable of measuring NO directly within vehicle exhaust was developed and tested. The sensor design was enabled by key advances in the construction of optical probes that are sufficiently compact for deployment in real-world exhaust systems and can survive the harsh, high-temperature, and strongly vibrating environment typical of exhaust streams. Prototype test campaigns were conducted at high-temperature flow facilities intended to simulate exhaust gas conditions and within the exhaust of vehicles mounted on a chassis dynamometer. Results from these tests demonstrated that the sensor prototype is fundamentally free of cross-interference with competing species in the exhaust stream, can achieve a 1 ppmv NO detection limit, and can be operated across the full range of thermodynamic conditions expected for typical vehicle exhausts. These features address the key technological drawbacks associated with electrochemical NO_x sensors widely used in current aftertreatment systems while enabling an on-board diagnostic capable of determining NO_x output at the tailpipe at a level of accuracy comparable to laboratory-grade instrumentation. Broadly, this novel sensor provides high-quality emissions data needed to help vehicle manufacturers develop powertrains and aftertreatment systems that meet future, more stringent emissions regulations.

Introduction

Modern vehicles are typically equipped with sophisticated exhaust aftertreatment devices needed to mitigate the release of harmful nitrogen oxides (NO and NO_2, collectively referred to as NO_x), particulate matter, unburned hydrocarbons, and carbon monoxide into the atmosphere. For diesel powertrains, a typical aftertreatment system includes an oxidation catalyst followed by a particulate filter and a SCR for NO_x abatement [1]. Typical SCR control schemes require accurate knowledge of the upstream and downstream NO_x concentrations to inject the optimal amount of DEF. This knowledge is typically provided by electrochemical NO_x sensors embedded within the exhaust flow. There are, however, several key drawbacks associated with these existing sensors, including:

(1) NO_x specificity: current electrochemical sensors are sensitive to competing species in the exhaust stream. Most notably, current sensors exhibit a high cross-sensitivity with ammonia (NH_3)[2], the key reactant species formed during pyrolysis of DEF in the SCR. Since these sensors cannot distinguish between NH_3 and NO_x, the measured signals cannot typically be used directly for post-SCR feedback-control of DEF dosing.

(2) Cold-start/low-load operability: these sensors suffer from significant thermal and moisture cutoffs that render them inactive during the periods of high NO_x emissions at engine cold start and low loads. As a result, DEF dosers must rely on imprecise lookup-table based feedforward controllers during cold-start.

(3) Measurement sensitivity: studies conducted by the Southwest Research Institute [2] indicate that current electrochemical sensors operate with minimum detection limits on the order of 10 ppmv NO_x. This sensitivity may be insufficient for meeting Ultra-low NO_x regulations.

There is a growing need to install advanced NO_x sensors that address the aforementioned issues in order for next-generation diesel aftertreatment systems to meet the increasingly stringent NO_x emissions requirements set to be enforced starting in MY 2024 [3]. Additionally, there is a growing push to simplify the OBD suite needed to accurately diagnose the health of aftertreatment components. For example, in the OBD-REAL program [4], aftertreatment systems can employ a sensor that can accurately compute the tailpipe NO_x output from vehicles, which may allow automotive OEMs to eliminate certain complicated and costly OBD systems along with validation tests needed to verify aftertreatment system health. Such a sensor must deliver the performance of laboratory-grade Fourier Transform Infrared (FTIR) and Chemiluminescence detector (CLD) instruments while also continuing to meet the stringent reliability, durability, form-factor, and cost requirements currently met by on-board sensors. It may be added that a class of portable-grade emissions sensors based on these technologies are commercially available under the name "Portable Emissions Monitoring System (PEMS)"[5–7]. However, such devices are extractive sample-based and not suitable for high-volume manufacturing, and are also much larger in size/cost/weight, and therefore impractical for on-board monitoring for on-road vehicles.

This paper describes Indrio Technologies Inc.'s recent efforts to develop the Ignis line of advanced in-exhaust NO_x sensors that are fundamentally immune to the aforementioned drawbacks. The sensor is based on a novel application of narrowband LAS, a widely used technique capable of achieving high species sensitivities and specificity across a wide range of operating temperatures, pressures, and sensing environments [8]. The sensor design is enabled by recent developments in materials that allow for sensitive optical components to survive in harsh, high-temperature, and particulate-laden exhaust flows [9]. Testing of a proof-of-concept prototype at Indrio flow facilities and on a chassis dynamometer demonstrated NO measurement accuracy and detection limits similar to the co-located FTIR and CLD results.

The remainder of this paper is organized as follows: (1) a high-level description of the initial proof-of-concept prototype constructed to de-risk key uncertainties associated with the LAS-based architecture is provided, (2) results from preliminary testing performed at Indrio and at VERL are described, and finally, (3) a high-level description of work currently being undertaken for the sensor to reach a mature technological readiness is provided.

Sensor prototype design

LAS is the underlying physical principle of the sensor technology for measuring concentrations of NO_x in engine exhaust streams. The Ignis prototype detailed in this paper was designed for detecting NO only since it is typically the majority component of total NO_x in diesel exhaust and, consequently, is a priority for automotive OEMs. In LAS, radiation from monochromatic laser is transmitted through the exhaust stream and collected with photodetectors to measure the wavelength-specific light absorption. The absorption fraction is related to fundamental properties associated with the molecules present in the absorbing medium, number density of the molecules, and other fixed geometric parameters. Through accurate knowledge of these fundamental properties, the molecular concentration of the target species can be inferred from these photodetector signals.

Selecting appropriate laser wavelengths and absorption transitions for detection is critical to the performance of any LAS sensor. Key criteria for optimal wavelength selection include strong absorption by the target species and minimal spectral interference from other exhaust species within the design range of thermodynamic conditions. The NO absorption spectrum was thoroughly inspected together with the spectrum of other major infrared-active exhaust species (namely H_2O, CO_2, CO, NO_2, and NH_3) at typical diesel engine operating conditions to search for an absorption transition that minimizes spectral interference with these competing species and has sufficient absorption strength to enable sensitive detection within the confined geometries of an exhaust system. The details of this spectroscopic search are withheld from disclosure, but a suitable absorption transition was identified that allows for (1) NO-specific detection, (2) compatibility with the entire expected thermodynamic operating envelope (especially during cold-start/low-load operations) expected within vehicle exhaust, and (3) highly sensitive detection owing to its strong absorption cross-section. These features address the key technical issues associated with existing electrochemical sensors and demonstrate that LAS may be a viable technological path for next-generation exhaust system diagnostics.

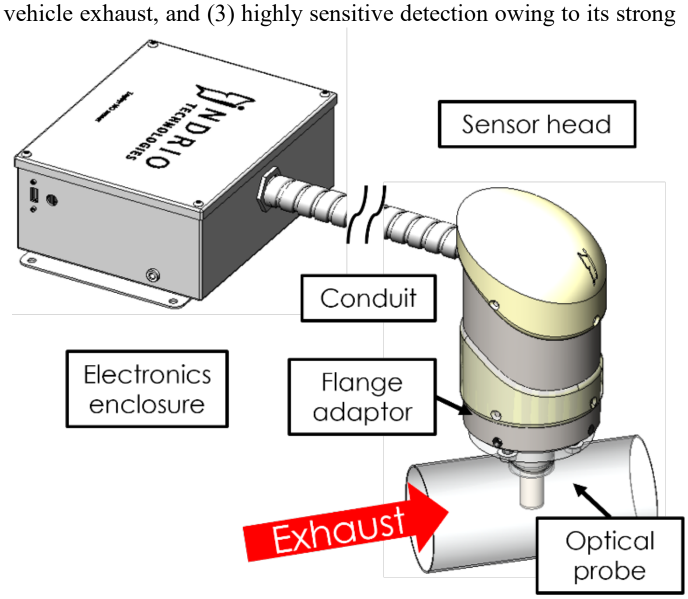

Figure 1. Schematic of the sensor apparatus with key elements labelled

With key spectroscopic details known, the design constraints for the Ignis exhaust NO sensor prototype may be discussed. Based on the absorption spectrum of the selected wavelength range used for NO detection, optical path lengths need to be on the order of 1 meter to enable detection of NO at single ppmv levels while also remaining sensitive to peak NO concentrations approaching 2000 ppmv at engine-out. Given that the inner diameter of typical exhaust pipe assemblies rarely exceeds ~10 cm, the absorption path must be amplified using mirror-based multi-pass optical cells in order for the sensor to fit within the compact sensor form-factor requirements needed for on-board diagnostics. However, commercially available mirrors and mirror coatings are generally rated for operation at temperatures less than 250°C, far lower than the peak temperatures approaching 600°C in diesel engine exhaust. Given that the transmissive performance of an optical cavity is strongly impacted by reductions in mirror reflectivity, significant degradation of mirror reflectivity at high temperature is unacceptable. Indrio's patented mirror coating architecture is designed to survive these previously inaccessible engine exhaust environments [9] and enables, for the first time, a compact long-path optical probe capable of surviving exhaust-relevant conditions.

Figure 1 shows a high-level rendering of the Ignis NO sensor prototype. A sensor head containing lasers, optics, supporting optomechanics, a high-temperature optical probe, and a photodetector is connected to a vehicle exhaust pipe via a flange adaptor. Cables needed to control and collect signals from these components are routed to an electronics enclosure via a flexible conduit. The electronics enclosure consists of power supplies, various controllers, a data acquisition system, and a microcomputer needed to control, collect, and process data gathered by the sensor head. This arrangement allows for sensitive electronics to be isolated from the optical probe, which is directly exposed to the exhaust.

It should be noted that the current electronics enclosure and sensor head assemblies occupy significantly more space than existing electrochemical sensors and is therefore not yet suitable for integration with vehicle exhaust systems. This is largely due to the extensive use of commercial off-the-shelf components and electronics and the need for adjustability and serviceability during testing operations. The optical probe, however, is already compliant with the form-factor requirements for current exhaust systems. It is anticipated that, with further maturation of the electronics and photonics packaging, the Ignis sensor will approach a form-factor similar to existing electrochemical sensors.

Test results

The Ignis in-exhaust NO sensor prototype was tested in both an Indrio-operated high-temperature flow facility and while installed at the tailpipe of a vehicle in a dynamometer test cell. The results from these testing operations are described in the following sections.

Flow facility testing

The Ignis prototype was installed on the high-temperature flow facility depicted in Figure 2(a) that can heat inlet flows up to 900°C. Gas bottles containing certified mixtures of NO, CO_2, N_2, and air are mixed at various flow rates using calibrated flow controllers to produce gas mixtures similar in composition to what is expected in engine exhaust. A separate constant-temperature flow humidifier is used to add known quantities of water vapor of up to 20% by volume into the flow to simulate the water content in exhaust streams. The sensor head mounts directly onto the flange adjacent to the tube furnace, which exposes the optical probe to the high-temperature gases, thus allowing for in-laboratory characterization and validation of the sensor prototype across a wide range of temperatures with well-known gas compositions and NO concentrations.

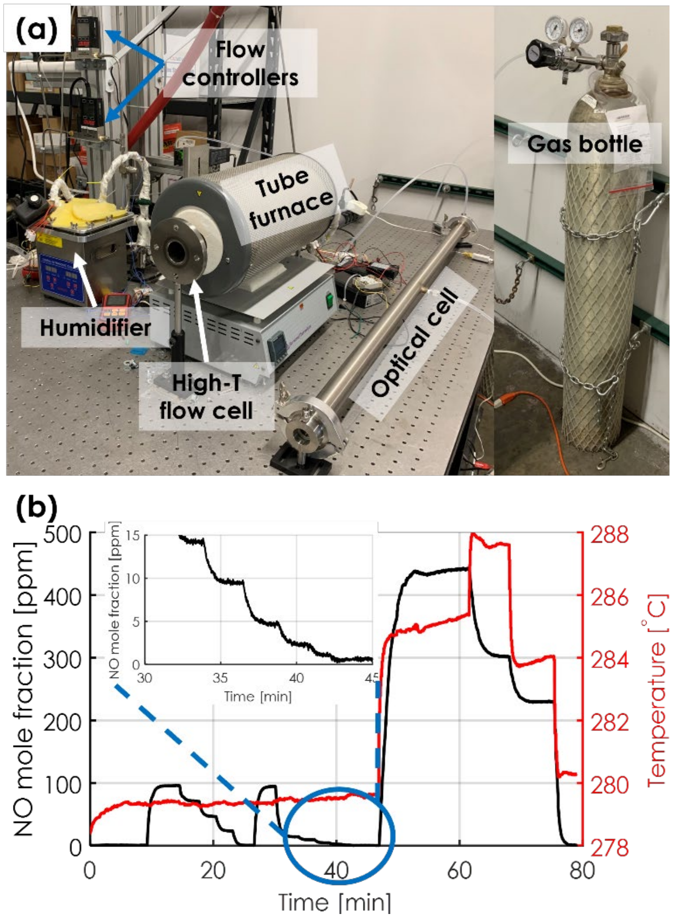

Figure 2. (a) Photograph of the Indrio-operated high-temperature flow facility used to simulate engine exhaust flows and temperature. (b) Sample data collected with the full assembly at flow temperatures near 280˚C with H_2O and CO_2 content approaching maximum values expected from diesel engines. NO measurements match expected values based on flow rates to within 4% across the full range of concentrations shown here.

Measurements of NO were conducted at various temperatures up to 300˚C. A sample data set collected with flow temperatures near 280˚C is shown in Figure 2(b). CO_2 and H_2O mole fractions were maintained at 7.28% and 8.99%, respectively throughout this measurement set. NO measurements at each flow setting matched expected values to within 4% across the full range of concentrations shown here and subsequent repeat test runs. The figure inset shows sensor measurements at low NO concentrations below 15 ppm, with a minimum detection limit of 1 ppmv NO and a noise floor averaging at 0.5 ppmv. These performance figures are superior to state-of-the-art electrochemical NO_x sensors and demonstrate that the prototype sensor can achieve sensitivity levels needed for next-generation on-board NO_x sensors.

On-vehicle testing at VERL

An on-vehicle test campaign was completed at Ford Motor Company's Vehicle Emissions Research Laboratory (VERL) in Dearborn, Michigan. A photograph of the prototype Ignis sensor integrated onto the exhaust of an 8-cylinder diesel test vehicle is shown in Fig. 3. A co-located electrochemical NO_x sensor and a sampling boom leading to a laboratory-grade FTIR emissions analyzer and a CLD NO_x analyzer provided reference data for comparison against the Indrio prototype results. FTIR NO_x measurements matched CLD measurements to a high degree of accuracy throughout all tests; therefore, CLD measurements are omitted from the graphs presented in this section for clarity.

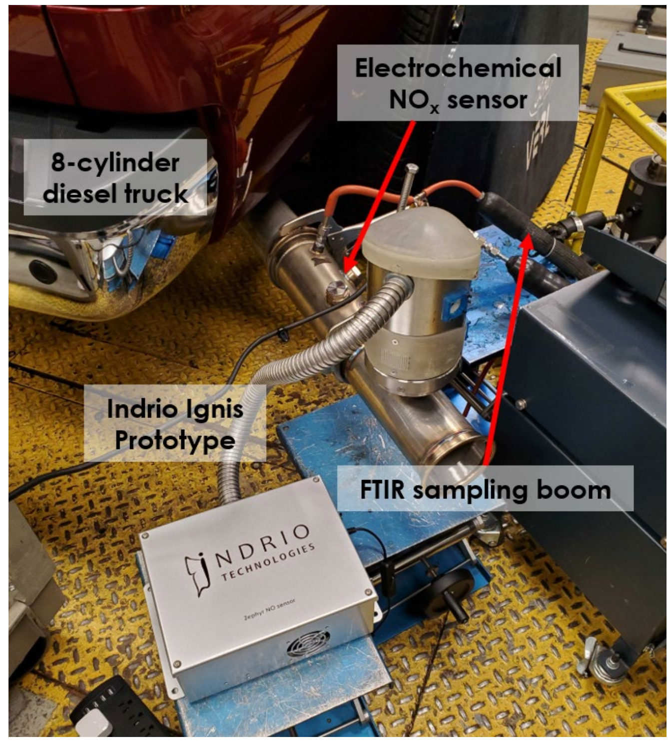

Figure 3. Photograph of the Indrio NO sensor prototype mounted on the exhaust pipe of a diesel test vehicle attached to a dynamometer.

Figure 4(a) shows a sample set of data collected from a standard FTP drive cycle representing a mixture of highway and suburban driving. It should be noted that the characteristic time-constants from all three sensor datasets are different. Ignis, with its longer time-constant due to slower gas diffusion through the optical probe, generally measures smaller NO concentration peaks and larger concentration troughs than the FTIR or electrochemical sensors. Nevertheless, the time-integrated NO concentration (which is expected to be invariant across all sensors) during the high-NO_x cold start period between 0 and 250 seconds was measured to be 16766 ppm-s for the Indrio prototype, which is comparable to the 16708 ppm-s and 16955 ppm-s measured with the electrochemical and FTIR sensors, respectively. Figure 4(b) zooms in on the low-NO_x operating periods between 750 and 1000 seconds. As can be seen, Ignis was able to clearly resolve the small 5 ppm bursts of NO near 855, 930, and 950 seconds whereas the electrochemical sensor was unable to distinguish those features from background noise. This demonstrated the laser sensor's ability to resolve NO features previously unresolvable with existing on-board electrochemical NO_x sensors. It should also be noted that even though the electrochemical sensors were comparable in the time-integrated NO_x measurements over the selected period, inaccuracies (e.g., zero offset) can accumulate

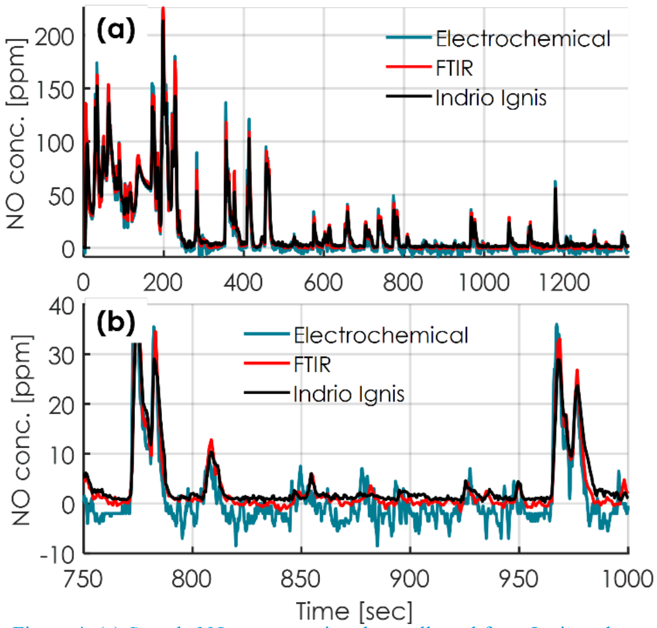

Figure 4. (a) Sample NO concentration data collected from Ignis and co-located FTIR and electrochemical sensors. (b) Zoomed view of the low-NO_x operating conditions between 750 and 1000 seconds after the start of the diesel vehicle test.

over longer periods of time, challenging its robustness for the OBD-REAL program [4].

It is worth noting that the exhaust output of the diesel vehicle did not contain significant amounts of ammonia or NO_2 because the diesel oxidation catalyst was likely designed to output NO:NO_2 ratios greater than one. Therefore, all the injected DEF and NO_2 entering the SCR catalyst was consumed prior to exiting the vehicle. As a result, there was, in general, good agreement between Ignis, electrochemical NO_x, and FTIR NO/CLD NO_x measurements across all diesel test cycles. For gasoline vehicles, however, the three-way catalyst can sometimes over-reduce NO_x to produce ammonia during sub-optimal operations. Figure 5 shows a gasoline vehicle test (4-cylinder PFI engine) demonstrating this effect, with FTIR measurements of NH_3 and NO shown in orange and green, respectively, and measurements from the electrochemical NO_x and Ignis NO sensors shown in blue and black, respectively. As can be seen, the electrochemical NO_x sensors are unable to distinguish the NO_x in the gasoline exhaust from the NH_3 content, which is a significant shortcoming that limits the utility of electrochemical sensors as a control signal for SCR dosing control systems. The Ignis measurements, on the other hand, fundamentally does not suffer from cross-interference with other species in the combustion stream and accurately tracks the true NO content in the exhaust as measured by the FTIR.

Heat-induced thermal expansion inevitably caused some misalignment between the laser, optical cell, and the detector. For standard LAS measurement methods that require a-priori knowledge of the non-absorbing laser intensity, these alignment changes would normally result in unacceptably high noise in the measured species concentrations. Fortunately, the 1*f*-normalization scheme employed in the WMS technique used in Ignis was able to correct for these bulk laser intensity changes during engine operation [10,11]. Even when close to 50% of the initial laser intensity was lost to temperature-induced misalignment during an aggressive highway drive cycle as seen in Figure 6(b), the measured NO concentrations never deviated from the FTIR measurements as seen in Figure 6(a). Across more than six hours of on-engine testing involving 7 heating/cooling cycles and

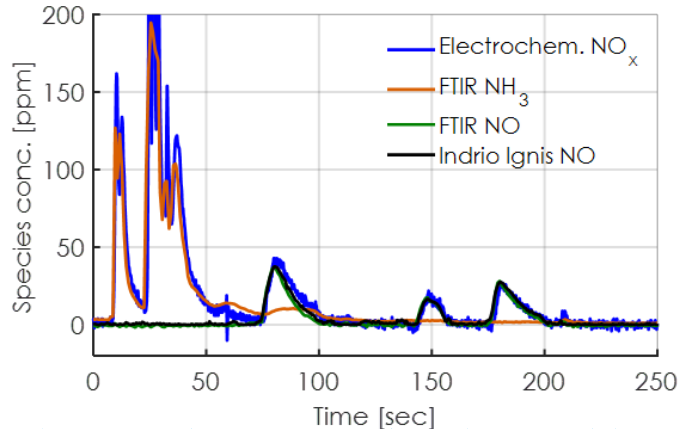

Figure 5. NO and NH_3 measurements from various sensors during a gasoline vehicle test.

exhaust temperatures periodically exceeding 300°C, Indrio did not observe overall reductions in the laser intensity collected by the photodetector (upon restoring alignment after cooling), demonstrating the durability of the optical cell across multiple hours of engine operations. It should also be noted that, during some of the diesel test cycles, a fraction of the exhaust gas was intentionally bypassed around the diesel particulate filter, thus exposing the Ignis prototype to high levels of particulate matter (~3mg/mi) content during portions of the test campaign. Despite this, no significant impact on the measured laser intensity was observed, although it remains to be seen how well the optical cell would perform over multiple months of operation.

Summary/Conclusions

The development, validation, and initial demonstration of a novel sensor for measuring NO concentration directly within the exhaust stream of vehicles was presented. The sensor is based on the principles of laser-absorption spectroscopy and is fundamentally immune to key technical issues associated with existing on-board electrochemical NO_x sensors. The use of LAS was enabled by key advances in the construction of optical probes that can survive the harsh, high-temperature, strongly vibrating, and particle-laden exhaust environment. Prototype tests performed on a high-temperature flow facility and on vehicle exhaust streams demonstrated that the sensor was (1) fundamentally free of cross-interference with key exhaust species (especially NH_3), (2) can be operated across a wide range of expected vehicle operating conditions, including cold-start/low-load, and (3) demonstrated detection limits of less than 1 ppmv and accuracy that matched the results from co-located FTIR and CLD instruments.

Significant efforts are currently underway to mature the LAS sensing platform to a point where it may be deployed in production vehicle aftertreatment systems. Among these developments include the miniaturization of the electronics and optomechanical packaging to a form-factor and level of robustness suitable for on-road sensing. Custom software will support these developments to provide a seamless sensing platform that can serve as a near drop-in replacement option for existing electrochemical sensors. In addition to these efforts, Indrio is investigating the detection of NO_2 and NH_3 in the exhaust stream, including methods for co-packaging the sensor so that multiple species may be detected using a single sensor apparatus. Broadly, the in-exhaust sensors should enable higher-quality OBD data for vehicle emissions that will help automotive OEMs improve aftertreatment system performance and achieve future model year vehicle emission targets.

References

1. Yuan, X., Liu, H., and Gao, Y., "Diesel Engine SCR Control: Current Development and Future Challenges," *Emiss. Control Sci. Technol.* 1(2):121–133, 2015, doi:10.1007/s40825-015-0013-z.

2. Premnath, V. and Khalek, I.A., "Laboratory Investigation Of Exhaust NOx/NH3 Sensors using bench testing," 2021.

3. Miller, E., "CARB Ahead of EPA in Bid to Establish NOx Rule for Heavy Trucks," 2020.

4. Caesar, K., "CARB gets 'REAL' to further cut pollution from diesel and gas vehicles," 2018.

5. Vojtisek-Lom, M. and Allsop, J.E., "Development of heavy-duty diesel portable, on-board mass exhaust emissions monitoring system with NOx, CO2 and qualitative PM capabilities," *SAE Tech. Pap.* (724), 2001, doi:10.4271/2001-01-3641.

6. Durbin, T., "Portable Emissions Measurement Systems that Can be Used for Emissions Inventory Development and Implementation of the Heavy-duty Diesel Engine," *Calif. Air Resour. Board*, 2008.

7. Kousoulidou, M., Fontaras, G., Ntziachristos, L., Bonnel, P., Samaras, Z., and Dilara, P., "Use of portable emissions measurement system (PEMS) for the development and validation of passenger car emission factors," *Atmos. Environ.* 64(x):329–338, 2013, doi:10.1016/j.atmosenv.2012.09.062.

8. Goldenstein, C.S., Spearrin, R.M., Jeffries, J.B., and Hanson, R.K., "Infrared laser-absorption sensing for combustion flows," *Prog. Energy Combust. Sci.* 60:132–176, 2016, doi:10.1016/j.pecs.2016.12.002.

9. Sur, R., "Laser-based in-situ exhaust gas sensor," PCT/US2020/013255, United States, 2020.

10. Rieker, G.B., Jeffries, J.B., and Hanson, R.K., "Calibration-free wavelength-modulation spectroscopy for measurements of gas temperature and concentration in harsh environments.," *Appl. Opt.* 48(29):5546–60, 2009, doi:10.1364/AO.48.005546.

11. Peng, W.Y., "Single-Ended Laser-Based Diagnostics for Thermometry and Speciation in Detonation-Driven Combustors," Stanford University, 2019.

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Acknowledgments

This work is supported by the National Science Foundation under Small Business Innovation Research grant number 2036398 and monitored by Benaiah Schrag. The authors would like to thank VERL for providing comparison measurements on a chassis dynamometer.

Definitions/Abbreviations

SCR	Selective catalytic reduction
DEF	Diesel exhaust fluid
OBD	On-board diagnostics
OEM	Original equipment manufacturer
FTIR	Fourier-transform infrared
CLD	Chemiluminescence detector
LAS	Laser-absorption spectroscopy
VERL	Vehicle Emissions Research Laboratory (Ford Motor Company)
WMS	Wavelength-modulation spectroscopy