





Emissions Challenge SESAM-FTIR Emissions Data Summary

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1 Abstract

The recent introduction of bio-fuels and the development of new exhaust after-treatment catalyst technologies for both on-road and off-road vehicles have resulted in additional challenges for engine and vehicle manufacturers when measuring vehicle exhaust. These new fuels and technologies often carry with them the potential for producing previously non-regulated components that are no less toxic or hazardous to the environment. Some of these non-regulated components include ammonia (NH₃), nitrous oxide (N₂O), isocyanic acid (HNCO), hydrogen cyanide (HCN), alcohols, and aldehydes. As a result, it has become increasingly necessary for manufacturers and regulatory agencies to have a way to measure not only the exhaust components currently regulated, but these other emissions components as well.

An emissions measurement system that integrates an FTIR analyzer is one tool that provides manufacturers and regulatory agencies the capability to measure many of the non-regulated components of interest. AVL manufactures such a system, the SESAM-FTIR emissions bench, which incorporates an FTIR analyzer in a system designed to measure raw exhaust. This system is also capable of having integrated additional analyzers to provide a complete emissions measurement system that can measure regulated emissions components, in addition to the non-regulated emissions of interest. AVL also brings over 15 years of industry experience providing an FTIR analyzer system that is used world wide for the research and development of engines and engine systems.

2 Introduction

2.1 FTIR Analyzer

The following is a brief description of Fourier Transform Infrared spectroscopy and its application for quantitative measurement of exhaust gas components from internal combustion engines.

2.1.1 Measuring Principal

Using a Fourier transform instrument to measure all wavelengths at once, a beam of infrared light is passed through the sample, and the amount of energy absorbed at each wavelength is recorded. From this, an absorbance spectrum may be plotted which shows at which wavelengths the sample absorbs the IR light. The spectrum allows an interpretation of which bonds are present, and, consequently, which compounds are present in the sample.

Additional information on the background and theory of FTIR measurement can be found in the following publications:

Brian C. Smith (1995). *Fundamentals of Fourier Transform Infrared Spectroscopy*. CRC. ISBN: 0-8493-2461-0. ISBN-13: 978-0-8493-2461-1

Peter Griffiths and James A. De Haseth (2007). *Fourier Transform Infrared Spectrometry*, 2nd Edition. Wiley. ISBN: 978-0-471-19404-0



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2.1.2 Calibration and Quantitative Analysis

The calibration procedure for each component measured by the FTIR analyzer in the SESAM emissions bench is the same. A known concentration of a component is actively supplied to the FTIR and a sample spectra is collected for a range of concentrations. These calibration spectra, or reference spectra, are stored on the system and used by the FTIR software when determining the concentration of a component in a sample.

For each data point collected for a sample, the FTIR software uses the calibration spectra for configured components of interest to solve a series of matrix equations that compare the combinations of the calibration spectra to the actual sample spectrum. In conjunction with additional mathematical corrections for factors such as actual sample pressure, temperature, baseline shift, and others the FTIR software calculates the quantitative concentrations of the various species measured.

2.1.3 Advantages of FTIR Multi-Component Analysis

The broad spectrum analysis of the FTIR analyzer provides several advantages in the research and development of new engine and exhaust after-treatment technologies. The wide range of species that can be quantitatively measured using an FTIR analyzer allows for a fuller understanding of combustion chemistry, exhaust catalyst chemistry, alternative fuel use, and the by-products of the introduction of these technologies.

The primary impetus for the introduction of these technologies is the improvement of fuel economy and the reduction of regulated exhaust emissions. While these improvements are the primary drive toward developing and optimizing the technology, regulatory agencies such as the Environmental Protection Agency and California Air Resources Board explicitly state that any technology used to reduce regulated emissions must not increase non-regulated emissions that are recognized as detrimental to human health or the environment. Some of these non-regulated components include nitrogen dioxide (NO₂), nitrous oxide (N₂O), ammonia (NH₃), and aldehydes. A significant advantage of the FTIR analyzer is its ability to measure these, and other, components to provide guidance to developers when determining the full impact of a new technology, as well as to the regulatory agencies when determining if they should set limits for these components.

The FTIR analyzer is also capable of measuring speciated hydrocarbons, which can be instrumental in determining optimum catalyst formulation and loading for various exhaust after-treatment catalysts. Oxidation catalysts used to reduce hydrocarbon and carbon monoxide emissions can have significantly different reaction rates for different hydrocarbons. Being able to measure which hydrocarbons are present in an exhaust stream can provide critical input for selecting catalyst formulations and loadings. It is also possible to have nitrous oxide (N_2O) production from these catalysts, which can also be a factor in choosing an after-treatment technology. The same can be said for reduction catalysts used to mitigate emissions of the oxides of nitrogen (NO and NO_2).

2.1.4 Traditional Emissions Measurement Requirements – FTIR Limitations

One of the regulatory requirements of emission measurements is the measurement of Total Hydrocarbon (THC) emissions. This emission value has traditionally been measured using a Flame Ionization Detector (FID) analyzer, which is assumed to measure all hydrocarbons in the exhaust sample and reports that concentration on a 1-carbon (C1) or 3-carbon (C3) basis. In contrast, an FTIR analyzer actually measures individual hydrocarbons and reports each concentration separately. It is possible to mathematically sum the speciated hydrocarbons



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reported by an FTIR analyzer to produce a value similar to that reported by a FID analyzer, but it is impractical to configure an FTIR analyzer to generate a THC value equivalent to that measured by a FID.

Two primary factors that prevent a FID equivalent THC concentration from being reported by an FTIR analyzer are knowledge of exactly which hydrocarbons are present in the exhaust and a lack of understanding of the response factors for all hydrocarbons measured by a FID. In order for an FTIR analyzer to be able to report a FID equivalent THC concentration, the FTIR would have to be configured to measure for all hydrocarbon species present in the sample. This would require either previous knowledge of exactly which hydrocarbons are present in the sample, or to have the FTIR configured to measure a large enough set of hydrocarbons to ensure all those present in the sample are included in the measurement. In addition, it is known that not all hydrocarbons have the same response factor when measured by a FID analyzer. Since a FID analyzer is calibrated using propane only, it would be necessary to know the response factors for each hydrocarbon being measured by the FTIR in order to use the FTIR measurements to generate a FID equivalent concentration. A full catalog of FID response factors for hydrocarbons is not currently available in order to properly account for this phenomenon.

Traditionally, emissions measurement systems have measured the oxygen content of the exhaust. The measurement technology used in these systems is a paramagnetic detector (PMD) analyzer. Due to the atomic structure of oxygen, it is not possible to measure oxygen with an FTIR analyzer.

To accommodate the need to measure a FID equivalent THC concentration and an oxygen concentration, AVL can integrate a FID analyzer and PMD analyzer in the SESAM-FTIR emissions bench. By doing so, the SESAM-FTIR system can provide all of the same measurement capability of a traditional emissions bench while providing the added benefit of multi-component analysis with an FTIR analyzer.

3 Testing Setup

An AMA-i60 emissions bench was provided for measuring raw exhaust from the snowmobile. The bench contained the traditional analyzers used for measuring internal combustion engine exhaust, which include a FID analyzer for total hydrocarbons (THC), NDIR analyzers for both CO_2 and CO, a CLD analyzer for NOx, and a PMD analyzer for O_2 . The AMA-i60 emissions bench was connected to a ¹/₄" outer diameter stainless steel probe supplied by the participating teams. The final results of the emissions challenge were calculated using the emissions values as measured by the AMA-i60.

A SESAM-FTIR emissions bench with only an FTIR analyzer was provided as a secondary measurement tool for this year's competition. The emissions concentrations measured by the SESAM-FTIR system were not used in the calculation of final results for the emissions challenge. The SESAM-FTIR emissions bench was setup with a 3/8" outer diameter stainless steel, open end tube sample probe. The probe was inserted into the snowmobile tail pipe as far as possible without interfering with any exhaust components installed on the snowmobile. This probe set up is not optimum for ensuring accurate, consistent sampling of the exhaust.

The potential problems associated with the probe setup used include dilution of the exhaust by room air and inconsistent mixing of the exhaust being sampled (whether diluted or not). It





was acknowledged that these problems would likely exist with a varying degree during the emissions challenge, but a more ideal probe configuration was not attempted to avoid interfering with the official results testing for the emissions challenge.

4 Discussion

4.1 Comparison of SESAM-FTIR to Traditional Emissions Bench

4.1.1 Analyzer Calibration and Calibration Check

The standard accepted procedure for preparing a traditional emissions bench for exhaust measurement includes a check of the calibration linearity of each of the analyzers (known as a linearization check). A linearization check of the AMA-i60 emissions bench analyzers was performed prior to the emissions challenge. For those components common to both the SESAM-FTIR system and the AMA-i60 system – CO, CO₂, and NOx – a similar calibration check was done for the FTIR analyzer. The results of these calibration checks demonstrate that both systems are well calibrated.

Figure 1 shows the linearization check for CO_2 . The AMA-i60 analyzer had a curve error of 0.001%. The FTIR analyzer had a curve error of 1.062%.

Figures 2, 3, and 4 show the linearization checks for CO. The AMA-i60 low range analyzer (Figure 2) had a curve error of 0.006%. The FTIR analyzer, for the same concentration range (Figure 2), had a curve error of 0.110%. The AMA-i60 high range 1 analyzer (Figure 3) had a curve error of -0.233%. The FTIR analyzer, for the same concentration range (Figure 3), had a curve error of -1.434%. The AMA-i60 high range 2 analyzer (Figure 4) had a curve error of 0.473%. The FTIR analyzer, for the same concentration range (Figure 4).

Figure 5 shows the linearization check for NOx. The AMA-i60 analyzer had a curve error of 0.050%. The FTIR analyzer had a curve error of -0.034%.







Figure 1: CO₂ Linearization Check Results; AMA-i60 CO₂ and SESAM-FTIR CO₂



CO Lin Check Plot SESAM-FTIR and AMA-i60 NDIR COL R4

Figure 2: CO Linearization Check Results; AMA-i60 CO Low Range 1 and SESAM-FTIR CO







Figure 3: CO Linearization Check Results; AMA-i60 CO High Range 1 and SESAM-FTIR CO



CO Lin Check Plot SESAM-FTIR and AMA-i60 NDIR COH R4

Figure 4: CO Linearization Check Results; AMA-i60 CO High Range 2 and SESAM-FTIR CO







NOX Lin Check Plot SESAM-FTIR and AMA-i60 CLD

Figure 5: NOx Linearization Check Results; AMA-i60 NOx and SESAM-FTIR NOx

4.1.2 Raw Exhaust Measurement Comparison

The limitations of the sample probe setup used for the SESAM-FTIR during the emissions challenge testing introduces an unknown number of uncertainties in the absolute concentration values reported by the SESAM-FTIR. As a result, a direct comparison of the AMA-i60 raw emissions data and SESAM-FTIR raw emissions data will not be done for this report.

Comparisons that are presented below will include a calculation of the Emissions Challenge E-Score for each team. For the calculation of the E-Score from the SESAM-FTIR system, the CO_2 , CO, and NOx concentrations as measured by the FTIR were used in the calculations, but the THC concentrations used for the calculations were from the AMA-i60 FID analyzer. Reasons for this can be found in the previous section discussing THC measurement above (i.e. the SESAM-FTIR bench can have the same analyzer incorporated in the system and produce the same result).

Also presented here will be time plots of the raw emissions data for CO_2 , CO, and NOx from both the AMA-i60 system and the SESAM-FTIR system. These plots demonstrate that both systems experienced similar changes in the raw exhaust at roughly the same time scale.

To further support the position that the FTIR analyzer is capable of measuring accurate, comparable results to that of traditional emissions analyzers, this report provides engine out exhaust emissions measurements from comparison tests performed by AVL customers, in conjunction with AVL. AVL is not at liberty to disclose the names of the customers at whose facilities the tests were done or the exact details of the engines used for the testing.





4.1.2.1 E-Score Comparison

Of the 8 snowmobiles that competed in the emissions challenge, the emissions scores for 6 of the snowmobiles as calculated from the FTIR emissions data were within $\pm 2\%$ of the scores calculated from the AMA-i60 emissions data (see Figure 6). Using the SESAM-FTIR results, the final ranking of the teams for the emissions challenge would have remained the same.



E-Score Comparison

Figure 6: E-Score Comparison Plot

4.1.2.2 Time-Line Plots of Raw Emissions

The following figures compare the real-time plots of the AMA-i60 emissions data and the SESAM-FTIR emissions data for CO_2 , CO, and NOx. It should be noted that the scan rate for the AMA-i60 analyzers was configured at 10Hz, while the scan rate of the FTIR analyzer was configured at 1Hz. The slower scan rate of the FTIR analyzer is why the SESAM-FTIR time plots look more "stepped" than the AMA-i60 time plots. It is possible to configure the FTIR analyzer in the SESAM-FTIR bench to scan at 5Hz. Also, small differences in the time-alignment of the data or the total measurement times for the two systems are likely do to the way that a start of measurement was indicated during the event. A start of measurement was indicated by a "thumbs up" signal from one of the judges when it was deemed that a sled had reached stable operation for a given mode.

The results displayed here are all from one sled that competed in the emissions challenge. The plots demonstrate that both emissions systems experienced the same relative change in component concentration at similar times throughout the data collection period.

Figures 7 through 11 display the dry CO_2 emissions for each of the 5 modes. Figures 12 through 16 display the dry CO emissions for each of the 5 modes. Figures 17 through 21 display the wet NOx emissions for each of the 5 modes.





Figure 7: Mode 1 CO₂ Emissions Plot

Mode 2 CO2 Dry



Figure 8: Mode 2 CO₂ Emissions Plot







Figure 10: Mode 4 CO₂ Emissions Plot





Figure 11: Mode 5 CO₂ Emissions Plot



Figure 12: Mode 1 CO Emissions Plot





Figure 13: Mode 2 CO Emissions Plot

400

Mode 3 CO Dry

00:00.0 00:10.0 00:20.0 00:30.0 00:40.0 00:50.0 01:00.0 01:10.0 01:20.0 01:30.0 01:40.0 01:50.0 Elapsed_Time



Figure 14: Mode 3 CO Emissions Plot





00:00.0 00:10.0 00:20.0 00:30.0 00:40.0 00:50.0 01:00.0 01:10.0 01:20.0 01:30.0 01:40.0 01:50.0 02:00.0 Elapsed_Time

6.0 5.5 5.0 4.5 4.0 3.5 3.0



SESAM NOX Wet [ppm]

60 55 50





Figure 17: Mode 1 NOx Emissions Plot

Mode 2 NOX Wet



Figure 18: Mode 2 NOx Emissions Plot





Figure 19: Mode 3 NOx Emissions Plot

Elapsed_Time

Figure 20: Mode 4 NOx Emissions Plot

Figure 21: Mode 5 NOx Emissions Plot

4.1.2.3 Diesel Internal Combustion Engine Results

The data represented in Figure 22 through Figure 25 was collected on a Diesel internal combustion engine. Engine out raw exhaust was collected for seven different steady-state engine conditions using a SESAM-FTIR emissions bench with only an FTIR analyzer and a traditional emissions bench sampling from the same relative location in the exhaust train. The probe for the SESAM-FTIR was placed approximately 1 foot down stream of the probe for the traditional emissions bench.

The data shows excellent agreement between the FTIR analyzer measurements for CO_2 , CO, NO and NOx, and the corresponding analyzer measurements on the traditional emissions bench.

Figure 22 shows the correlation of the CO_2 emissions measurements (on a dry basis), with a maximum difference of -1.20%.

Figure 23 shows the correlation of the CO emissions measurements (on a dry basis), with a maximum difference of 1.87%.

Figure 24 shows the correlation of the NOx emissions measurements (on a dry basis), with a maximum difference of -2.28%.

Figure 25 shows the correlation of the NO emissions measurements (on a dry basis), with a maximum difference of 3.77%.

CO2 Engine Out SESAM FTIR to Bench NDIR Comparison

Figure 22: CO₂ Engine Out Raw Emissions – Diesel Engine

CO Engine Out SESAM FTIR to Bench NDIR Comparison

Figure 23: CO Engine Out Raw Emissions – Diesel Engine

NOx Engine Out SESAM FTIR to Bench CLD Comparison

Figure 24: NOx Engine Out Raw Emissions – Diesel Engine

NO Engine Out SESAM FTIR to Bench CLD Comparison

Figure 25: NO Engine Out Raw Emissions – Diesel Engine

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4.1.2.4 Gasoline Internal Combustion Engine Results

The data represented in Figure 26 through Figure 30 was collected on a Gasoline internal combustion engine. Engine out raw exhaust was collected for seven different steady-state engine conditions using two SESAM-FTIR emissions benches which included integrated PMD O_2 and FID THC analyzers in addition to an FTIR analyzer, and two traditional emissions benches sampling from the same relative location in the exhaust train. The probes for the SESAM-FTIR benches were placed approximately 1 foot apart in the exhaust train. One of the probes for the traditional emissions bench was approximately 2 feet upstream of the SESAM-FTIR probes, with the second probe approximately 3 feet further upstream.

The data shows excellent agreement between the FTIR analyzer measurements for CO_2 , CO and NOx, and the corresponding analyzer measurements on the traditional emissions bench. In addition, there is excellent agreement between the integrated FID and PMD analyzers on the SESAM-FTIR and their counterparts on the traditional emissions benches. The agreement of the FID and PMD analyzers demonstrates the ability of the SESAM-FTIR system to have these analyzers seamlessly integrated with the FTIR without adversely affecting their performance.

Figure 26 shows the correlation of the CO_2 emissions measurements (on a dry basis), with a maximum difference of -5.17%.

Figure 27 shows the correlation of the CO emissions measurements (on a dry basis), with a maximum difference of 1.37%.

Figure 28 shows the correlation of the NOx emissions measurements (on a dry basis), with a maximum difference of 4.01%.

Figure 29 shows the correlation of the O_2 emissions measurements (on a dry basis as measured by a PMD analyzer in both systems), with a maximum difference of 1.65%.

Figure 30 shows the correlation of the THC emissions measurements (on a wet basis as measured by a FID analyzer in both systems), with a maximum difference of -3.34%.

16.000 14.000 12.000 CO2 Concentration (% Dry) 10.000 SESAM FTIR 1 SESAM FTIR 2 8.000 Bench NDIR 1 Bench NDIR 2 6.000 4.000 2.000 0.000 0.56% -5.17% -1.32% -1.23% -1.61% -1.71% -1.29% Average Percent Difference SESAM FTIR to Bench NDIR

CO2 Engine Out SESAM FTIR to Bench NDIR Comparison

Figure 26: CO2 Engine Out Raw Emissions – Gasoline Engine

CO Engine Out SESAM FTIR to Bench NDIR Comparison

Figure 27: CO Engine Out Raw Emissions – Gasoline Engine

NOX Engine Out SESAM FTIR to Bench CLD Comparison

Figure 28: NOx Engine Out Raw Emissions – Gasoline Engine

O2 Engine Out SESAM PMD to Bench PMD Comparison

Figure 29: O₂ Engine Out Raw Emissions – Gasoline Engine

THC Engine Out SESAM FID to Bench FID Comparison

4.2 Non-Regulated Exhaust Component Measurement with FTIR

One of the primary advantages that an FTIR analyzer brings to exhaust gas measurement is its ability to measure a multitude of non-regulated exhaust components that are still of interest to the regulatory agencies. These additional components include ammonia (NH₃), nitrous oxide (N₂O), alcohols, and aldehydes. With the recent advent of "bio-fuels" – ethanol blended gasoline, ethanol blended diesel, biodiesel, etc. – these particular components have become a point of interest and focus for the regulatory agencies. In addition, there are other components that regulatory agencies may become interested in if significant emissions of these are seen as well. Among these are isocyanic acid (HNCO) and hydrogen cyanide (HCN). The SESAM-FTIR system gives development teams the ability to measure these components modally to help evaluate everything from engine calibration adjustments to exhaust catalysts for emissions abatement.

Figures 31 - 35 show non-regulated emissions for the 5 modes from all snowmobiles that competed in the emissions challenge.

Figure 30: THC Engine Out Raw Emissions – Gasoline Engine

Figure 31: Mode 1 Non-Regulated Emissions

Figure 32: Mode 2 Non-Regulated Emissions

Figure 33: Mode 3 Non-Regulated Emissions

Figure 34: Mode 4 Non-Regulated Emissions

Figure 35: Mode 5 Non-Regulated Emissions

4.3 SESAM-FTIR Raw Emissions Data – Full Data Sets

Below are tables of the average raw emissions (wet concentrations) for each component measured with the SESAM-FTIR, for each mode of the emissions challenge, and each team that competed in the emissions challenge.

Mode 1 Data 1 able										
		1-Clarkson	2-ldaho	4-MTU	5-Madison	7-Kettering	8-ETS	9-Maine	14-Buffalo	
H2O	[ppm]	121452.69	97823.06	119247.67	135101.04	129022.39	77152.79	127080.44	81542.97	
CO2	[ppm]	95845.06	65468.84	91282.16	122839.60	108536.73	42375.79	84680.80	72926.11	
CO	[ppm]	32353.15	39000.74	38555.64	1921.60	232.32	59203.18	52167.69	23307.04	
NO	[ppm]	321.07	279.99	139.07	27.32	2610.10	4.12	622.28	187.78	
NO2	[ppm]	0.00	118.88	0.02	0.00	11.57	16.26	0.18	0.23	
NOX	[ppm]	321.07	398.86	139.09	27.32	2621.66	0.00	622.47	188.02	
NH3	[ppm]	422.55	12.86	537.63	50.49	15.18	18.15	52.65	110.14	
N2O	[ppm]	0.00	0.00	0.00	0.06	3.16	0.05	0.00	0.00	
HCN	[ppm]	5.31	10.64	7.39	0.03	0.20	6.13	23.27		
HNCO	[ppm]	12.06	42.43	10.94	1.47	3.74	0.00	7.21		
CH4	[ppm]	181.50	450.76	260.42	8.66	13.30	0.36	463.06	183.21	
C2H2	[ppm]	11.10	97.89	3.67	2.04	1.70	167.90	77.09	8.86	
C2H4	[ppm]	43.75	1053.22	189.67	0.59	14.48	183.31	328.33	7.66	
C2H6	[ppm]	5.97	86.76	13.43	2.12	2.32	0.88	26.13	0.56	
C3H6	[ppm]	1.27	736.86	33.79	0.00	0.00	117.32	87.88	1.68	
C3H8	[ppm]	0.00	0.00	1.59	0.00	0.00	0.92	6.08		
C4H6	[ppm]	18.22	58.42	26.81	4.68	1.57	7.15	18.85	3.81	
C4H8	[ppm]	6.01	473.07	15.66	0.68	-0.24	71.20	36.84		
NC5	[ppm]	1.21	906.76	3.51	0.00	3.25	7.48	16.60		
AHC	[ppm]	9.77	911.16	27.24	0.00	0.05	0.00	73.47	0.00	
ETOH	[ppm]	12.44	1442.07	15.60	5.52	2.00	5030.87	32.14		
HCHO	[ppm]	2.30	1056.27	0.91	0.31	5.85	185.31	49.61	6.43	
MECHO	[ppm]	1.04	856.69	2.94	0.00	0.01	638.77	32.37	0.00	
SO2	[ppm]	1.46	22.04	0.00	0.69	0.27	106.67	3.10	33.73	

Mode 1 Data Table

CSC SESAM-FTIR Emissions Challenge Data . 1. 1

Mode 2 Data Table									
		1-Clarkson	2-ldaho	4-MTU	5-Madison	7-Kettering	8-ETS	9-Maine	14-Buffalo
H2O	[ppm]	118865.19	105581.86	118230.64	125755.62	126862.17	72997.80	128028.19	50611.97
CO2	[ppm]	116357.03	76785.96	105263.66	125213.52	118529.36	37531.75	123131.85	59171.39
CO	[ppm]	594.64	35185.56	20786.39	785.65	3196.27	61985.99	3062.73	14.31
NO	[ppm]	841.40	38.78	13.76	6.97	345.61	2.12	421.34	370.94
NO2	[ppm]	0.00	166.14	0.00	0.00	0.06	7.08	0.00	200.09
NOX	[ppm]	841.40	204.91	13.76	6.97	345.67	0.00	421.34	571.03
NH3	[ppm]	5.58	7.77	299.99	29.77	60.13	18.97	10.91	0.42
N2O	[ppm]	1.45	0.00	0.00	0.15	1.00	0.03	1.39	1.10
HCN	[ppm]	0.85	4.48	0.16	0.01	0.19	8.06	4.17	
HNCO	[ppm]	1.77	1.17	6.89	0.88	1.70	0.00	0.83	
CH4	[ppm]	1.43	209.21	110.46	14.33	50.45	0.36	17.47	1.04
C2H2	[ppm]	1.23	84.08	1.64	1.88	0.79	367.98	3.19	0.64
C2H4	[ppm]	0.73	264.18	28.82	0.62	11.24	199.07	5.45	0.28
C2H6	[ppm]	1.44	46.58	2.02	2.24	5.73	0.88	1.88	0.28
C3H6	[ppm]	0.00	147.57	0.28	0.00	0.83	89.57	0.08	0.42
C3H8	[ppm]	0.00	0.00	0.03	0.00	0.00	0.92	0.00	
C4H6	[ppm]	0.98	11.54	11.10	3.02	3.34	5.53	1.49	3.00
C4H8	[ppm]	0.20	129.06	2.65	0.78	1.68	44.34	0.27	
NC5	[ppm]	0.70	1892.26	0.06	0.00	0.82	7.48	1.19	
AHC	[ppm]	0.00	866.24	0.13	0.00	0.10	0.00	0.00	0.03
ETOH	[ppm]	2.70	1686.82	10.81	4.87	6.15	5316.86	4.60	
HCHO	[ppm]	1.25	195.89	0.26	0.12	1.09	139.84	2.26	1.92
MECHO	[ppm]	0.07	362.43	0.05	0.00	0.07	642.55	0.03	0.00
SO2	[ppm]	3.33	0.00	0.02	0.01	0.35	114.40	0.08	1.54

Mode 3 Data Table

		1-Clarkson	2-Idaho	4-MTU	5-Madison	7-Kettering	8-ETS	9-Maine	14-Buffalo
H2O	[ppm]	118655.79	112448.15	119459.47	124993.45	125402.41	64004.68	125103.05	43256.26
CO2	[ppm]	116554.05	99173.60	112636.85	125279.29	86659.89	34138.89	111308.79	49481.62
CO	[ppm]	213.15	13718.46	10470.10	496.24	38842.34	52208.88	18985.64	8.72
NO	[ppm]	1079.91	63.69	5.64	1.09	8.97	0.00	221.97	319.31
NO2	[ppm]	0.00	137.33	0.00	0.00	0.03	5.39	0.02	199.44
NOX	[ppm]	1079.91	201.01	5.64	1.09	8.99	0.00	221.99	518.75
NH3	[ppm]	0.17	4.70	202.66	27.14	323.50	16.79	23.96	0.18
N2O	[ppm]	1.10	0.00	0.00	0.11	0.00	0.00	0.02	1.14
HCN	[ppm]	0.04	1.73	0.00	0.00	12.18	7.47	14.46	
HNCO	[ppm]	1.09	9.62	4.24	0.90	6.05	0.00	4.34	
CH4	[ppm]	2.38	406.65	36.89	12.63	221.66	115.12	165.06	0.96
C2H2	[ppm]	1.21	21.71	1.94	1.86	0.98	507.73	29.13	0.60
C2H4	[ppm]	1.55	704.36	7.91	0.22	93.89	264.34	88.76	0.19
C2H6	[ppm]	1.26	166.91	1.40	2.01	14.07	0.00	8.48	0.20
C3H6	[ppm]	0.00	548.55	0.00	0.00	36.91	93.54	10.83	0.65
C3H8	[ppm]	0.00	0.00	0.00	0.00	0.00	351.76	0.01	
C4H6	[ppm]	0.62	61.81	7.53	3.07	13.86	4.70	5.21	2.22
C4H8	[ppm]	-0.02	368.22	1.80	0.73	22.40	38.34	5.01	
NC5	[ppm]	0.39	1223.12	0.01	0.00	85.14	502.97	2.95	
AHC	[ppm]	0.00	707.19	0.00	0.00	48.95	97.32	7.23	0.07
ETOH	[ppm]	2.99	955.65	11.46	4.84	15.85	6879.63	8.14	
HCHO	[ppm]	0.83	374.55	0.19	0.16	1.30	158.29	12.42	0.91
MECHO	[ppm]	0.00	438.09	0.01	0.00	6.77	714.68	3.26	0.00
SO2	[ppm]	0.04	4.23	0.00	0.00	0.00	7.32	0.27	1.68

CSC SESAM-FTIR Emissions Challenge Data

Mode 4 Data Table											
		1-Clarkson	2-ldaho	4-MTU	5-Madison	7-Kettering	8-ETS	9-Maine	14-Buffalo		
H2O	[ppm]	119409.90	118389.96	119725.07	125166.49	102150.66	54856.18	123144.52	34323.26		
CO2	[ppm]	117526.08	51306.21	120300.23	125669.71	109944.94	28653.66	103245.23	38389.68		
CO	[ppm]	181.57	68138.34	180.07	5.32	88.69	48893.97	29401.98	5.37		
NO	[ppm]	631.36	7.87	10.00	61.48	343.93	0.00	157.21	309.75		
NO2	[ppm]	0.00	0.01	0.00	0.00	0.00	3.24	0.00	110.78		
NOX	[ppm]	631.36	7.88	10.00	61.48	343.93	0.00	157.22	420.52		
NH3	[ppm]	0.13	2.47	13.79	0.13	13.36	11.70	15.06	0.13		
N2O	[ppm]	0.62	4.14	0.18	0.28	1.30	0.00	0.00	1.57		
HCN	[ppm]	0.02	6.19	0.00	0.00	0.00	7.71	14.16			
HNCO	[ppm]	0.30	38.31	0.38	0.02	0.81	0.00	4.02			
CH4	[ppm]	1.21	3119.57	45.81	0.52	22.77	115.12	279.90	0.98		
C2H2	[ppm]	1.25	551.65	1.61	1.79	0.38	839.93	91.48	0.50		
C2H4	[ppm]	0.70	3618.53	0.32	0.05	0.87	478.54	172.72	0.34		
C2H6	[ppm]	1.28	661.55	2.08	1.83	2.35	0.00	16.73	0.17		
C3H6	[ppm]	0.00	1039.36	0.00	0.00	0.00	137.95	35.77	0.61		
C3H8	[ppm]	0.00	0.00	0.00	0.00	0.00	351.76	10.96			
C4H6	[ppm]	0.45	202.75	0.90	0.43	1.28	13.03	6.31	1.32		
C4H8	[ppm]	0.08	352.60	0.20	-0.15	0.63	56.46	16.66			
NC5	[ppm]	1.05	100.06	0.04	0.00	0.91	502.97	16.33			
AHC	[ppm]	0.00	871.90	0.00	0.00	0.00	97.32	38.07	0.15		
ETOH	[ppm]	2.33	343.38	3.20	2.73	4.18	7305.60	19.70			
HCHO	[ppm]	0.59	715.92	0.28	0.16	0.40	173.69	29.17	0.64		
MECHO	[ppm]	0.01	502.44	0.01	0.00	0.00	691.17	16.07	0.04		
SO2	[ppm]	0.04	32.56	0.00	0.00	0.03	6.37	1.96	1.84		

Mode 5 Data Table

		1-Clarkson	2-Idaho	4-MTU	5-Madison	7-Kettering	8-ETS	9-Maine	14-Buffalo
H2O	[ppm]	91844.62	119877.07	106292.34	112181.57	40080.27	47002.37	49288.96	20080.96
CO2	[ppm]	90820.77	116379.33	107099.17	114081.54	39559.80	17944.15	48542.02	22188.72
CO	[ppm]	806.65	4023.64	4.25	1.22	700.89	40769.29	1851.63	6.29
NO	[ppm]	8.30	16.44	74.36	129.01	0.09	0.00	13.23	262.73
NO2	[ppm]	0.00	0.00	0.00	4.21	0.00	4.64	0.00	48.66
NOX	[ppm]	8.30	16.44	74.36	133.22	0.09	0.00	13.23	311.39
NH3	[ppm]	0.17	0.59	7.28	0.00	18.25	7.74	1.61	0.08
N2O	[ppm]	0.15	0.02	0.28	0.54	0.15	0.00	0.14	1.15
HCN	[ppm]	0.00	1.10	0.00	0.00	0.04	0.52	0.18	
HNCO	[ppm]	0.50	1.38	0.62	0.54	1.41	0.00	0.81	
CH4	[ppm]	5.02	70.55	15.55	17.61	68.75	115.12	56.00	1.16
C2H2	[ppm]	1.43	17.48	1.17	1.34	0.41	1303.38	6.47	0.48
C2H4	[ppm]	3.24	22.89	0.09	0.12	0.89	901.30	29.32	0.44
C2H6	[ppm]	1.21	3.10	0.99	1.81	3.97	0.00	6.12	0.16
C3H6	[ppm]	0.01	0.10	0.00	0.00	0.02	205.73	8.57	0.49
C3H8	[ppm]	0.00	0.00	0.00	0.00	0.00	351.76	22.90	
C4H6	[ppm]	0.73	0.43	0.75	0.62	0.74	26.72	0.73	0.78
C4H8	[ppm]	0.36	0.42	0.09	-0.33	0.54	109.09	4.62	
NC5	[ppm]	1.90	7.14	0.00	0.00	5.31	502.97	28.42	
AHC	[ppm]	0.00	1.63	0.00	0.00	0.06	97.32	1.03	0.50
ETOH	[ppm]	2.99	1.96	2.73	2.92	3.15	7832.87	13.32	
HCHO	[ppm]	2.06	4.16	0.36	0.28	0.16	255.12	15.78	0.58
MECHO	[ppm]	0.00	0.00	0.00	0.00	0.01	618.38	10.03	0.09
SO2	[ppm]	0.04	0.05	0.00	0.00	0.00	83.55	0.00	1.36

5 Conclusions

The use of bio-fuels and new catalyst technologies has resulted in additional challenges for engine and vehicle manufacturers when it comes to measuring vehicle exhaust. The potential for the production of previously non-regulated components that are no less toxic or hazardous to the environment brings into focus the question of how to adequately define "cleaner" emissions. Manufacturers and regulatory agencies alike require a means to continue to measure those components already regulated, while also having the capability to determine if undesired by-products are present in significant enough quantities to warrant consideration.

The SESAM-FTIR emissions bench with integrated FID (for THC) and PMD (for O₂) analyzers is capable of measuring raw exhaust from internal combustion engines equivalent to a traditional emissions bench for all regulated and previously monitored emissions components. In addition to the regulated exhaust components, the FTIR analyzer has the ability to measure a variety of non-regulated exhaust components that are of particular interest to the regulatory agencies, including ammonia (NH₃), nitrous oxide (N₂O), isocyanic acid (HNCO), hydrogen cyanide (HCN), alcohols, and aldehydes. This added measurement capability provides a new level of evaluation for the development of new engine calibrations and emissions abatement technologies that allows for a more complete assessment of whether such technologies are truly reducing harmful emissions, or simply changing the nature of those emissions.