Remote Sensing of Railroad Locomotive Emissions: A Feasibility Study

Peter J. Popp, Gary A. Bishop and Donald H. Stedman

Department of Chemistry and Biochemistry
University of Denver
Denver, CO 80208

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Prepared for:

Michael Koontz
Federal Highway Administration
400 7th Street, S.W. HEP-40
Washington, DC 20590

INTRODUCTION

Many cities in the United States are in violation of the air quality standards established by the Environmental Protection Agency. Carbon monoxide (CO) levels become elevated primarily due to direct emission of the gas. Ground-level ozone, a major component of urban smog, is produced by the photochemical reaction of nitrogen oxides (NO_x) and hydrocarbons (HC). As of 1997, railroad locomotives contributed an almost negligible amount of the CO and HC to the national emissions inventory (0.1% of the CO and 0.25% of the HC). Nitrogen oxide emissions contributed to the atmosphere by locomotives, however, were 4% of the national inventory[1], and in urban areas with high rail traffic locomotives are thought to represent as much as 10% of the total NO_x inventory.[2]

As a result of the 1990 Clean Air Act Amendments, the United States Environmental Protection Agency (EPA) will be enacting emissions standards for railroad locomotives beginning in the year 2000. There are three separate sets of standards, with the applicability of the standard dependent upon the date the locomotive was first manufactured. The first set of standards, Tier 0, apply to locomotives manufactured in the years from 1973 to 2001, anytime they are first manufactured or remanufactured. Tier 1 regulations apply to locomotives originally manufactured in the years 2002-2004. These locomotives will be required to meet the Tier 1 standards at the time of manufacture and at any subsequent remanufacture. Locomotives manufactured in 2005 and later will be required to meet the Tier 2 standards, again at the time of manufacture and at each remanufacture during the useful life of the engine. It is thought that regulation of the remanufacturing process is critical, since a locomotive engine may be remanufactured 5-10 times during a typical 40 year service lifetime.[3]

Practically all of the 21,000 locomotives owned by Class I railroads in the United States are diesel-electrics[4] produced by one of two manufacturers; the Electromotive Division of General Motors (EMD) or General Electric Transportation Systems (GETS). A diesel-electric locomotive generates power by means of a high-output compression ignition engine, designed to operate at a maximum speed of approximately 1000 rpm. The output power from the engine is converted to electrical energy by means of a generator or alternator that is directly connected to the engine. The electricity is then used to drive electric motors, called traction motors, which are connected to the drive wheels. Modern locomotives make use of alternating current traction motors, but many older locomotives in the U.S. fleet are equipped with direct current motors.

The electrical connection between the powerplant and the drive wheels is in contrast to most other motor vehicles, which use a direct mechanical connection (the transmission). Due to this mechanical connection, there is a direct relationship between engine speed and vehicle speed, and as a result, engine speed in direct-drive vehicles is highly variable and dependent upon operating mode. Because the powerplant in a locomotive is electrically connected to the drive wheels, however, the locomotive engine can be operated at a preset power output and fixed engine rpm without any obligation to match the vehicle speed. The locomotive engine, therefore, can operate in an essentially steady-state mode, in a number of discrete power settings that are referred to as notches. Railroad engines have eight throttle notch positions, in addition to idle and dynamic brake settings. The notch positions are numerically identified, with notch 1 being the lowest drive power setting, and notch 8 being the highest setting. Each notch corresponds to a discrete setting on the fuel delivery system in the engine, and these are the only drive power settings at which the engine can be operated.[5]

In addition to mechanical brakes, most diesel-electric locomotives in use are equipped with dynamic brakes. In dynamic braking mode, the traction motors are operated as generators resisting the rotation of the drive wheels and exerting a braking effect on the train. The current generated by the traction motors is dissipated as heat through a high-resistance cooling grid on the roof of the locomotive. While the engine is not generating motive power in the dynamic braking mode, electrical power is generated to operate cooling fans on the resistance grids. The power output of a locomotive engine in dynamic braking mode is typically lower than that when generating drive power.[5]

This report describes a study conducted by the University of Denver to assess the feasibility of measuring railroad locomotive emissions by remote sensing. The results described here are the first direct measurements of emissions from in-use locomotives. Support for this project was provided by the Federal Highway Administration under the Transportation Environmental Research Program.

TECHNICAL DESCRIPTION

The remote sensor used in this study was developed at the University of Denver for measuring pollutants in motor vehicle exhaust, and has previously been described in the literature.[6,7] The instrument consists of a non-dispersive infrared (IR) component for detecting carbon monoxide, carbon dioxide (CO_2), and hydrocarbons, and a dispersive ultraviolet (UV) spectrometer for measuring nitric oxide. The system is shown schematically in Figure 1. The light source and detector units are positioned on opposite sides of the rail, elevated to a height above the locomotive exhaust port. Collinear beams of IR and UV light are passed across the rail into the IR detector unit, and are then focused onto a dichroic mirror, which serves to separate the beams into their IR and UV components. The IR light is then transmitted to a spinning polygon mirror, which spreads the light across the four infrared detectors; CO, CO_2, HC and reference.

The UV light is reflected off the surface of the beam splitter and is focused into the end of a quartz fiber-optic cable, which transmits the light to an ultraviolet spectrometer. The UV unit is then capable of quantifying nitric oxide by measuring an absorbance band at 226 nm in the ultraviolet spectrum and comparing to a calibration spectrum in the same region.

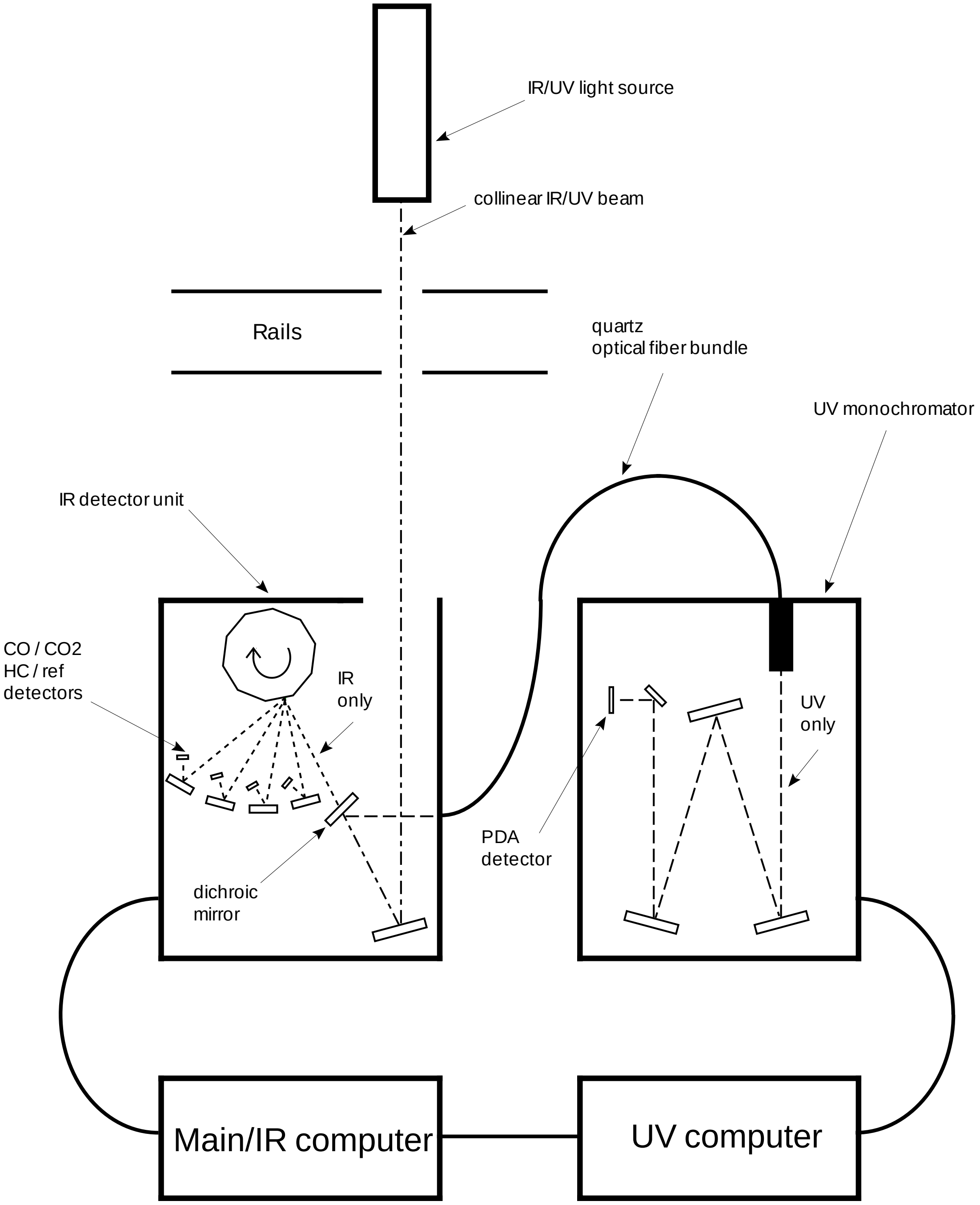

Figure 1. University of Denver remote sensing system configured for measuring locomotive emissions.

When measuring locomotive exhaust in this study, the system was manually triggered when the operator determined that the exhaust port was about to pass under the sensing beam. Once data collection was initiated, the instrument sampled continuously at 100 Hz for a period of either 2 s or 10 s, depending on the data collection routine being used. At the end of the sampling period, a data file was compiled containing voltages from each of the 4 IR detectors as well as simultaneous NO concentrations reported by the UV system. The data file contains 100 voltages from each of the IR detectors and 100 simultaneously measured NO concentrations for each second of measurement.

Data post-processing first involves converting the 4 IR voltages to concentration values for CO, CO_2, and HC for each of the 10 ms measurements. The ratios of CO/CO_2, HC/CO_2 and NO/CO_2 in the exhaust are then determined by a classical least squares analysis. In this study, the least squares regression was performed using 50-100 data points collected after the exhaust plume passed the sensor. The number of data points used in the analysis varied, because every locomotive passed the sensor at a different time during the data collection period. One hundred data points were used whenever possible, and a measurement attempt was determined to be unsuccessful if the plume measurement contained less than 50 data points. This procedure is illustrated in Figures 2a and 2b for a measurement taken of an EMD SD-40-2, operating in notch 7. Figure 2a illustrates the simultaneous NO and CO_2 concentrations in the plume, as observed by the remote sensor. Both gases are shown as a percent of full scale because the CO_2 concentrations are much higher than the NO concentrations. Figure 2b illustrates the least squares plot obtained from the traces in Figure 2a. The slope of the line given by a least squares regression of the data in this plot represents the NO/CO_2 ratio in the locomotive exhaust. On their own, the ratios of CO/CO_2, HC/CO_2 and NO/CO_2 are useful parameters to describe a hydrocarbon combustion system[6], but a knowledge of combustion chemistry allows one to use these ratios to further calculate the mass emissions of CO, HC, and NO in the exhaust, in units of g/kg of fuel consumed. To follow convention, we are reporting nitric oxide in units of grams of NO_2 per kg of fuel consumed. Most of the NO_x emitted from an internal combustion engine is in the form of NO.[8] The relatively small amount of NO_2 means that the NO emissions we report are close to lower limits for total NO_x. The remote sensor used in this study does report measured opacity, but the instrument has not been optimized for the measurement of this parameter so it is not reported herein.

There were two field locations used for data collection in this study. On January 26, 1999, measurements were conducted at the Burlington Northern Santa Fe (BNSF) facility at Alliance, Nebraska. The instrument configuration at this location is illustrated in Figure 3a. Scaffolding was erected on both sides of a closed siding to elevate the instrument to a height of 17 feet. Burlington Northern Santa Fe supplied two locomotives for testing at this location; a 3000 horsepower 1978 EMD SD-40-2 (BN7833) and a 4000 horsepower 1995 EMD SD70MAC (BN9663). Each of the two locomotives was measured at least once in notches 1-7, and 5 times at notch 8.

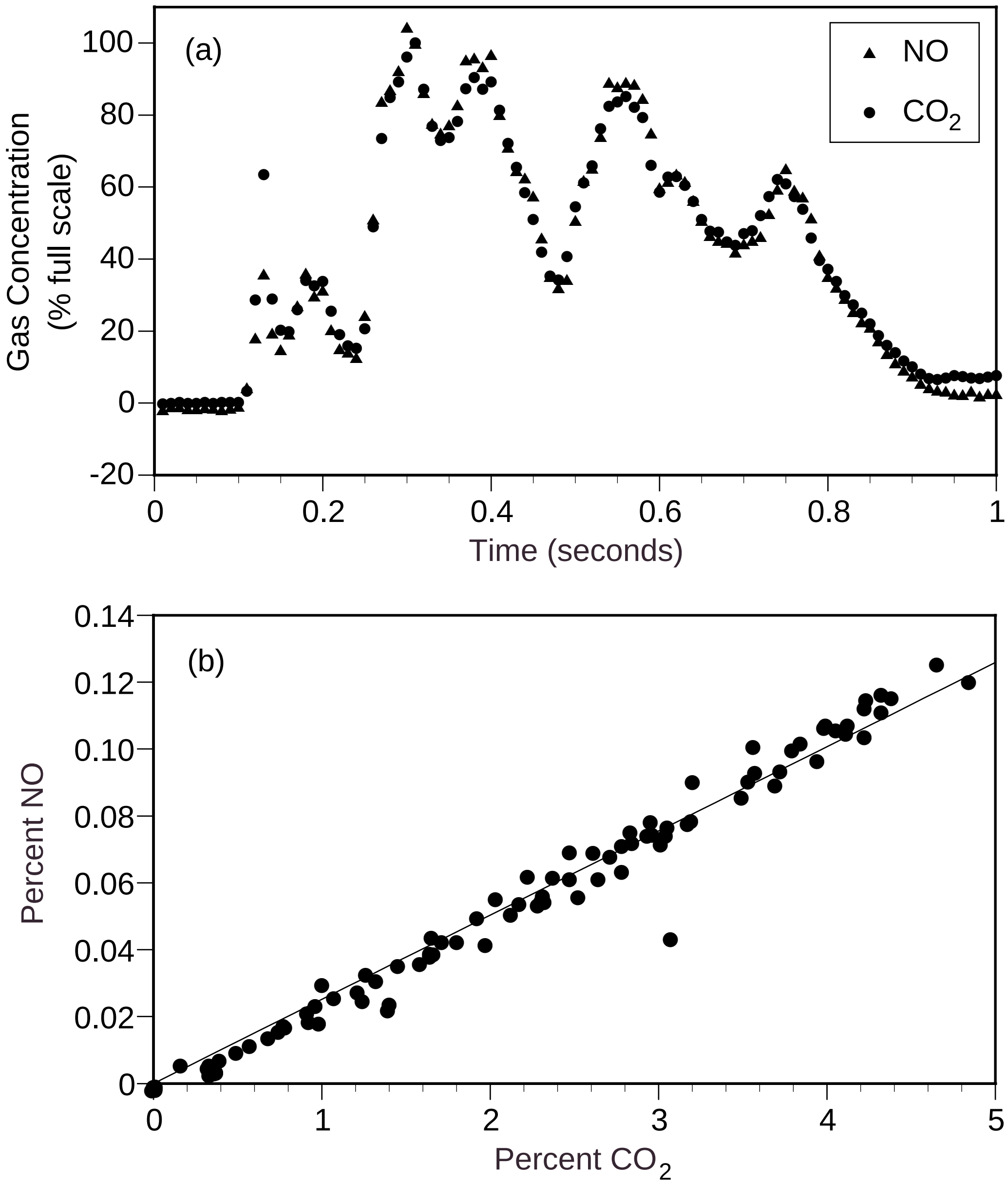

Figure 2. Simultaneous NO and CO_2 traces observed in the plume of an EMD SD-40-2 (a) and the least squares plot obtained from the same data (b). Data in (a) are represented as a percent of full scale because of the difference in magnitude of the NO and CO_2 concentrations.

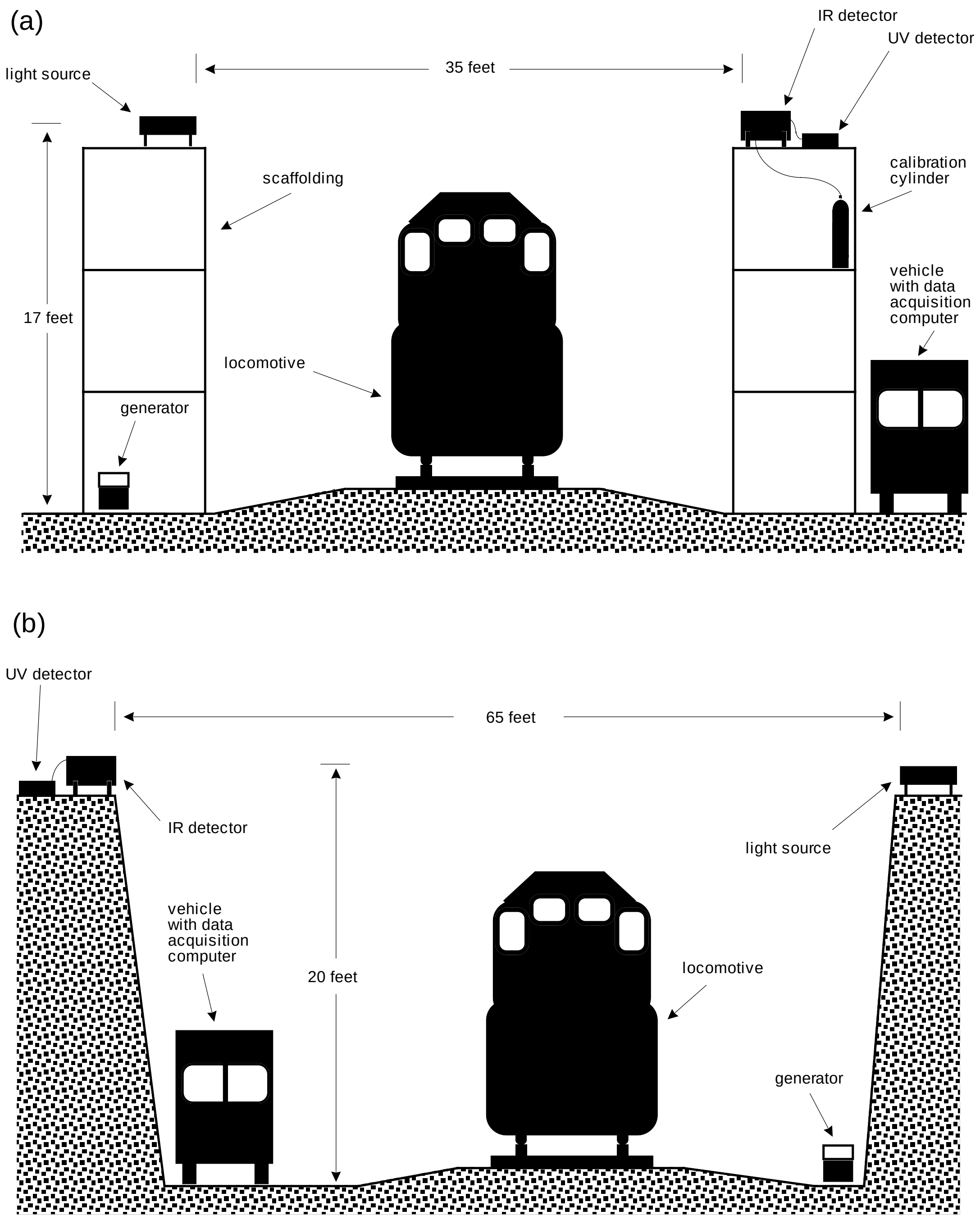

Figure 3. Instrument configuration at the BNSF yard (a) and at the cut 3 miles north of Northport, NE (b).

The SD-40-2 was measured first, followed by the SD-70MAC. The locomotives were linked for the duration of the test period. Each time a locomotive was driven past the sensor to be measured, the other was in tow and shut down. Approximately 300 feet of track was utilized on either side of the remote sensor location. The locomotive being tested was powered up, driven past the sensor and measured, and then decelerated to a stop. The next measurement would then be conducted with the locomotive driving past the sensor in the opposite direction. This continued until the locomotives were measured in notches 7 and 8. For safety reasons, measurements conducted in notches 7 and 8 were made with the train travelling in only one direction (southbound) because there was considerably more open track to the south of our location than there was in the northbound direction. After each run was made in the southbound direction in notch 7 or 8, the train would reverse in an unknown notch (no measurement was made) in preparation for another test run in the southbound direction.

On January 27, 1999, the second location was used to measure in-use locomotives hauling coal trains. This location consisted of a single track passing through a sandstone cut approximately 3 miles north of Northport, Nebraska. The track at this location has an uphill grade of approximately 1-1.5 % in the eastbound direction. The instrument configuration at this site is illustrated in Figure 3b, showing the light source and detector units positioned on top of the cut to achieve adequate clearance above the locomotives. A total of 10 locomotive measurements were made from 4 different trains at this location. These measurements include 2 locomotives being operated as helpers pushing in the eastbound direction and then returning to the bottom of the hill in the westbound direction.

RESULTS AND DISCUSSION

A complete listing of all measurements made during this study are shown in Appendix A. The results of the measurements conducted at the BNSF yard are summarized graphically in Figure 4. When more than one measurement was made of a locomotive in a specific notch setting, the mean emission for that notch is shown. As expected from a lean-burn compression-ignition engine, the CO and HC emissions are quite low. In the case of the HC measurements, the abundance and magnitude of negative reported emissions indicates the emissions are below the detection limit of the remote sensor. The NO emissions, meanwhile, appear consistent and show only a slight decrease as the notch setting increases. There is no statistical difference at the 95% confidence level between the emissions of the SD-40-2 and the SD-70MAC measured in notches 1 through 8.

There has been little information published relating to the emissions of railroad locomotives. Previous studies by the Southwest Research Institute (SwRI) have involved characterizing gaseous and particulate emissions from locomotive engines in a laboratory setting and from standing passenger locomotives.[9-11] More recent work by SwRI involved measurements of an EMD SD-75M with an engine similar in design to the SD-

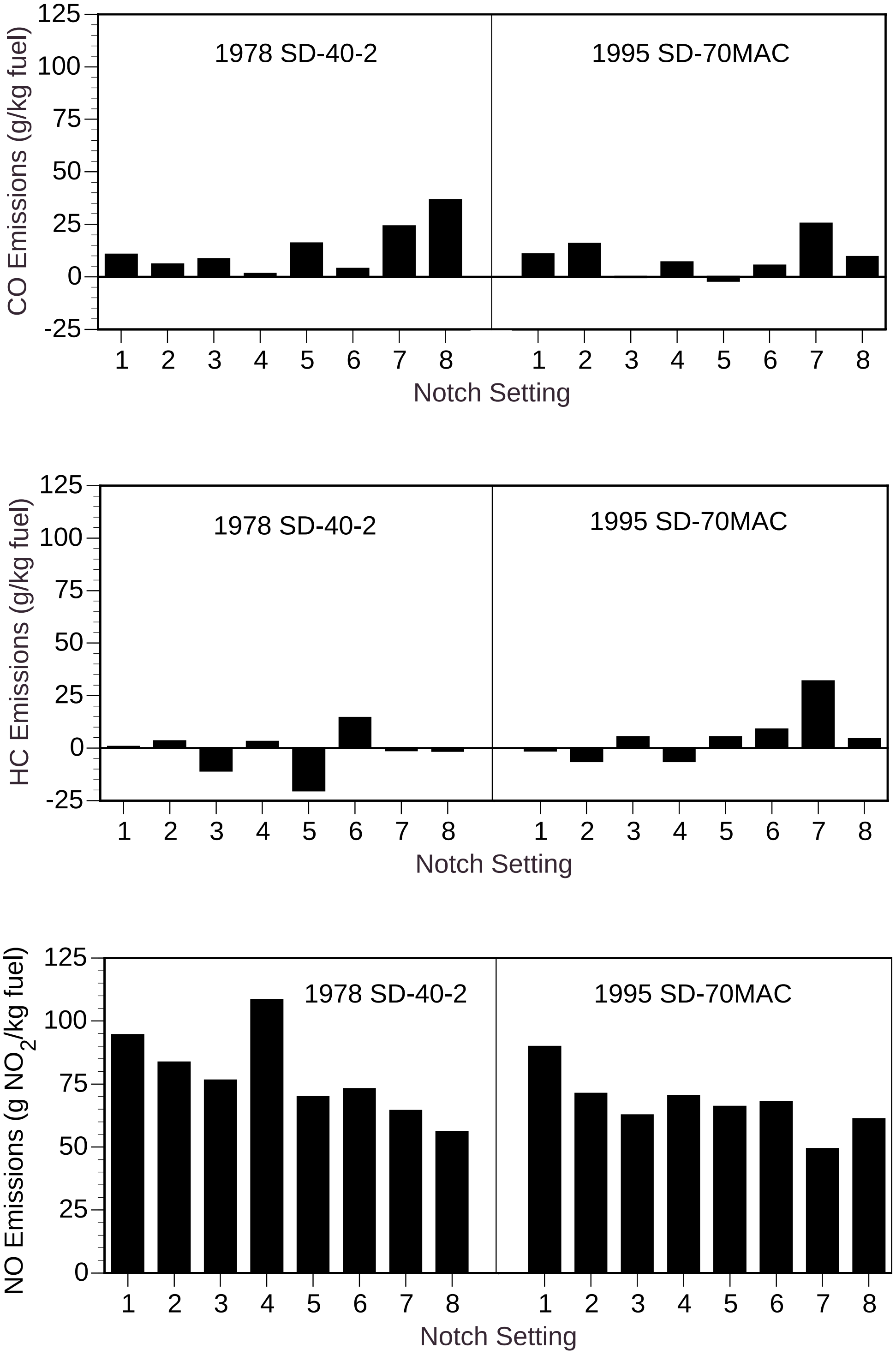

Figure 4. Carbon monoxide, hydrocarbon and nitric oxide emissions for the EMD SD-40-2 and SD-70MAC measured at the BNSF yard at Alliance, NE.

70MAC reported in this study.[12] Figure 5 illustrates the NO_x emissions measured from the SD-75M by SwRI when burning a conventional high sulfur (0.315% S) fuel. It should be noted that the emissions from the standing SD-75M have been converted to units of g/kg fuel burned from g/bhp·hr, and that these numbers represent a measurement of total NO_x, reported as grams of NO_2. Shown for comparison are the NO emissions by notch setting for the SD-70MAC measured in this study, also reported as grams of NO_2. In contrast to the emissions of the SD-70MAC, the NO_x emissions reported by SwRI increase with notch setting, and then decrease slightly at notch 8. The difference between the SwRI numbers and the emissions reported in this study can be partly attributed to SwRI measuring total NO_x while the remote sensor used in this study, as presently configured, measures only NO. As stated previously, most of the NO_x emitted from internal combustion engines is in the form of NO, but small amounts of NO_2 could be partly responsible for the differences shown in Figure 5. One also expects to see a difference in the emissions between different engines, and that may also be a partial cause for the observed effect.

The NO emissions from the in-use line-haul locomotives measured on the second day of data collection are shown in Figure 6. These measurements include a pair of helper locomotives pushing at the rear of a train in the eastbound direction, and then returning to the bottom of the hill in the westbound direction hauling only a fuel car. We were informed by BNSF personnel escorting us at this site that all locomotives measured in the eastbound (uphill) direction would be operating in notch 8, and that the helpers measured in the westbound direction (downhill) would be in dynamic braking mode. Also shown for comparison in Figure 6 is the mean NO emission for both locomotives measured in notch 8 at the BNSF yard, and the NO_x emissions for the SD-75M measured by SwRI in notch 8.

As seen in Figure 6, the NO emissions of the in-use locomotives are significantly higher (at the 95% confidence level) than the emissions of the two locomotives measured in notch 8 at the BNSF facility. Assuming that the in-use locomotives were in fact operating in notch 8, NO production appears to be somewhat dependent upon the load on the locomotive. The in-use NO measurements are generally higher but not statistically different (at the 95% confidence level) from the NO_x measurements of the SD-75M conducted by SwRI. Figure 6 also clearly indicates the difference in NO production by the helpers, per kg of fuel, when pushing in the uphill direction (in notch 8) and when operating in dynamic braking mode in the downhill direction (when their fuel consumption rate is also much lower).

Locomotive and Automobile NO Emissions in the Denver I-25 Corridor

Using the measured mass emissions of nitric oxide from locomotives, it is possible to draw a comparison between the contribution of automobiles and locomotives to the NO inventory in the Denver I-25 corridor. Approximately 100 locomotives travel the I-25 corridor in a given 24 hour period, and it is assumed that these locomotives are travelling

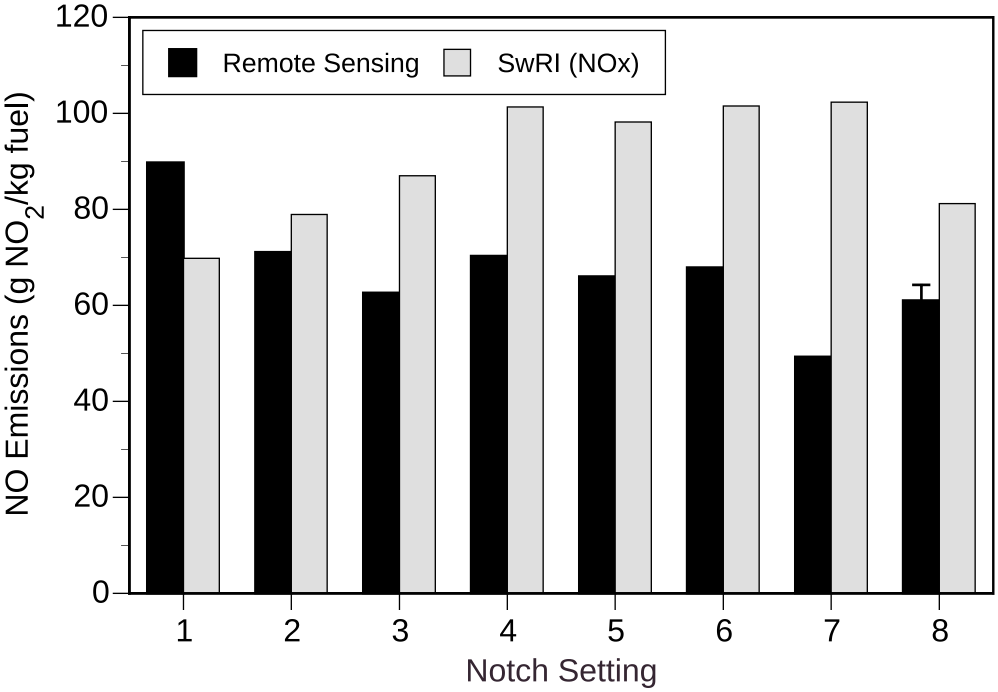

Figure 5. Comparison of NO emissions from an EMD SD-70MAC measured by remote sensing at the BNSF yard and NO_x emissions from an EMD SD-75M measured by Southwest Research Institute (SwRI). Both locomotives were equipped with EMD 16-710 series engines. Note that the SwRI data is a measure of total NO_x (NO and NO_2).

at 20 mph in notch 5. The NO emissions of the EMD SD-70MAC, judged to be representative of the fleet travelling through Denver, are 66.0 g/kg fuel (this study), and the fuel flow rate in notch 5 is approximately 300 kg/hour.[12] The resulting NO emissions are 19.8 kg/hour, or 990g g/mile when travelling at 20 mph. Through Denver, therefore, 100 locomotives emit 99 kg of NO/mile.

The NO emissions of automobiles at 6th Ave. and I-25 in Denver have recently been reported as 571 ppm[7], corresponding to mass emissions of 1.4 g of NO/mile (as NO_2) assuming a fuel density of 0.726 g/ml and a fuel mileage of 25 mpg. Approximately 225 000 automobiles per day travel I-25 in both directions through central Denver, and therefore these vehicles produce 310 kg of NO/mile. Despite the much greater number of automobiles travelling the I-25 corridor, it appears that locomotives produce almost one quarter of the combined NO emissions from locomotives and automobiles. It should be noted here, however, that automobile emissions occur throughout the Denver air basin, while locomotives are confined to the I-25 corridor.

CONCUSIONS AND FUTURE WORK

We have successfully demonstrated the use of an optical remote sensor in measuring nitric oxide emissions from railroad locomotives. The levels of carbon monoxide and hydrocarbons emitted from locomotive engines appear to be below the detection limit of the remote sensor. The remote sensor was shown to be effective at measuring nitric oxide both in controlled test situations and during normal line-haul operation. We could find no other reported work of nitric oxide emissions measured from in-use locomotives. The NO emissions measured from an individual EMD SD-70MAC are mostly lower than measurements conducted by Southwest Research Institute of a standing locomotive with a similar engine design.

Future work could involve the addition of a second high-speed monochromator to the system, for measuring NO_2 simultaneously with NO. Quantifying total NO_x would result in remote sensing measurements that show closer agreement with other methods of detection, such as chemiluminescence. Sulfur dioxide (SO_2) also displays absorption features in the ultraviolet region that should allow it to be quantified by the remote sensing method described here. Remote sensing of SO_2 emissions should allow a direct measurement of the sulfur content of in-use locomotive fuels.

ACKNOWLEDGEMENTS

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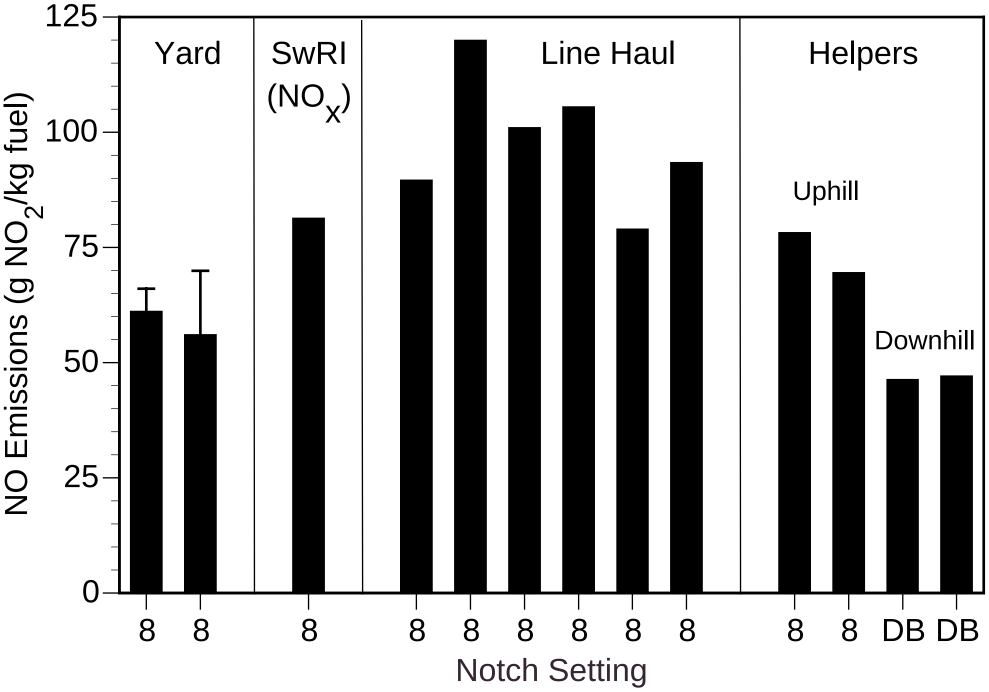

Figure 6. Nitric oxide emissions of line-haul locomotives measured at the cut 3 miles north of Northport, NE. Emissions of the helper locomotives are indicated for measurements taken during both uphill and downhill operation. Emissions from the two locomotives measured at notch 8 in the BNSF yard are shown for comparison.

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APPENDIX A – Locomotive Emissions Data.

Date	Data File	Registration	Type	Notch	CO (g/kg)	HC (g/kg)	NO (g NO_2/kg)
1/26/99	141403	BN 7833	SD-40-2	1	Insufficient plume detected.		
1/26/99	141543	BN 7833	SD-40-2	2	10.9	-4.2	84.1
1/26/99	141649	BN 7833	SD-40-2	3	7.8	-13.5	70.8
1/26/99	141758	BN 7833	SD-40-2	4	Insufficient plume detected.		
1/26/99	141850	BN 7833	SD-40-2	5	1.4	0.1	53.5
1/26/99	141954	BN 7833	SD-40-2	6	7.0	6.2	72.7
1/26/99	142042	BN 7833	SD-40-2	7	16.9	8.8	66.3
1/26/99	142226	BN 7833	SD-40-2	8	37.6	-1.6	60.0
1/26/99	142456	BN 7833	SD-40-2	1	10.5	0.6	94.5
1/26/99	142536	BN 7833	SD-40-2	2	0.7	10.8	83.0
1/26/99	142634	BN 7833	SD-40-2	3	9.1	-7.8	82.0
1/26/99	142715	BN 7833	SD-40-2	4	1.4	3.0	108.3
1/26/99	142813	BN 7833	SD-40-2	5	30.2	-40.4	86.2
1/26/99	142903	BN 7833	SD-40-2	6	0.5	22.6	73.2
1/26/99	143007	BN 7833	SD-40-2	7	31.1	-10.7	62.3
1/26/99	143055	BN 7833	SD-40-2	8	43.6	-2.3	65.8
1/26/99	144011	BN 7833	SD-40-2	8	31.1	8.5	61.2
1/26/99	144059	BN 7833	SD-40-2	8	46.6	-16.7	62.3
1/26/99	144143	BN 7833	SD-40-2	8	32.9	-0.7	24.8
1/26/99	144239	BN 7833	SD-40-2	8	24.9	8.3	63.9
1/26/99	144548	BN 7833	SD-40-2	8	38.8	-4.1	53.5
1/26/99	145742	BN 9663	SD-70MAC	1	10.6	-1.2	89.7
1/26/99	145829	BN 9663	SD-70MAC	2	15.8	-6.2	71.1
1/26/99	145921	BN 9663	SD-70MAC	3	-0.1	5.2	62.6
1/26/99	150017	BN 9663	SD-70MAC	4	6.9	-6.2	70.3
1/26/99	150208	BN 9663	SD-70MAC	5	-1.9	5.2	66.0
1/26/99	150301	BN 9663	SD-70MAC	6	5.3	8.8	67.9
1/26/99	150355	BN 9663	SD-70MAC	7	25.3	31.8	49.2
1/26/99	150444	BN 9663	SD-70MAC	8	18.1	8.8	61.5
1/26/99	150742	BN 9663	SD-70MAC	8	4.1	15.5	56.2
1/26/99	150821	BN 9663	SD-70MAC	reversing	-3.9	113.7	56.7
1/26/99	150908	BN 9663	SD-70MAC	8	8.0	-4.7	65.8
1/26/99	151030	BN 9663	SD-70MAC	8	4.7	3.2	61.0
1/26/99	151157	BN 9663	SD-70MAC	8	6.5	1.6	67.1
1/26/99	151339	BN 9663	SD-70MAC	8	15.0	1.07	54.6
1/27/99	115539	BNSF 9505	n/a	8	16.4	-1.3	89.4
1/27/99	115539	BNSF 9594	n/a	8	1.6	1.2	119.8
1/27/99	120109	BN 7261	n/a	8	8.3	3.9	78.1
1/27/99	120109	BN 7282	n/a	8	0.5	0.3	69.4
1/27/99	130536	BN 7282	n/a	DB	22.4	4.0	46.2
1/27/99	130536	BN 7261	n/a	DB	20.2	6.3	46.9
1/27/99	152621	BNSF 9576	n/a	8	8.2	1.0	100.8
1/27/99	153133	BN 7261	n/a	8	7.1	3.2	105.4
1/27/99	155537	BNSF 9866	n/a	8	-0.7	0.7	78.8
1/27/99	155537	BN 9691	n/a	8	5.6	0.8	93.2