Short communication

Bridge-based remote sensing of NOx emissions from locomotives

Matthew A. Breuer, Daniel A. Burgard*

Department of Chemistry, University of Puget Sound, Tacoma, WA, 98416, USA

ARTICLE INFO

Keywords:
Remote sensing
Locomotive
Nonroad emissions
NOx
Spectroscopy

ABSTRACT

While emissions from nonroad mobile sources, such as locomotives, have gained increased regulatory scrutiny, a surprisingly few number of real-world, in-use measurements exist. This paper reports the use of a Remote Sensing Device (RSD) to measure emissions from locomotives. This noninvasive technique measured NO and NO2 emissions from individually identified locomotives as their exhaust plumes passed through the sensing beam of the RSD on a bridge directly above the moving sources. NOx emissions from 143 in-use, predominantly line-haul locomotives were measured from two bridges near Tacoma, WA. Locomotive NOx emission factors were within levels reported in previous studies. While there is a 26% difference in certification standards, the real-world NOx measurements reported here found no statistical difference between mean emission factors for Tier 1 and Tier 2 locomotives. With the 2015 implementation of stringent Tier 4 emissions standards, remote sensing of NO2 emissions by RSD would provide a useful, real-world, check on the expected in-use NOx reductions.

1. Introduction

1.1. Background

Railroads are estimated to account for only a small fraction of all U.S. mobile source emissions, just 9% of the NOx and 5% of the PM (Gould and Niemeier, 2011). However, locomotives contribute to human exposure to diesel pollutants near ports, rail yards, and rail lines (Krasowsky et al., 2015). U.S. EPA Tier 0–2 standards were first enacted in 2000 to regulate locomotive engine emissions both manufactured and remanufactured from 1973 and beyond for line-haul, switch, and passenger rail diesel locomotives. Line-haul locomotives are defined to have an engine with a maximum rated power > 2300 hp. These locomotives are typically used to haul freight and typical of Class I railroads (a designation based on annual operating revenue). Then in 2008, EPA finalized stricter Tier 3–4 standards primarily designed to reduce PM and NOx emissions that were phased in from 2011 to 2015, and additionally required more stringent emission standards for remanufactured model year locomotives 1993–2001 (Office of Transportation and Air Quality, 2016).

It was assumed that the most likely technological pathway would be to transfer on-highway and nonroad heavy-duty engine selective catalytic reduction (SCR) systems to meet the low Tier 4 NOx locomotive standards (McDonald et al., 2011). Thus, in order to enable catalytic...
after-treatment technologies, ultra-low sulfur diesel fuel (< 15 ppm S) for locomotive engines was required starting in 2012. However, engine manufacturers listened to railroad concerns and designed new Tier 4 locomotives without the need for SCR and the accompanying Diesel Exhaust Fluid (DEF). Instead, these compliant engines use Exhaust Gas Recirculation (EGR) to be an adequate method to achieve the mandated NOx reductions. DEF has been shown to consume 4.8% of the fuel volume over the line-haul duty cycle (Osborne and Fritz, 2011) which would have required millions of gallons of DEF annually by the railroads. As of 2018, only GE and Progress Rail (EMD) have certified Tier 4 compliant line-haul locomotives and both use EGR (Progress Rail, n.d.; Union Pacific, 2016). While these new regulations are expected to have a reduction in locomotive emission rates, heavily used rail corridors may still have a significant pollution contribution from locomotives (Gould and Niemeier, 2011).

Locomotive emission inventories have been called “unreliable” or “have limited spatial detail” because they rely on “largely obsolete data” and “unsupported assumptions” (Gould and Niemeier, 2009). Reducing uncertainty in current estimates could improve health risk, air pollution, and climate assessments (Krasowsky et al., 2015). This uncertainty comes from the lack of real-world emission measurements of in-use locomotive engines and the “urgent need for rail side measurements of train engine emissions” (Johnson et al., 2013).

1.2. Remote sensing measurements

On-road vehicles have a more seasoned history than locomotives with changing regulations. Trends in on-road, mobile source emissions have been reported from in-use measurements by remote sensing devices and over the past two decades, oxides of nitrogen (NOx = NO and NO2) emissions from the light-duty, on-road fleet have shown a reduction of nearly 80% (Bishop and Haugen, 2018; Bishop and Stedman, 2008). Heavy Duty Diesel Vehicle (HDDV) and Medium/Light duty diesel vehicles have also showed substantial NOx reductions (Bishop and Haugen, 2018; Bishop et al., 2013; Bishop and Stedman, 2015). On-road emissions reductions have come from strict regulations, requiring advanced emissions control technologies and leading to significantly reduced emissions. Without these technologies, the same reductions, especially NOx, were not diminishing with nonroad sources (Dallmann and Harley, 2010). A real-world evaluation of the hopefully lower NOx levels from the Tier 4 compliant locomotives would seem prudent.

Regulations for locomotives and other heavy-duty “working” sources are power based and thus certification of these sources must include knowledge of engine operating parameters such as one of the eight engine notch settings, or idle, for locomotives. NOx emission standards are in the units of grams per brake horsepower hour (g/hp-h) and while testable on a dynamometer, to understand a locomotive’s in-use emissions requires multiple assumptions to estimate the locomotive’s real-world duty cycle. Alternatively, remote sensing measurements yield fuel-based units, pollutant mass per fuel use mass, as shown in Equation (S1) for NO. In the study presented here, the carbon mass balance was determined assuming emitted carbon was all CO2 as is often the case with remote sensing measurements from compression ignition engines (Krasowsky et al., 2015; Tang et al., 2015; Williams et al., 2009). Fuel-based emissions have the benefit that for emission inventory purposes, fuel consumption data are readily available. For example, in 2012 (the year of this study) locomotives used 3,118,150,000 gallons of diesel (“Sales of Distillate Fuel Oil by End Use,” 2017).

1.3. Locomotive emission factors

A review of the literature finds only a handful of in-use locomotive emissions studies. Measurements of Particulate Matter (PM) emissions from five locomotives in transient modes have been reported (Fritz, 1995; Yanowitz, 2003), then PM from 88 in-use, line-haul freight locomotives were measured near the ports of Los Angeles and Long Beach (Krasowsky et al., 2015), and another study used a sampling line from a portable analyzer on a pedestrian overpass to make 362 measurements of black carbon emissions from in-use Caltrain passenger trains (Tang et al., 2015). Both gaseous and PM emissions from three switching locomotives were measured using a modified heavy-duty diesel mobile emissions laboratory (Sawant et al., 2007), and in-use gaseous and PM emissions from passenger locomotives were measured with a portable emissions monitoring system (Graver et al., 2016; Graver and Frey, 2016). Real-world emissions were measured from in-use locomotives servicing an Australian shipping port. This study remotely captured gaseous and PM emissions from 56 train movements using a mobile monitoring station (Johnson et al., 2013). Nitric oxide (NO) emissions from a total of six locomotives in a rail yard have been measured by a remote sensing device (Popp et al., 1999). The largest sample of trains measured to date (1100 measurements) used a remote sensing device to measure line-haul trains in California (Feasibility of Using Remote Sensing Devices to Measure Locomotive Emissions: Report to California Legislature, 2010). This was a feasibility study by California Air Resources Board (CARB) to establish whether remote sensing could be used to determine if passing locomotives were performing at the applicable certification standard, typically performed in a highly controlled laboratory environment. As shown from these last four examples, remote sensing of locomotive emission plumes has the potential to yield a large number of train measurements, and while it may not be able to conclude certification parameters, these measurements can still identify trends in fleet emissions and identify individual outlying emitters.

This paper presents the use of a remote sensing device, optimized for on-road measurements, that has been modified to capture emission plumes from individual locomotives passing under a bridge. The objectives of this study were specifically to, 1) show that a remote sensing device, optimized for on-road use, can be configured on a bridge to measure in-use locomotives, 2) compare NOx values from the RSD to other in-use and rail-yard measurements, and modeled emissions from dynamometer measurements, and 3) show a proof of concept that an RSD could help to evaluate the extent of Tier-4 compliant locomotives at reducing in-use NOx emissions.

2. Experimental section

2.1. Apparatus

Gaseous emission ratios from in-use locomotives were measured noninvasively by the Fuel Efficiency Automobile Test (FEAT) remote sensing device, developed at the University of Denver. This RSD has been employed previously for both on-road and nonroad applications in over 150 peer reviewed papers and reports (see http://www.feat.biochem.du.edu/pub_list.shtml) for which a detailed review of the system exists (Burgard et al., 2006a). Briefly, the RSD consists of a collinear UV/IR light source that directs a beam across a roadway or other open path to a detector unit housing four non-dispersive IR detectors to measure an IR reference, CO2, CO, and HC. This unit is coupled via fiber optic to two dispersive UV spectrometers for measuring NO, SO2, and NH3 in one spectrometer and NOx in the other. The sensor measures only the pollutant molar ratio to CO2 because the pathlength of the locomotive exhaust is unknown. Quality assurance calibrations were performed in the field as dictated by atmospheric CO2 conditions using certified reference gas mixtures of pollutants with CO2 (Praxair, Fife WA). The measured gas ratios are normalized to the averaged results of these calibrations to adjust for inter or intraday variations in instrument sensitivity and changes in ambient CO2 absorption due to the background atmosphere. The grams of pollutant per kilogram of fuel consumed can be calculated with the pollutant gaseous ratios (Equation S1). NOx measurements presented here have not been adjusted for temperature and humidity (EPA, 2005), however,
temperature and humidity data were recorded and available in the supporting information (Table S1).

2.2. Instrumental set-up

The FEAT RSD was designed to space the light source from the detector approximately 10 m (or the width of a single lane of traffic with shoulders) and make 50 sequential 10 ms discrete measurements immediately after the car had physically passed through the beam for 0.5 s of acquisition time. For this study the distance between the source and detector was lengthened to ∼18 m and as with two previous marine studies with this instrument (Burgard et al., 2011; Burgard and Bria, 2016), the system employed 500 sequential 10 ms measurements following a manual physical disruption of the light beam to trigger the instrument to start collecting data for a 5-s acquisition time. The manual beam block was necessary because the locomotives passed underneath rather than through the light path and the longer monitoring time was needed in order to catch the plumes travelling at different rates up through the light beam on the bridge due to differing atmospheric and train speed conditions. Fig. 1a shows a typical passing locomotive plume measured with the 5-s software.

2.3. Field measurements

Remote sensing measurements were made between June 11th, 2012 and July 25, 2012 at two bridge locations in Pierce County, WA: the 4th Street Bridge, and the Chamber’s Bay Pedestrian Bridge. Fig. 2a shows the 4th Street Bridge, which is located at approximately sea level on the eastern shore of Tacoma, WA on Commencement Bay. The second location, the Chamber’s Bay Pedestrian Bridge, is also at approximately sea level on the western shore of University Place, WA, depicted in Fig. 2b. Extensive site details are available in the Supporting Information.

For each passing train, the individual locomotive(s) railway company and identification number were recorded and matched to make, model, and year using online sources (see SI). This study did not receive assistance from the railroad companies, thus there are no data on the notch setting of locomotives at the time of measurement in this study or any way to verify the engine information. In 2012 locomotive diesel was either at 15 ppm sulfur or in the process of being phased in. At 15 ppm in the fuel, SO2 levels are typically below the FEAT RSD’s detection and thus SO2 emission factors were not attempted and only NO, NO2, and the summed NOx (in NO2 equivalents) emission factors are presented.

2.4. Missed measurements

The modified 5-s software typically allowed for manual triggering of the instrument to record a portion of the emitted plume. However, there were a few missed plumes due to manual timing. With the distance between the top of the locomotive exhaust stack and the instrument light beam on the bridge, a strong cross wind would push the
plume away from the beam. The largest source of missed measurements came from the plume dissipating too quickly, either from high winds or the trains travelling too fast. The speed was recorded for each locomotive (Bushnell Velocity Speed Gun) and were observed travelling up to 127 km/h, however only trains travelling 64 km/h or less had plumes concentrated enough for valid emission measurements (the plume validity requirement is based on CO₂ and not NO or NO₂). This cut-off leaves a segment of the operating conditions unreported, however, in dense locomotive corridors near city centers and large populations where emission inventories are most important, this upper speed bin may be only a minor contributor.

3. Results and discussion

3.1. Emission factors

Over the 15-day measurement period, 143 remote measurements of locomotives were made. The fleet average for this sample was 51 ± 2 g NO/kg fuel, 4.2 ± 0.2 g NO₂/kg fuel, leading to 83 ± 4 g NOx/kg fuel in NO₂ equivalents. Most trains in this study were travelling with more than one locomotive, one after another in procession. The light beam of the instrument was more than three meters above the locomotive exhaust pipes at our measurement locations. With the exhaust from two locomotives exiting at close proximity from trains travelling at high speeds, the plumes from two locomotives can mix or pass through the instrument's beam in rapid succession. More than one exhaust plume may pass through the beam during the 5-s measurement period. For 30 samples in this study, separation was not seen or possible to account for the mixing of plumes. However, for many more, separation was achieved through manual peak picking. In many plumes, like the one in Fig. 1a, distinct areas exist in the CO₂ vs. time plot that represent two locomotives from a single train. When distinct peaks were noticed, data files were manually split based upon the CO₂ versus time plot, which created separate ratios for the pollutants. Fig. 1b and c shows that within the 5-s plume two sets of distinct NO/CO₂ and NO₂/CO₂ ratios exist. The first section of the plume from 0 to 3 s comes from Southern Pacific 107, a locomotive identified to have a GE AC4400CW engine built in 1995. This locomotive emitted 69 g/kg NO and 4.5 g/kg of NO₂. The second section of the plume from 3 to 5 s comes from a much newer Union Pacific 8685 locomotive with an EMD SD70Ace engine built in 2011. This locomotive emitted 44 g/kg NO and 6.8 g/kg NO₂.

Fig. 1 shows that individual plumes can be separated out of a combined plume even for two locomotives following immediately after one another. It is shown in this example that the 16 year newer locomotive emitted 33% less NOx. The remainder of the results presented here include only the 107 measurements matched to a locomotive made after 1972 and with complete identification data.

3.2. Emissions versus model year

Comparison of mean levels of NO, NOx, and NO₂ in grams per kilogram of fuel from different emissions certification periods is challenging for this group of locomotives during this study. Locomotive emissions are set by their year of manufacture which included 1973–2001 (Tier 0), 2002–2004 (Tier 1), and 2005–2011 (Tier 2). However, with the introduction of Tier 3 and 4 emission standards in 2008, a new remanufacture schedule and set of emission standards were put in place. Interim standards applied for some locomotives and the year of refurbishing had bearing on how clean the replacement engine needed to be. The same model year could have two different emissions standards. For example at remanufacture, Tier 0 standards still applied only for 1993–2001 model year locomotives and were in place for a separate loop intake cooling system, for all others in that time period an advanced standard applied. Fig. 3a shows a comparison among locomotives, grouped by their original manufacture date (and initial certification Tier). Although there is a 26% decrease in certified NOx emissions between Tier 1 and Tier 2, this difference is not observed for the mean emissions for those model years at the 95% confidence limit. Fig. 3b shows a comparison among locomotives, grouped by the remanufacture levels required in 2012 (this causes one 1992 locomotive to be dropped from the data which would not be required to meet Tier 1 remanufacture). When the measurements were made in 2012 it could be assumed that all 1993–2001 locomotives had been brought up to the newly required Tier 1 NOx levels and that there would only be two groups to compare. The mean NOx emission factors between the two groups in Fig. 3b are also not statistically different at the 95% confidence interval even though there was still a required NOx reduction for certification from Tier 1 to Tier 2 locomotives. While our measured units (g/kg) are different than the emission standards (g/bhp-h), these locomotives are measured at the same location and it would seem reasonable that the power requirements would be evenly distributed across the model years. Thus the percent reductions would be similar for both emission units and thus be observable assuming similar fuel consumption. The comparison of locomotives during this time period is complicated, however, results from this real-world, in-use study do not show an obvious (and assumed) average emission factor difference among tiers.

The mean levels of NO₂ show little variation across model year as shown in Table 1. NO₂ absolute levels and ratio of total NOx have been shown to change significantly with the on-road light duty and HDDV fleets after the introduction of PM and NOx after treatment such as diesel oxidation catalysts and diesel particulate filters (Bishop et al., 2013; Bishop and Stedman, 2015). It has not been shown how the locomotive Tier 4 emissions will change in regards to the NO₂ fraction of the total NOx.

3.3. Emissions versus speed

Mean NOx emissions factors were also compared for locomotives travelling at different speeds as shown in Figure S1. Mean levels of NO and NOx from locomotives travelling above 40 km/h appear to be 23% higher than levels from locomotives travelling between 16 and 40 km/h. Locomotives travelling less than 16 km/h had NO and NOx levels between the other two speed bins. Mean NOx levels were significantly higher for locomotives travelling less than 16 km/h, a 43% and 35% increase from the 16–40 km/h bin and the > 40 km/h bin, respectively. Speed is not a replacement for notch settings but fuel intensity (the amount of fuel used to move a unit weight a unit distance) is largely a function of train speed (Gould and Niemeier, 2011).

3.4. Emissions of specific locomotive type

Identifying plumes from individual locomotives and then referencing the identifying numbers to particular engine models allows for further investigation into emission factor by engine make and model. The seven most measured models at the sites were four GE models and three EMD models. A comparison of specific engines grouped by Tier certification can be seen in Figure S2. There do not seem to be significant differences among the engines or certifications, or between the engine makers.

3.5. Comparison to other locomotive studies

To place the current results in context, Table 2 shows a comparison of emission factors both directly measured and modeled. The table includes modeled numbers presented in Gould and Niemeier in their estimates labeled University of California Davis (UCD) and a comparison they performed using EPA methods. The results from four other in-use published measurement studies and two other modeled studies are also compared in Table 2. These comparisons show that the emission factors from the present study are on the high side of the available comparisons but within the range of emission factors of other remote studies.
3.6. A look to the future

Remote sensing in this type of configuration will not lead to in-use validation of locomotive certification. Certification requires performance over duty cycles that include different weighting factors for each of the 8 throttle notch modes. Typically remote sensing field measurements would not have knowledge of the notch setting of the locomotive at that point in time, nor would the plume measurement last long enough to be acceptable to account for a certification duty cycle. However, remote sensing would be able to identify outlier, broken, or gross-emitting locomotives as this study shows that fuel-specific real-world emissions can be obtained and compared among different locomotives. The FEAT RSD has been used to identify real-world operating conditions that both confirm and deviate from expected operating conditions. The on-road light-duty fleet has made significant emission reductions in line with the introduction of new emission control technologies (Bishop et al., 2013). The FEAT RSD has also shown unexpected emissions results. For years individual gross emitting vehicles have been found in the light-duty on road fleet when emission control systems are broken (Beaton et al., 1995). On road vehicles driven atypically have also been shown to have higher emissions than expected such as hybrid and other taxi fleets (Bishop et al., 2016). Bad actors such as Volkswagen 2.0 L diesel engines were determined to have NOx emissions no lower than previous emissions standards (a function of installed defeat devices) before the scandal was announced (Bishop and Stedman, 2015). Individual heavy-duty trucks were identified with very high SO2 emissions, suggesting the use of illegal off-road diesel with higher sulfur content. (Burgard et al., 2006b).

Tier 4 compliant locomotives should emit lower levels of NOx due to the regulated 86% reduction from Tier 0 levels. Locomotive manufacturers GE and Progress Rail did not follow the strategy of their on-road counterparts and instead employ EGR to achieve the required NOx levels. EGR is not a new technology and while these locomotives have been tested extensively and certified on dynamometer and on-rail duty cycles, these certification cycles and thus the emission factors may deviate from expectations in real-world operation. This has been shown with on road HDDV certification cycles and that real-world NOx control efficiency deviates from control efficiency observed during engine certification (Boriboonsomsin et al., 2018). The use of a field deployed remote sensor would help to understand the effectiveness of Tier 4 NOx emission reductions as their use is phased into the locomotive fleet. Unfortunately, the introduction of Tier 4 compliant locomotives have been slowed by an industry that recently peaked just before the 2015 required introduction of these low NOx locomotives. In 2015 there were 855 new units sold to Class 1 railroads, however, many of these were not Tier 4 compliant due to an intricate pre-Tier 4 credit system. By 2017 many locomotives have been put in storage and only 236 new units were sold (Popke, 2017; Railroad Ten-Year Trends, 2007–2016, 2018), but by July 2016, 1000 GE EVO Tier 4 locomotives had been built (Aishwarya, 2016). Unfortunately this downturn will cause a

### Table 2
Comparison among previous locomotive emission factors and those determined in this study.

<table>
<thead>
<tr>
<th>Study</th>
<th>NOx g/kg Fuel</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Study</td>
<td>83 ± 4</td>
<td>In-Use</td>
</tr>
<tr>
<td>Popp et al.</td>
<td>54–108</td>
<td>Line-haul</td>
</tr>
<tr>
<td>1978 SD-40-2</td>
<td>49–90</td>
<td>Line-Haul</td>
</tr>
<tr>
<td>1995 SD-70MAC</td>
<td>46–120</td>
<td>In-use</td>
</tr>
<tr>
<td>Sawant et al.</td>
<td>36–73</td>
<td>In-Use</td>
</tr>
<tr>
<td>UCD</td>
<td>45–78</td>
<td>Switching</td>
</tr>
<tr>
<td>EPA</td>
<td>56–88</td>
<td>All Class 1 freight In CA</td>
</tr>
<tr>
<td>Frey et al.</td>
<td>67–76</td>
<td>In-Use</td>
</tr>
<tr>
<td>Johnson et al.</td>
<td>28 ± 14</td>
<td>In-Use</td>
</tr>
<tr>
<td>Transport Canada</td>
<td>75.5</td>
<td>Line-haul</td>
</tr>
</tbody>
</table>

*a* Measured as NO emission but reported in NOx equivalents.

*b* Range across measured Notch settings 1-8.

*c* Originally expressed in units of g NOx/kg CO2, changed to g/kg fuel assuming the average mass fraction of carbon in the fuel is 860 g C/kg fuel.

*d* Originally expressed in units of g/L or g/gal, changed to g/kg by assuming fuel density of 820 g/L.

*e* Modeled data

## Figure 3
Mean levels of NO, NO2, and NOx emissions in grams per kilogram of fuel grouped by a) Tier 0, Tier 1, and Tier 2 model year and b) Tier 1 and Tier 2 model year based on remanufactured groupings as of 2008. Uncertainties are the standard error of the mean.

### Table 1
Measured locomotive fleet NO, NO2, NOx, and NO2/NOx results.

<table>
<thead>
<tr>
<th></th>
<th>EPA NOx Standard g/bhp-h</th>
<th>NO g/kg</th>
<th>NOx g/kg</th>
<th>NO2 g/kg</th>
<th>NO2/NOx</th>
<th>Number of measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>1973–2001 (Tier 0)*</td>
<td>9.5</td>
<td>54 ± 4</td>
<td>3.9 ± 0.2</td>
<td>86 ± 6</td>
<td>0.050</td>
<td>55</td>
</tr>
<tr>
<td>2002–2004 (Tier 1)</td>
<td>7.4</td>
<td>61 ± 5</td>
<td>4.5 ± 0.3</td>
<td>99 ± 8</td>
<td>0.048</td>
<td>28</td>
</tr>
<tr>
<td>2005–2011 (Tier 2)*</td>
<td>5.5</td>
<td>45 ± 5</td>
<td>4.1 ± 0.5</td>
<td>73 ± 8</td>
<td>0.060</td>
<td>24</td>
</tr>
</tbody>
</table>

*a* The uncertainties are the standard errors of the mean.

*b* Reported in NO2 equivalents.

*c* Tier associated with manufacture date.

much slower introduction of the new low NO\textsubscript{x} locomotives as old units will likely be pulled from storage before new Tier 4 compliant units are purchased and put on the rails.

4. Conclusions

A remote sensing device was used to measure 143 locomotive plumes and individually identify emission factors for 107 locomotives under real-world conditions over a 15 day period. These emission factors generally agreed with previous studies. The FEAT RSD is effective at producing fleet average data and identifying individually high emitters. The setup of this system could be a useful way to monitor the effectiveness of low NO\textsubscript{x} Tier 4 locomotives as they enter the fleet and monitor their real-world NO\textsubscript{x} levels as they age.

Data available


Acknowledgements

The logistics for bridge set up were approved through the help of the City of Tacoma and Chamber’s Bay Properties. Funding was provided by the University of Puget Sound Enrichment Committee and the Puget Sound Summer Research Grants in Math and Science.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.atmosenv.2018.10.046.

References


