**California Environmental Protection Agency**

# Air Resources Board

# Feasibility of Using Remote Sensing Devices to Measure Locomotive Emissions

## Report to the California Legislature

**December 2010**

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# Acknowledgements

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Report may be found at http://www.arb.ca.gov/mandrpts/mandrpts.htm. A hard copy may be obtained by contacting Harold Holmes, Manager of Engineering Evaluation Section, (916) 324-8029.

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# Executive Summary

Assembly Bill 1222[1] directed the Air Resources Board (ARB/Board) to implement a pilot program to determine locomotive emissions using remote sensing devices (RSDs). A summary of the pilot program and general findings is presented in this Executive Summary. Details of the pilot program are presented in subsequent sections.

## What does AB 1222 require?

The three objectives of the AB 1222 pilot program were to determine whether an RSD could accurately and repeatedly determine, with a reasonable level of precision:

1. The levels of nitrogen oxides ($NO_x$), particulate matter (PM), and carbon monoxide (CO) emissions from locomotives;

2. Whether a locomotive is subject to Tier 0, 1, or 2 federal certification emission standards; and

3. Whether the measured results could be calibrated to determine whether the locomotive is above or below the applicable federal certification standards.

In support of the objectives, the remote sensing testing was to include data from a sufficient number of locomotives that would be representative of the locomotive fleet operating in California and to ensure that data collection be performed under representative conditions in northern and southern California. In conducting the pilot program, ARB was to establish an Advisory Group to make recommendations regarding the design and implementation of the pilot program. Finally, the ARB was to submit a report to the Legislature that included both of the following:

1. A summary of data acquired through the pilot program; and

2. The ARB's determination as to whether RSDs can meet the objectives of the pilot program.

If ARB determined that RSDs could be expected to meet objectives of the pilot program to an extent reasonably sufficient to allow the ARB to make the following projections and recommendations, the report was also to include both of the following:

1. To the extent feasible, a projection of the amount, location, and timing of emission reductions that could be expected from the use of RSDs to identify locomotives to be repaired or maintained; and

[1] Assembly Bill 1222; Statutes 2005-Jones; Chapter 574; Section 1; Health and Safety Code sections 39940–39944, effective January 1, 2006. Note that section 39941 was amended by Senate Bill 1852 to correct a subsection number from subsection number (2) to subsection (c), effective January 1, 2007. Appendix A contains the corrected text of the applicable sections.

2. An ARB projection of the cost to deploy, maintain, and use data from a system of RSDs in areas of high priority in the State, recommendations regarding the funding of such a project, and the expected cost-effectiveness of such a program compared to other opportunities for air quality improvement in the covered areas.

## What is remote sensing for locomotives?

Remote sensing is a way to determine pollutant levels in a locomotive's exhaust while the locomotive is traveling. Unlike most equipment used to determine emissions, an RSD does not need to be physically connected to the locomotive. In general, RSD systems employ infrared and ultraviolet beams that remotely measure concentrations of pollutants that can be correlated to desired concentrations of $NO_x$, PM, and CO. In addition, RSD systems employ video camera equipment to digitize an image of the locomotive, allowing processing of the emissions information for each monitored locomotive based on the locomotive's identification.

## How does remote sensing compare to federal locomotive testing?

The federal measurement standard for locomotive emissions is contained in Title 40, Code of Federal Regulations (CFR), Part 92. The U.S. Environmental Protection Agency (U.S. EPA) uses this test method to determine compliance with federal locomotive emission standards. The emission testing is performed on stationary locomotives under highly controlled laboratory testing conditions, with a load bank used to simulate operating conditions. The locomotive is run for at least six minutes in each of eleven power settings, with data from each power setting weighted over the line haul duty cycle.[2] Under the line haul duty cycle, emissions are distributed over each of the power settings on a percentage basis that is designed to be representative of average operations for the locomotive fleet.

The RSD, on the other hand, is applied to a moving locomotive under normal operating conditions. There is no federal test procedure that measures emissions for a moving locomotive. Although Title 40 CFR Part 92 uses a load bank to simulate operating conditions, a number of variables are introduced when a locomotive is actually moving under normal operating conditions. These variables include wind speed, turbulence, ambient temperature, humidity, and the power setting (or possible transitioning between power settings). As the locomotive passes by the RSD, a reading is taken from part of the plume for half a second. The RSD reading is an instantaneous plume reading in a specific locomotive power setting. By collecting multiple readings, an estimate of the emissions from a locomotive can be made.

[2] See Appendix E for a more detailed explanation of Title 40 CFR Part 92.

## How did ARB conduct the pilot program?

ARB conducted the RSD study with support from two contractors and an Advisory Group. The contractors were Environmental Systems Products (ESP) and Southwest Research Institute (SwRI). ESP configured the RSD devices for application to locomotives and conducted the field study. SwRI performed the emission testing using the federal test procedure that allowed for the parallel correlation testing of the RSD.

As specified in AB 1222, the Advisory Group consisted of representatives of local air districts and the railroads, and their respective appointees. A complete listing of the members is presented in Table 1, in Section II. In general, the Advisory Group consisted of members from the local air districts, the railroads, local community organizations, and experts in the field of locomotives and remote sensing. Throughout the AB 1222 pilot program, considerable effort was made to accommodate and address the concerns, questions, and issues raised by the Advisory Group in an effort to achieve consensus. Over the duration of the study, the Advisory Group held 35 meetings.

The Advisory Group first met on January 31, 2006; the report on the RSD study was to be submitted to the California Legislature by December 31, 2006. Unfortunately, remote sensing of locomotives was found to pose unique technical challenges, necessitating the development of a much more complex program than had been anticipated when AB 1222 was written. Thus, the original deadline was not met. However, the study, as completed, is the most comprehensive study ever conducted on the remote sensing of locomotives.

To conduct the study, the ARB in consultation with the Advisory Group developed a pilot program that consisted of three phases:

Phase 1: Adaptation of the RSD to read locomotive emissions;
Phase 2: Field deployment and sampling; and
Phase 3: Correlation testing.

The development and implementation of each phase of the RSD study is discussed below.

### *Phase 1*

In Phase 1, ESP modified RSDs used for gasoline vehicles to take readings of diesel emissions from locomotive exhaust stacks. This process entailed numerous technical modifications over several months. The RSDs were loaned to ARB by the Bureau of Automotive Repair (BAR).

The following two different sampling configurations[3] for the modified RSDs were then studied at a locomotive testing facility in Colorado in January and February 2007:

[3] For illustration, see Figure 3 on Page 21.

1. A direct RSD configuration, with the RSD equipment positioned above the track at the height of the locomotive exhaust; and

2. An indirect RSD configuration, which is an extraction system with a sampling tube located above the track at the height of the locomotive exhaust, piping a sample of the locomotive exhaust for reading in a ground-level station.

The emissions readings for the direct RSD configuration were adversely affected by the high exhaust temperatures at the point of measurement. Therefore, the Advisory Group decided that the indirect RSD configuration was the only system ready to be used for the Phase 2 field deployment.

However, the indirect RSD (or extraction, or vacuum advance) system had limitations that needed to be addressed prior to use in the Phase 2 field study. Before proceeding to Phase 2, the indirect RSD configuration was further studied at the Colorado locomotive testing facility in an additional round of work in May 2007 to resolve some of the issues encountered in Phase 1. This effort was referred to as the Phase 2a testing.

Based on the Phase 2a testing, it was determined the indirect RSD would be more effective in locations where:

- Locomotives approached, but did not exceed, 40 miles per hour;

- There would be a high probability that locomotives would operate under high loads; and

- There was sufficient locomotive traffic to justify the placement and testing of the indirect RSD.

***Phase 2***

In Phase 2, the indirect RSD was deployed in the field for use under normal operating conditions. Consistent with the objectives, sites were chosen to obtain data from a sufficient number of locomotives to be representative of the locomotive fleet operating in California. Once the Advisory Group agreed in mid-2007 on the locations for the Phase 2 field testing, there were multiple steps that needed to be taken before in-field testing of the indirect RSD could start. These steps included issuing a task order, permitting at the site, and drawing up an access agreement.

Testing under highly controlled laboratory conditions has shown that emissions measured in the highest power setting (and under the greatest load) are generally representative of the line haul duty cycle as a whole. This power setting is referred to as Notch 8. However, Notch 8 power setting emissions can vary widely for individual line haul locomotive makes and models. For example, Notch 8 emissions can be below or above the line haul duty cycle emission standards. For a locomotive in normal operating conditions, the indirect RSD takes a 0.5 second reading of the emissions for the power setting in which the locomotive is operating (or transitioning between power settings). Therefore, the locations for Phase 2 testing were chosen such that locomotives would typically be operating in Notch 8.

The Phase 2 testing of the indirect RSD on line haul locomotives was first done in September and October 2007 at two locations in southern California, then in January and February 2008 at one location in northern California. These locations were selected for the Phase 2 field study in southern and northern California because the locomotives would operate ascending a grade of 1 to 3 percent. At such a grade, line haul locomotives would be more likely to be operating in Notch 8, and also would be operating at speeds approaching but not exceeding 40 miles per hour. There were few locations in California that would meet all of the above criteria. However, the Cajon Pass in southern California and Weimar Pass in northern California were selected, since they met the necessary grade and locomotive speed requirements. Also, the Cajon Pass provided the greatest volume of potential locomotives to test in California.

The indirect RSD provided a sampling of emissions from about 1,100 locomotives. ARB staff went through an extensive quality control process to review and analyze the indirect RSD data that ESP submitted. This process took about seven months. The indirect RSD data were then presented to the Advisory Group in June 2008. The Advisory Group review brought several data quality issues to light, requiring further data review. In January 2009, ARB staff presented the final corrected data to the Advisory Group.

#### *Phase 3*

Phase 3 was designed to relate indirect RSD emission readings to federal certification standards for locomotives. In January and February 2008, Phase 3 testing of the indirect RSD was performed under controlled laboratory conditions, in parallel with the U.S. EPA Title 40 CFR Part 92 locomotive exhaust emissions certification testing. The controlled conditions include, among other provisions, requiring the locomotive to be stationary during testing. This testing was done at the UP Roseville Railyard. To conduct the federal certification testing, SwRI brought portable equipment from their Texas location. In Phase 3, comparison testing was conducted on one Tier 0 and one Tier 2 locomotive.

## How do the results compare to the program objectives?

#### *Objective 1: Can an RSD accurately and repeatedly determine, with a reasonable level of precision, the levels of $NO_x$, PM, and CO emissions from locomotives.*

The determination of whether the RSD meets the first objective is based on an evaluation of the field testing of over 1,100 locomotives, the repeat testing of four locomotives in the field at different times, the comparison of the RSD testing to the federal test program, and the evaluation of the Colorado test track data.

Based on an evaluation of these data, ARB staff believes that the test program demonstrated that an RSD cannot accurately and repeatedly determine, with a reasonable level of precision, the levels of $NO_x$, PM, and CO emissions from locomotives. The results were relatively precise and repeatable for $NO_x$, but not sufficiently accurate to allow for the equipment's use as an enforcement mechanism. For example, 22 individual readings on a single locomotive tested at different times showed that the $NO_x$ readings average 9.2 g/bhp-hr, with a relative standard deviation of about 12 percent. Furthermore, under controlled conditions, such as at the Colorado test site, the data demonstrate that the same locomotive can yield the same repeatable values when operating at the same notch setting, speed, and load.[4]

However, due to the lack of notch setting information, there are inherent difficulties with relating the indirect RSD readings to the measurement standard in the field. These difficulties include the following:

- The locomotives were assumed to be operating in the highest power setting, Notch 8. While Notch 8 emissions levels can be representative of a full line haul duty cycle for some locomotive makes and models, there are many locomotive makes and models for which they are not. The indirect RSD cannot determine the notch settings of the locomotives passing by, nor can it be determined from the indirect RSD readings whether a locomotive was transitioning from one notch setting to another. The power setting, and transitions between power settings, can significantly impact locomotive emissions and indirect RSD readings. By comparison, the federal measurement standard is weighted over the entire line haul duty cycle of eleven power settings. Additional uncertainty is introduced in the assumptions made to calculate the resulting emissions data.

- The indirect RSD provides NO, PM, and CO data from a partial extraction of a locomotive plume. $NO_x$, the sum of $NO_2$ and NO, varies with the humidity. ARB staff had to make assumptions regarding humidity and the ratio of $NO_2$ to NO in order to convert the indirect RSD NO reading to an $NO_x$ reading. Then, based on available data, ARB staff assumed a conversion factor to convert the indirect RSD $NO_x$, PM, and CO readings to standard measurement units to allow for a comparison with the Title 40 CFR Part 92 emission results. These assumptions each introduce uncertainties in the calculated data, which combined are about ±30 percent for nitrogen oxides and particulate matter, and about ±50 percent for carbon monoxide. Also, if a locomotive was operating in a power setting other than Notch 8, or transitioning between notch settings, the uncertainty would be much greater.

Under the controlled conditions of the Phase 3 testing, the indirect RSD meets part of the first objective of the pilot program; it provides readings of locomotive $NO_x$ emissions

[4] Data from Phase 2a, Phase2, and Phase 3 testing are presented on the ARB website at http://www.arb.ca.gov/msprog/offroad/loco/loco.htm.

that are reasonably comparable to the federal test procedure data (within ±5%). However, even with these levels of comparability, the indirect RSD is not precise enough to avoid identifying complying (per Title 40 CFR Part 92) locomotives as noncomplying even under controlled conditions for $NO_x$. In addition, even under controlled laboratory conditions, the indirect RSD PM and CO readings vary considerably (±50%) from the Title 40 CFR Part 92 data. Furthermore, there was no independent verification that the indirect RSD method was accurate for determining emissions for a moving locomotive.

***Objective 2: Can an RSD accurately and repeatedly determine, with a reasonable level of precision, whether a locomotive is subject to Tier 0, 1, or 2 federal certification emission standards.***

The determination of whether the RSD meets the second objective is based on an evaluation of the field testing of over 1,100 locomotives and the comparison of the RSD testing to the federal test program.

Based on an evaluation of these data, ARB staff believes that the indirect RSD cannot directly ascertain whether a locomotive is subject to Tier 0, Tier 1, or Tier 2 federal certification standards. However, the data from the field testing generally indicate that cleaner locomotives have lower emissions, particularly for $NO_x$. This is less certain for PM and CO, although the general trend is still apparent. When a video camera is used to record the road numbers of passing locomotives, subsequent review of the road numbers and correlation to locomotive roster information can usually determine when a locomotive was built or rebuilt, and thereby the locomotive's emission tier level. However, in the case of a pre-2000 model year locomotive, the railroads' databases need to be checked to determine whether the locomotive has been remanufactured to Tier 0.

Under the controlled conditions of the Phase 3 testing, the indirect RSD readings for $NO_x$ and PM were reasonable close, and were generally within the range of the emissions expected for a Tier 0 or Tier 2 locomotive. However, for the indirect RSD, the standard deviation of the test results was higher than for the federal test procedure. This result indicates that there is greater uncertainty with the indirect RSD approach than for the federal test procedure.

***Objective 3: Can an RSD accurately and repeatedly determine, with a reasonable level of precision, whether the measured results could be calibrated to determine whether the locomotive is above or below the applicable federal certification standards.***

The determination of whether the RSD meets the third objective is based on an evaluation of the field testing of over 1,100 locomotives and the comparison of the RSD testing to the federal test program.

Based on an evaluation of these data, ARB staff believes that the test program demonstrated that an RSD cannot accurately and repeatedly determine, with a reasonable level of precision, whether the measured results could be calibrated to determine whether the locomotive is above or below the applicable federal certification standard. The field test data indicate that the average indirect RSD $NO_x$ readings are highest for unregulated (pre-Tier 0) locomotives and lowest for Tier 2 locomotives. The PM averages for Tiers 0 and 1 are about the same, while the $NO_x$ and CO averages are slightly higher for Tier 0 than for Tier 1. Nevertheless, the deficiencies and limitations noted in reading $NO_x$, PM, and CO emissions in the field make it very challenging to calibrate the indirect RSD readings to determine whether a given regulated locomotive is above or below the U.S. EPA standard.

As discussed above, under the controlled conditions of the Phase 3 testing, the indirect RSD readings for $NO_x$ and PM were reasonably close to one other for the two tested locomotives, indicating that the indirect RSD can be reasonably calibrated to approach federal test procedure readings, particularly for $NO_x$. The PM and CO values were more variable. Even so, given the variability even for the $NO_x$ readings, a precise determination of whether the locomotive is above or below the applicable federal standard would be difficult to determine on an ongoing enforceable basis.

***Overall ARB Staff Conclusions***

Based on the test program, ARB staff does not believe that the indirect RSD met the three objectives of the pilot program. Therefore, ARB staff does not recommend implementing an RSD program. However, the test program was extremely useful in answering questions about the use of RSD equipment for locomotives. For example, the field test data did generally indicate that cleaner locomotives had lower emissions than older locomotives, indicating that the U.S. EPA program for reducing locomotive emissions is working. In addition, the field test data indicated that locomotives are generally operating within the ranges expected, although not with sufficient accuracy to use the data reliably for field enforcement.

One issue that was raised during the Advisory Committee meetings was whether indirect RSD could be used to identify any specific “gross” emitters. These would be locomotives that had unusually high emissions relative to the applicable standards. The field test data identified very few incidents that would qualify a locomotive as a potential “gross” emitter, as nearly all of the readings were within the normal range of emissions readings that would be expected from pre-Tier 0, Tier 0, Tier 1, and Tier 2 locomotives. In addition, there were insufficient data to confirm that a particular locomotive was actually malfunctioning versus going through a notch setting change which might explain the higher emissions. This uncertainty does not justify cost of taking a locomotive out of service on the possibility that it might be exceeding an applicable standard by a large margin. As a result, ARB staff does not recommend deploying the indirect RSD for purposes of “gross” emitter evaluations.

Implementation of an indirect RSD monitoring program should also be analyzed in consideration of two existing monitoring programs, the visible emissions reduction program and the U.S. EPA in-use test program. The visible emissions reduction program shows that greater than 99 percent of up to 20,000 annually tested locomotives comply with the visible emissions standard. In addition, the U.S. EPA in-use test program has not yet tested one locomotive failing to meet federal certification standards. Furthermore, locomotives are required by federal regulation to have regularly scheduled maintenance (at least every 92 days), and are diagnostically checked at each refueling to identify any potential fuel injector or other potential engine problems to avoid engine de-rating (i.e., a loss of horsepower and not being able to pull a train over a mountain or long range route) and a loss in fuel efficiency.

Locomotives are also generally subject to more stringent maintenance requirements than diesel trucks or other related transportation sources. This stringency is necessary to ensure a much higher level of reliability and durability so that trains do not block the movement of goods on single or double tracks along the nation's rail system. As discussed above, locomotive maintenance requirements are complemented with an ongoing national opacity testing program and a federal in-use locomotive emission testing program to also ensure that locomotives are running properly on an ongoing basis.

## What comments did the Advisory Group have on the report?

In the entire process of developing and implementing the remote sensing device study, considerable effort was always extended to accommodate and address the specific concerns, questions, and issues raised by the AB 1222 Advisory Group in order to reach a broad consensus on the test program. This consensus process, although time-consuming, resulted in a more comprehensive program to test RSD than originally envisioned.

In general, the Advisory Committee members agreed with the overall findings of the report. Dr. Donald Stedman, the Brainerd Phillipson Professor of Chemistry and Biochemistry at the University of Denver, went further in commenting on the report, stating that even a perfect sensor of emissions of passing locomotives, whether RSD or any other sensor, would probably not be able to meet the initial goals of the pilot program.

However, some participants believe the indirect RSD has more value than does ARB staff. The South Coast Air Quality Management District (SCAQMD) staff commented that the pilot study showed that the indirect RSD is a viable tool in identifying high emitting locomotives and that the report should provide recommendations to implement an RSD emissions monitoring program. The SCAQMD comments are presented as Appendix C. ESP representatives also generally concurred with the SCAQMD's conclusion and wrote that the indirect RSD system successfully measured emissions from 1,100 passing locomotives, and that the operational issues associated with field deployment should be separated from the capabilities of the indirect RSD. Although

ARB staff does not support further deployment, the report does provide some data on the cost of deploying an indirect RSD system.

# I. Introduction

## A. Summary of Assembly Bill 1222 Requirements

On October 6, 2005, Governor Schwarzenegger signed Assembly Bill 1222 (AB 1222, Health and Safety Code Sections 39940 – 39944: See Appendix A). This bill, proposed by Assemblyman Dave Jones, required the Air Resources Board (ARB) to implement a pilot program to determine emissions from locomotives, using a wayside remote sensing device (RSD). The objectives of the pilot program were to determine whether an RSD could accurately and replicably determine, with a reasonable level of precision:

1. The levels of nitrogen oxides ($NO_x$), particulate matter (PM), and carbon monoxide (CO) emissions from locomotives;

2. Whether a locomotive is subject to Tier 0, 1, or 2 federal certification emission standards; and

3. Whether the measured results could be calibrated to determine whether the locomotive is above or below the applicable federal certification standards.

In support of the objectives, the remote sensing testing was to include data from a sufficient number of locomotives that would be representative of the locomotive fleet operating in California, and to ensure that data collection be performed under representative conditions in northern and southern California. In conducting the pilot program, ARB was to establish an advisory group to make recommendations regarding the design and implementation of the pilot program. Finally, the ARB was to submit a report to the Legislature that included both of the following:

1. A summary of data acquired through the pilot program; and

2. The ARB's determination as to whether RSDs can meet the objectives of the pilot program.

If ARB determined that RSDs could be expected to meet objectives of the pilot program to an extent reasonably sufficient to allow the ARB to make the following projections and recommendations, the report was also to include both of the following:

1. To the extent feasible, a projection of the amount, location, and timing of emission reductions that could be expected from the use of RSDs to identify locomotives to be repaired or maintained; and
2. An ARB projection of the cost to deploy, maintain, and use data from a system of RSDs in areas of high priority in the State, recommendations regarding the funding of such a project, and the expected cost-effectiveness of such a program compared to other opportunities for air quality improvement in the covered areas.

AB 1222 required that the pilot program be developed and implemented in consultation with an Advisory Group comprised of a total of 14 members representing the Union Pacific Railroad (UP), BNSF Railway (BNSF), South Coast Air Quality Management District (SCAQMD), Sacramento Metropolitan Air Quality Management District (SMAQMD), citizen groups, and remote sensing and locomotive technology experts. AB 1222 also required that the remote sensing testing for the pilot program include data from a sufficient number of locomotives that would be representative of the locomotive fleet operating in California.

A report was to be submitted to the Legislature on or before December 31, 2006 containing:

- **Monitoring Results:** A summary of the monitoring results;
- **Use:** Recommendations of the applicability of remote sensing devices and the associated system to meet the specified objectives;
- **Emissions Reductions:** Estimates (if the remote sensing devices meet the objectives), of the amount, location and timing of emissions reductions that could be expected from using such devices to identify locomotives in need of repair and/or maintenance;
- **Costs:** Estimates of the cost to establish, maintain and use data from such remote sensing systems in areas deemed to be high priority by the ARB; and
- **Effectiveness:** Recommendations on the effectiveness of this program compared to others for improvement of air quality in the covered areas.

However, remote sensing of locomotives was found to pose unique technical challenges, necessitating the development of a much more complex program than had been anticipated when AB 1222 was written. Therefore, completion of the program was delayed to ensure that a thorough assessment of identified issues was conducted and the program was completed in a sound and scientifically defensible manner.

## B. Background on Remote Sensing

Remote sensing is a way to determine pollutant levels in a vehicle's exhaust while the vehicle is traveling. Unlike most equipment used to determine vehicle emissions, an RSD does not need to be physically connected to the vehicle.

An RSD system employs an infrared (IR) beam to determine hydrocarbon (HC) and CO emissions, and an ultraviolet (UV) beam to determine PM and nitric oxide (NO) emissions. As the vehicle passes through the IR and UV beams, the device calculates the ratio of CO, HC, and NO to carbon dioxide before the exhaust plume and in the exhaust plume. The system uses the reading before the exhaust plume as a baseline to correct the plume reading for ambient effects, then calculates ratios of pollutant to expected exhaust gases assuming normal combustion chemistry. PM is calculated from a smoke factor determined by the UV beam. $NO_x$, the sum of NO and nitrogen dioxide ($NO_2$), is calculated from the NO reading by using an empirically determined $NO_2$ to NO ratio.

RSD systems employ video camera equipment to digitize an image of the vehicle, allowing processing of the emissions information for each monitored vehicle based on the vehicle's identification (license plate number, road number, etc.).

The first published study of remote sensing of railroad locomotive emissions was a feasibility study performed by the University of Denver (DU) in 1999 [Popp, P. et al., 1999: See Appendix B]. This study consisted of two field locations in Nebraska, using two locomotives at one location and four locomotives at the second location. An RSD previously developed by DU for determining pollutants in motor vehicle exhaust was used to evaluate NO, CO, and HC emissions from the locomotive engines. Under the controlled conditions of the DU study, the RSD results for NO were shown to be comparable to laboratory testing results for a similar locomotive engine; CO and HC appeared to be below the RSD's detection limit.

The AB 1222 pilot program is the most comprehensive test program ever conducted to evaluate RSDs for locomotives, with data collected from more than a thousand locomotives, in three different locations, and under normal operating conditions.
For locomotive emissions, the federal measurement standard is Title 40 Code of Federal Regulations (CFR) Part 92. This is the U.S. EPA test method used to determine compliance with federal locomotive emission standards. Title 40 CFR Part 92 emission testing is performed on stationary locomotives under highly controlled laboratory testing conditions, with a load bank used to simulate operating conditions. The locomotive is run for at least six minutes in each of the eleven power settings, with data from each power setting weighted over the entire line haul duty cycle.[5]

The RSD, on the other hand, is applied to a moving locomotive under normal operating conditions. As the locomotive passes by the RSD, a reading is taken from part of the plume for half a second. The RSD reading is an instantaneous plume reading in a specific locomotive power setting – the power setting in which the locomotive happens to be operating. The RSD reading is then correlated to a stationary line haul duty cycle emission testing performed under controlled conditions.

This report presents the results of the RSD test program.

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[5] See Appendix E for a more detailed explanation of Title 40 CFR Part 92.

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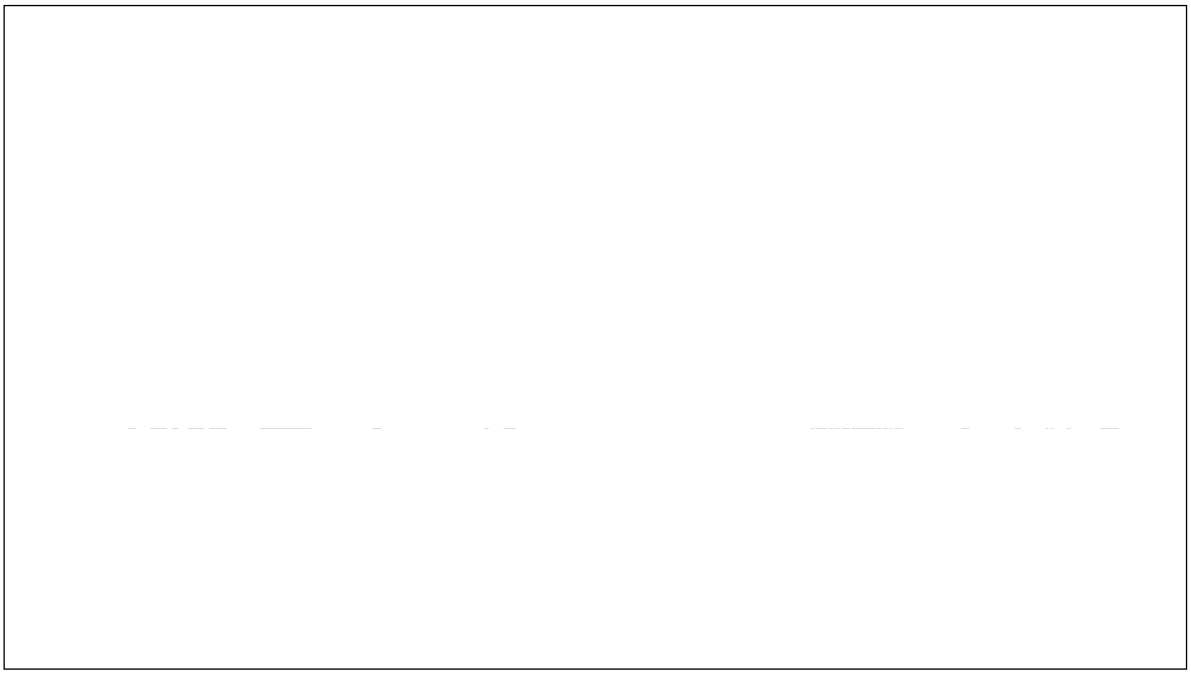
## II. The Remote Sensing Pilot Program

ARB staff leased the RSDs used for the study from the Bureau of Automotive Repair (BAR) of the Department of Consumer Affairs. Studies had already been published on the use of the RSD to collect emission data for motor vehicles.[6] The schematic below shows a typical setup for a motor vehicle RSD.[7]

**Figure 1: Automobile RSD**



AB 1222 required that the pilot program be developed and implemented in consultation with an Advisory Group comprised of a total of 14 members from the Union Pacific Railroad (UP), BNSF Railway (BNSF), South Coast Air Quality Management District (SCAQMD), Sacramento Metropolitan Air Quality Management District (SMAQMD), citizen groups, and remote sensing and locomotive technology experts. AB 1222 provided that UP and BNSF railroads would appoint 50 percent of the members to the Advisory Group, and that the other 50 percent would be appointed by the SCAQMD and SMAQMD. AB 1222 permitted the ARB to contract with an independent entity to conduct the pilot program in consultation with the Advisory Group.

[6] See, for example: Kolb, C., Herndon, S., et al., *Mobile Laboratory with Rapid Response Instruments for Real-Time Measurements of Urban and Regional Trace Gas and Particulate Distributions and Emission Source Characteristics.* Environmental Science and Technology, 2004, pp. 5694-5703. Eastern Research Group, Inc., *Evaluation of Remote Sensing for Improving California's Smog Check Program*, March 2008.

[7] Stedman, D. and Bishop, G., *An Analysis of On-Road Remote Sensing as a Tool for Automobile Emissions Control*, University of Denver Chemistry Department, February 1990.

Based on the selection criteria, the following fourteen people were appointed in January 2006 to serve as the AB 1222 Advisory Group members to assist the ARB in the development and implementation of the remote sensing pilot project. Table 1 lists the members and their affiliations.

**Table 1**
**AB 1222 Advisory Group Member List**

| Name | Affiliation |
|---|---|
| Chung Liu<br>(Alternate: Dean Saito) | South Coast Air Quality Management District (SCAQMD) |
| Tom Christofk<br>(Alternate: Larry Greene) | Placer County Air Pollution Control District<br>(Alternate: SCAQMD) |
| James R. Hazelton | Hazelton Consulting, Ltd. |
| Franklin Weinstein | Community Representative from Placer County |
| Douglas Lawson | National Renewable Energy Laboratory |
| Penny Newman<br>(Alternate: Rachel Lopez) | Center for Community Action and Environmental Justice (CCAEJ) |
| Angelo Logan<br>(Alternate: Sylvia Betancourt) | East Yard Communities for Environmental Justice (EYCEJ)<br>(Alternate: CCAEJ) |
| Mike Iden | Union Pacific Railroad (UP) |
| Lanny Schmid | UP |
| Gary Rubenstein | Sierra Research, Inc. |
| Mike Stanfill | Burlington Northern Santa Fe Railway Company (BNSF) |
| Larry Milhon | BNSF |
| David Brann | Electro-Motive Diesel, Inc. (EMD) |
| Peter Okurowski | California Environmental Associates (CEA) |

The Advisory Group held its first meeting on January 31, 2006. From January 2006 through May 2009, the Advisory Group has held a total of 35 meetings. Table 2 presents the dates of the meetings. All meetings were held in Sacramento.

**Table 2**
**AB 1222 Advisory Group Meeting Dates**

| Advisory Group Meeting | Meeting Date |
|---|---|
| 1st | January 31, 2006 |
| 2nd | March 3, 2006 |
| 3rd | March 22, 2006 |
| 4th | April 5, 2006 |
| 5th | April 13, 2006 |
| 6th | May 3, 2006 |
| 7th | May 18, 2006 |
| 8th | June 1, 2006 |
| 9th | June 20, 2006 |
| 10th | July 12, 2006 |
| 11th | July 25, 2006 |
| 12th | August 8, 2006 |
| 13th | September 6, 2006 |
| 14th | October 31, 2006 |
| 15th | November 8, 2006 |
| 16th | November 10, 2006 |
| 17th | January 10, 2007 |
| 18th | January 31, 2007 |
| 19th | February 23, 2007 |
| 20th | March 27, 2007 |
| 21st | April 24, 2007 |
| 22nd | May 21, 2007 |
| 23rd | June 15, 2007 |
| 24th | July 9, 2007 |
| 25th | July 19, 2007 |
| 26th | August 23, 2007 |
| 27th | September 25, 2007 |
| 28th | October 2, 2007 |
| 29th | November 6, 2007 |
| 30th | November 27, 2007 |
| 31st | December 18, 2007 |
| 32nd | January 11, 2008 |
| 33rd | January 17, 2008 |
| 34th | June 12, 2008 |
| 35th | January 6, 2009 |

In the three initial advisory committee meetings in early 2006, the Advisory Group discovered that remote sensing of locomotives posed unique technical challenges, necessitating the development of a much more complex pilot program than had been anticipated. Numerous technical issues had to be resolved.

The major task for the Advisory Group was to develop and agree on a complete test plan that met all of the requirements of AB 1222. Some issues in developing the test plan were:

- If and where remote sensing equipment pre-deployment testing should occur;
- Where and how much field testing of the remote sensing equipment should occur;
- If and where testing of the remote sensing equipment would be conducted in parallel with the U.S. EPA Federal Testing Procedure protocol for locomotives (Title 40, U.S. Code of Federal Regulations, Part 92); and
- What testing made sense to do in California, and what testing should be done at facilities located outside of California.

This whole process took about nine months and thirteen Advisory Group meetings, from January 2006 to the fall of 2006, when the Advisory Group approved a three-phase test plan for the RSD:

- Phase 1: Adaptation of the RSD to measure locomotive emissions.
- Phase 2: Field deployment and field sampling.
- Phase 3: Correlation testing.

As planned, Phase 2 would provide a sampling of emissions from a large group of locomotives that travel in California, and would also address the AB 1222 requirement that readings be obtained for an adequate sample to be representative of the locomotive fleet operating in California. The data from Phase 2 would be sorted to develop population distributions for the sampled fleet, potentially allowing for parameters to be established for identification of “gross” or “excessive” polluters in the California locomotive fleet.

## A. Phase 1: Adaptation of RSD to Read Locomotive Emissions

This phase was designed to make the necessary adjustments to the RSD unit leased from BAR so that it could read diesel locomotive NO[8], PM[9], and CO emissions. The RSD reads NO, PM, and CO. The necessary adjustments would be determined through multiple locomotive emission readings under controlled conditions to establish ‘precision’ levels for the RSD. Phase 1 included two elements. These elements are discussed in the following sections.

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[8] AB1222 specifies $NO_x$, the sum of NO and nitrogen dioxide $NO_2$. $NO_x$ is calculated from the RSD NO reading by using an assumed $NO_2$ to NO ratio.
[9] Determined from a smoke factor, which is used as a surrogate for PM.

### *Element 1: Evaluation of field installation logistics*

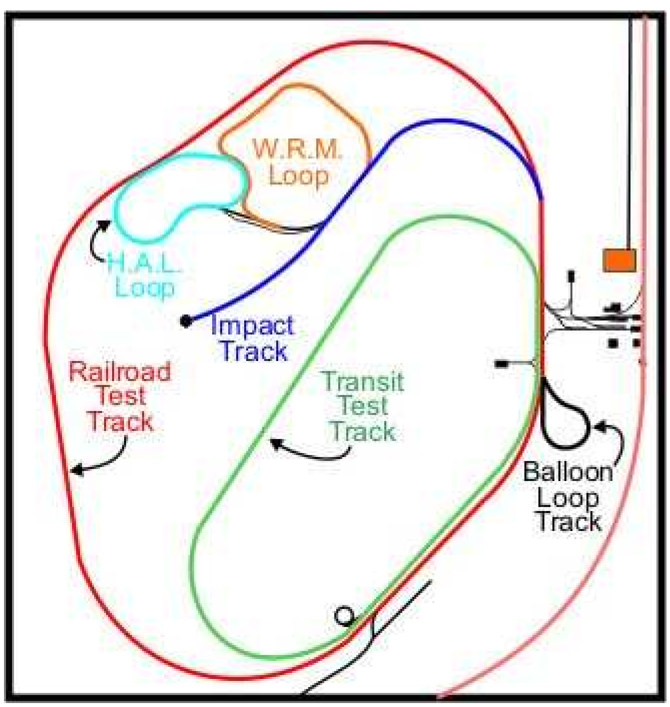
This element was for the evaluation and assessment of RSD equipment to read locomotive emissions and to make the RSD equipment adjustments needed for use both in the field and for laboratory correlation.

BAR provided four gasoline vehicle RSDs from their inventory. The four RSDs were manufactured by Environmental Systems Products (ESP) in 2002. The gasoline vehicle BAR RSDs were modified by ESP to read diesel emissions from locomotive exhaust stacks. The changes in the RSDs entailed numerous technical modifications by ESP at their facility in Tucson, Arizona. This work was initiated in September 2006 and took about two months.

### *Element 2: Testing for establishing field deployment issues*

In this second element of Phase 1, the modified RSD was used at the Railroad Test Track at the Transportation Technology Center Inc. (TTCI) testing facility in Pueblo, Colorado to sample plumes from locomotives. TTCI was made available for this study by UP and BNSF. The Railroad Test Track at TTCI provides controlled track conditions for safety, accessibility, and availability issues that would arise in attempting to use an active railyard.

**Figure 2: TTCI Testing Facility**



After reviewing BNSF and UP railyard operations and line operations, the Advisory Group decided to pursue two separate configurations for the RSD equipment at TTCI, a direct RSD configuration and an indirect RSD configuration (see Figure 3):

- **Direct RSD Configuration –** a conventional remote sensing approach, designed for testing of locomotives during line operations, with the entire RSD equipment set positioned above the track and at the height of the locomotive exhaust. The IR and UV beams cross the locomotive exhaust.

- **Indirect RSD Configuration –** designed to allow repeated testing of switcher (yard) locomotives moving slowly in a railyard. The indirect RSD is a large sample extraction system, with a sampling tube located directly above the track at the height of the locomotive exhaust. An air diluter blower extracts a sample from the locomotive's exhaust, and then pipes it to a ground-level accumulator box, wherein the IR and UV beams cross the sample. The indirect RSD can be operated as a static test station or, with addition of a camera and triggering subsystems, as a pass-through station.

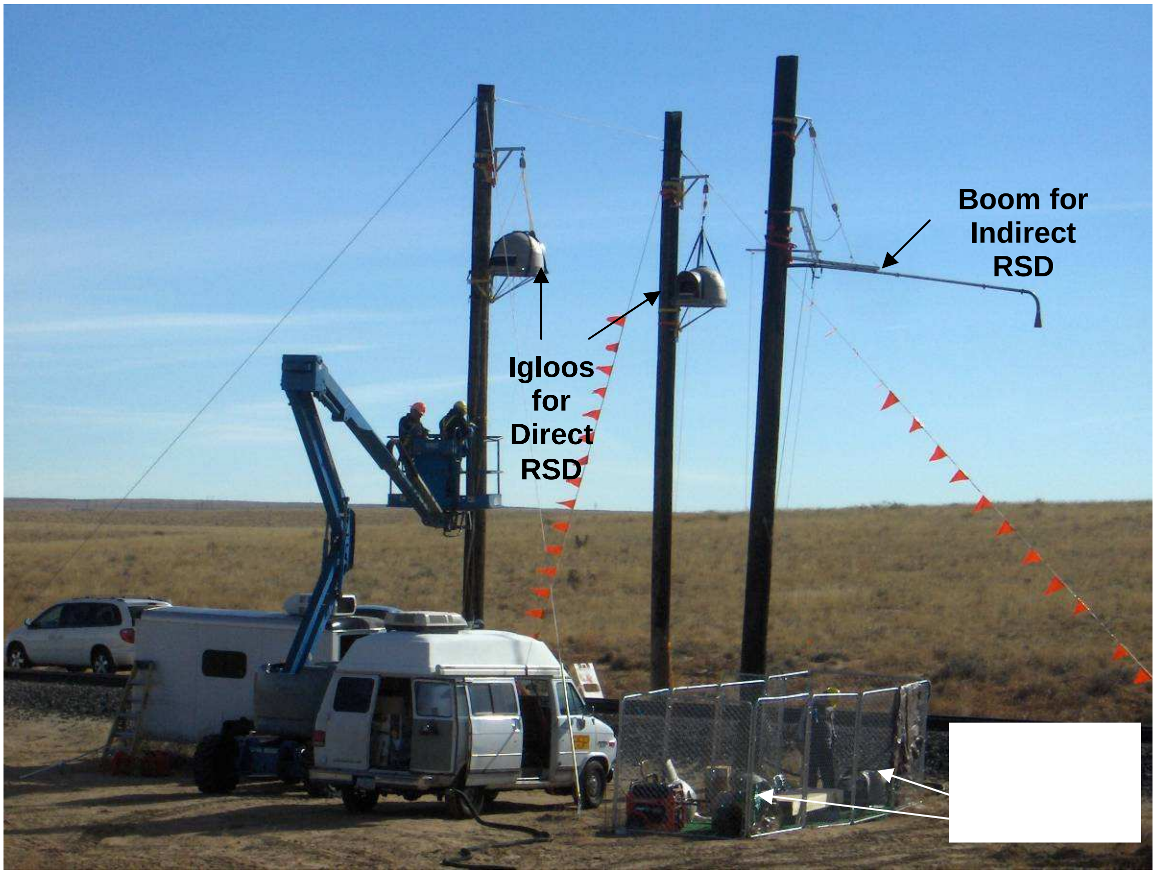
For both the direct RSD configuration and the indirect RSD configuration, a two-locomotive consist was used, with a BNSF Tier 2 locomotive and a UP pre-Tier 0 locomotive.

Two weeks of testing took place at TTCI in January and February 2007. Looping the consist around the track provided information on the precision of the RSD system through repeat sampling of emission plumes from the same group of locomotives.

The direct and indirect RSD configurations were set up as shown in Figure 3.

As the locomotive went by, a motion detector triggered the recording device. At that time, both the direct RSD configuration and the indirect RSD configuration took instantaneous NO, CO, ultraviolet smoke (for PM calculations), and $CO_2$ data every 10 milliseconds. Fifty data points, over a total of 0.5 second, are recorded. The recorded data are then used to calculate an NO reading, a CO reading, and a PM reading for the plume.

**Figure 3: Direct and Indirect RSD Configurations**




Some technical issues arose during the testing:

- Neither the direct RSD nor the indirect RSD configuration was able to distinguish between locomotive steady-state operation and transitions between notch (i.e., power) settings. This would significantly limit the selection of sites for field implementation in Phase 2. Sites would need to be chosen where locomotives generally operate in a steady-state mode, and in the same notch (power) setting.

- With the direct RSD configuration, the NO readings were consistently about half the level of the NO readings with the indirect RSD configuration: locomotive emission readings for the direct RSD were significantly affected by the hot exhaust plume temperature. The indirect RSD, however, was able to provide stable and reproducible NO readings for the Tier 2 locomotive:
  - Within a range of 0 to about 40 miles per hour,
  - Operating in higher notch settings (Notches 5 through 8), and
  - Operating in lower notch settings under low wind conditions.

- Even with the indirect RSD configuration, emission readings from the pre-Tier 0 locomotive were neither stable nor reproducible.

In view of the technical issues that arose in Element 2 of Phase 1, the Advisory Group conferred in March 2007 and made several decisions:

- More testing was needed before proceeding to the Phase 2 field deployment and sampling.

- While compensation for the effect of high exhaust temperatures on the direct RSD configuration might be feasible, further testing would be done only with the indirect RSD configuration.

- The indirect RSD (or extraction, or vacuum advance) system had limitations that needed to be addressed by the Advisory Group before proceeding to the Phase 2 field study:

  - The indirect RSD configuration needed modifications to provide readings for large numbers of locomotives in line haul operation.

  - Pre-Tier 0 locomotives needed further evaluation in order to determine whether the stability and reproducibility issues encountered in Phase 1, Element 2 were due to the RSD technology or due to pre-Tier 0 locomotives themselves.

In the March 2007 meeting, the Advisory Group decided to test the indirect RSD configuration on a group of pre-Tier 0 locomotives in a new round of testing, Phase 2a, at the TTCI facility in Pueblo, Colorado before proceeding with Phase 2 field deployment.

### B. Phase 2a: Unresolved Issues from Phase 1, Element 2

Phase 2a testing of the indirect RSD configuration (hereinafter referred to as the indirect RSD) was performed over four days at the TTCI facility in Pueblo, Colorado in early May 2007, five months after completion of Phase 1, Element 2. A group of four pre-Tier 0 locomotives connected in series was used for the testing. Additional funding for Phase 2a was provided by ARB and SCAQMD.

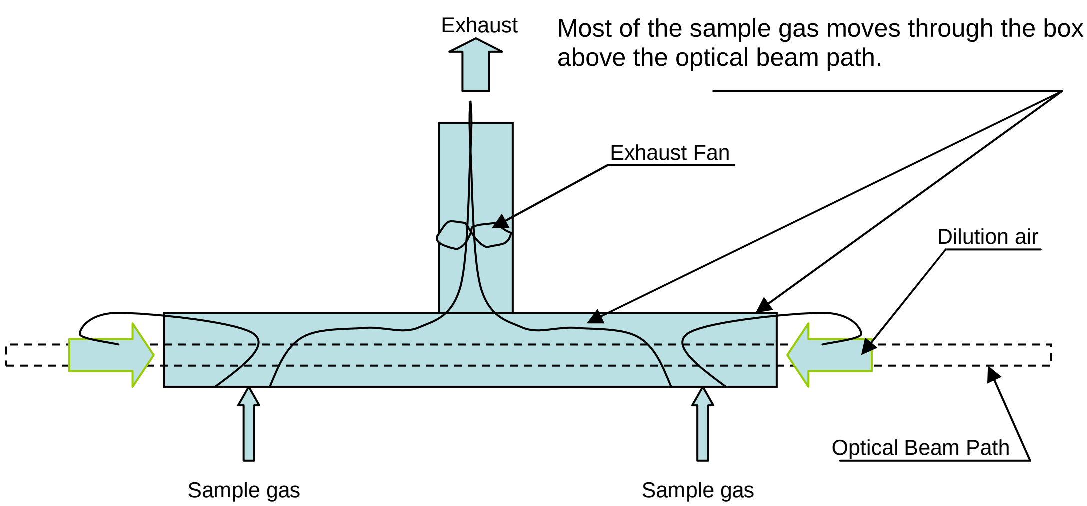
When the locomotives were operating in a constant notch setting, the NO data for each locomotive fell within about ±20 percent of the mean. The indirect RSD station was positioned where the locomotives were operating in the highest power setting, Notch 8, at about 40 miles per hour. However, the amount of established time in Notch 8 could vary considerably. Prior Phase 1 test results indicated that the tested pre-Tier 0 locomotives could produce unstable emissions for up to 2 minutes after a notch transition. The ±20 percent $NO_x$ variability could be due to the amount of time in Notch 8, rather than lack of precision on the part of the indirect RSD.

Data from the Phase 2a testing are presented on the ARB website at http://www.arb.ca.gov/msprog/offroad/loco/loco.htm. Analysis of the results indicated that there were several remaining technical issues associated with remote sensing of locomotive emissions:

- **Equipment Reliability:** Generator failure resulted in non-collection of data on one of the four days.

- **Low Rate of Valid Readings:** About 20 percent of the NO readings for the locomotive in the front position of the four-locomotive consist were valid; for the subsequent three locomotives in the consist, about 30 to 40 percent of the NO readings were valid. Further analysis by ESP showed that dynamic effects in the accumulator box were a significant cause of the high rate of invalid readings. Performance of the indirect RSD varies considerably with positioning of the beam path within the accumulator box. Sufficient gas must be sampled to obtain a valid reading. As the sample gas was moving through the accumulator box during Phase 2a, most of the sample flow was at the top of the box – above the optical beam path – with some leakage out the ends. The expected amplification was not obtained and there was too much accumulation. Subsequent to Phase 2a testing, a flow direction grill was added to direct the sample gas velocity to the middle of the accumulator box, in the path of the optical beam.

**Figure 4: Flow in Accumulator Box During Phase 2a**




- **Wind Turbulence:** The large wind pressure front faced by the front locomotive could significantly compress the sample head to an extent that the sampling flow could be significantly reduced, leading to the lower rate of valid readings noted for the front locomotive.

- **Billowing Effect:** For locomotives operating specifically within a railyard, the low velocity could potentially allow for locomotive plumes to billow, making it difficult or impossible to distinguish among the plumes in a multiple-locomotive consist.

The Advisory Group addressed the challenges encountered in Phase 2a before proceeding with Phase 2 field testing. More expensive and rugged generators were purchased. The equipment for the indirect RSD was modified by the addition of direction grills to direct the sample gas flow to the middle of the accumulator box, directly in the path of the optical beam. Also, the amount of overall flow in the sampling system needed to be significantly increased in order to minimize dwell time in the optical sampling path to avoid accumulating and mixing the readings from individual locomotives at speeds greater than 40 miles per hour. Reinforcements were added to the sample head to prevent compression due to wind turbulence from affecting the emissions readings for the front locomotive.

The Advisory Group decided that, with these modifications, the indirect RSD units were able to provide stable, reproducible readings regardless of locomotive tier, and were now ready for Phase 2 field deployment.

### C. Phase 2: Field Deployment and Fleet Sampling

For Phase 2, the indirect RSD configuration was tested both for line haul locomotives operating within a railyard and for line haul locomotives in rail operation (road use). The data from Phase 2 would be sorted to develop population distributions for the sampled fleet. Potentially, this would then allow for parameters to be established for identification of “gross” or “excessive” polluters in the California locomotive fleet.

From the earliest Advisory Group meetings, the selection of sites for implementation of Phase 2 was a frequent topic of discussion. Consistent with the direction of AB 1222, the Advisory Group looked for sites for both the rail line testing and yard testing of the indirect RSD in northern California and southern California. Also, the sites for yard testing would need to be larger railyards, and the sites for rail line testing would need to have heavy traffic of both BNSF and UP locomotives. Sites chosen according to these criteria would provide a sampling of emissions from a large group of geographically representative locomotives that travel in California, thereby addressing the AB 1222 requirement that sufficient data be obtained to ensure testing of a representative sample of the locomotive fleet operating in California. Furthermore, rail line and yard locations in northern and southern California needed to be chosen so as not to interrupt routine operations or to raise safety issues.

Examination of in-use testing data under the highly controlled laboratory testing conditions of Title 40 CFR Part 92, which measures and then weights emissions over the entire line haul duty cycle, had shown that locomotive emissions in the highest notch setting, Notch 8, were generally representative of the line haul duty cycle as a whole. However, Notch 8 power setting emissions can vary widely for individual line haul locomotive makes and models: Notch 8 emissions can be below or above the line haul duty cycle emission standards. For a locomotive in normal operating conditions, the indirect RSD takes a single reading, which is either at just one power setting or transitioning between power settings. Rail line locations with a positive grade were chosen for Phase 2 testing to increase the likelihood that the indirect RSD readings would be from locomotives operating in Notch 8.

As a result of the February 2007 Phase 1 testing and May 2007 Phase 2a testing at TTCI, additional factors came into play in the selection of Phase 2 sites. The TTCI Phase 1 and Phase 2a testing showed that the indirect RSD provided stable and reproducible NO readings for locomotives operating in higher notch settings, at speeds of about 40 miles per hour.

In mid-2007, the Advisory Group selected three locations for testing of the indirect RSD configuration on line haul locomotives in three rail locations: two in southern California, and one in northern California. These locations were selected for the Phase 2 field study in southern and northern California because the locomotives would operate ascending a grade of 1 to 3 percent. At such a grade, line haul locomotives would be more likely to be operating in Notch 8, and at speeds approaching but not exceeding 40 miles per hour.

The two locations in southern California were both at the Cajon Pass, which is about 13 miles northwest of San Bernardino, at the junction of I-15 and SR-138 (See Figure 5). The Cajon Pass is a mountain pass between the San Bernardino Mountains and the San Gabriel Mountains,[10] with a 2 to 3 percent eastbound grade, so there is a high probability that the eastbound locomotives would be operating in Notch 8. The Cajon Pass is within the South Coast Air Basin, near its northern boundary. Union Pacific Railroad has one railroad track through the pass, and BNSF Railway has two tracks: the three Cajon Pass tracks together have up to 100 trains per day inbound and outbound from the South Coast Air Basin. AB 1222 remote sensing testing was only performed in the outbound (eastbound) direction, because locomotives in the inbound direction (i.e., descending the Cajon grade) were more likely to be in dynamic brake mode.

[10] http://en.wikipedia.org/wiki/Cajon_Pass

**Figure 5: Field Deployment in Southern California at Cajon Pass**

The northern California location was about 50 miles northeast of Sacramento in Weimar, where UP has a railroad track (See Figure 6). The track at Weimar has an eastbound grade of about 1 percent, so there is a high probability that locomotives heading east would be operating in Notch 8. The Weimar location is in the Placer County Air Pollution Control District. Eastbound and westbound traffic totals about 20 trains per day. AB 1222 remote sensing testing was only performed in the eastbound direction, because locomotives in the westbound direction (i.e., descending the Weimar grade) were more likely to be in dynamic brake mode.

**Figure 6: Field Deployment in Northern California at Weimar**


For testing of the indirect RSD configuration on line haul locomotives in yard operation, the Advisory Group selected two locations: UP Colton (about 55 miles east of Los Angeles) in southern California and UP Roseville (about 20 miles northeast of Sacramento) in northern California.

Once the Advisory Group agreed in mid-2007 on the locations for Phase 2 rail line and yard operation, there were multiple steps that needed to be taken before in-field testing of the indirect RSD could start: issuing a task order to procure equipment; fabrication, testing, and delivery of the equipment; and site permitting. Site permitting consisted of preparation of engineering drawings, approval by UP and BNSF, and drawing up an access agreement.

***Line Haul Operations***

The Phase 2 testing of line haul locomotives in line haul operation was first done in southern California at the Cajon Pass, then in northern California at Weimar.

- BNSF Cajon - September 19, 2007 through October 5, 2007.
- UP Cajon - September 24, 2007 through October 7, 2007.
- Weimar - January 24, 2008 through February 7, 2008.

At all three locations, the indirect RSD took readings from locomotives ascending the grade; locomotive speeds were typically 15 to 20 miles per hour. Locomotives descending the grade were in dynamic brake mode and were not monitored by the indirect RSD. Fifty data points, over a total of 0.5 second, were recorded. The recorded data were then used to calculate an NO reading, a CO reading, and a PM reading for the plume. The indirect RSD would then wait 0.4 second. If it detected a plume, either from the same locomotive or from another locomotive, it would again record fifty data points over 0.5 second.

A video camera taped the passing locomotives, which provided locomotive identification information (i.e., company and road numbers). During nighttime video operation at Cajon, locomotive headlight blooming often created a problem in reliably identifying road numbers, especially for the first locomotive in a consist. This problem was corrected for northern California deployment at Weimar, where the camera was aimed in the direction of train traffic.

The indirect RSD data and video records were prepared and reviewed by ESP staff, then submitted to ARB in late 2007 and early 2008. The data submitted were average, maximum, and minimum indirect RSD readings for NO, PM, and CO as the locomotive ascended the grade at UP Cajon, BNSF Cajon, and Weimar.

ARB staff went through an extensive review process; this process took about seven months. The video records (most often video clips and JPEG photographs, but in some cases only JPEG photographs) were examined to ensure that the locomotives were correctly identified. The average indirect RSD readings were used to calculate $NO_x$, PM, and CO emissions for each locomotive. Some locomotives at UP Cajon and BNSF Cajon were noted to ascend the grade more than once. For the repeat locomotives, the

$NO_x$, PM, and CO emissions were calculated for each time the locomotive ascended the grade.

Statistical analyses were performed to compare the indirect RSD data to the U.S. EPA locomotive emissions standards. In June 2008, ARB staff made a presentation of the preliminary indirect RSD data to the Advisory Group.

Advisory Group review after the June 2008 presentation brought several issues to light:

- **Data Issue #1:** Some indirect RSD readings were assigned to the wrong locomotive.

- **Data Issue #2:** The average, maximum, and minimum indirect RSD readings as the locomotive ascended the grade were generally determined from a larger sample (from the main part of the plume) and one or more smaller samples (from the periphery of the plume, where the emission readings could be different).

- **Data Issue #3:** Some locomotives were assigned indirect RSD readings with samples from mixed plumes (i.e., the sample taken over the 0.5 second interval was from two locomotives).

- **Data Issue #4:** Some locomotive road numbers were incorrect.

To aid in resolving these data issues, ARB requested raw indirect RSD data. The raw data consisted of the fifty data points, taken over a total of 0.5 second, used to calculate each NO, PM, and CO reading for the plume. ARB staff then carefully reviewed the raw indirect RSD data. The video clips and JPEG photographs were reviewed once again in the light of the newly raised data issues.

- **Data Issue #1: Assigning indirect RSD readings to the right locomotive**

  Each NO, PM, and CO reading for the plume was time-stamped corresponding to the start of the 0.5 second collection interval. Each video clip was time-stamped at the beginning and each of the JPEG photographs was also time-stamped.

  Where the video clips were available, the start and finish time for each locomotive as it passed the indirect RSD was determined by adding the elapsed times at the locomotive's start and finish to the video clip's time stamp. Typically, the difference between the locomotive's start and finish was 2 to 3 seconds.

  Where video clips were not available, the JPEG photographs were used. If the photograph showed the locomotive's start, the time stamp was used as the start time, with 2.5 seconds added to estimate the finish time; if the photograph showed the locomotive's finish, the time stamp was used as the finish time, with 2.5 seconds subtracted to estimate the start time.

Indirect RSD readings within the start and finish time bin for a locomotive were assigned to that locomotive. Unfortunately, the indirect RSD clock and/or the camera clock drifted. This problem was not noted until ARB staff review of the raw indirect RSD data. ARB staff resolved this problem by determining a calibration factor for each day's indirect RSD time stamps, allowing each day's indirect RSD readings to be matched with each day's locomotive start and finish times. If, as a result of this procedure, an indirect RSD reading could not be attributed to a locomotive, the indirect RSD reading was not usable.

- **Data Issue #2: Indirect RSD readings with more than one sample**

  With the review of the raw indirect RSD data, ARB spoke with ESP and decided that sample bias could be avoided by:

  - Assigning only one indirect RSD reading to each locomotive.
  - Only using indirect RSD readings from large samples.[11] If, as the locomotive ascended the grade, there was more than one indirect RSD reading from a large sample, only the largest sample was used.
  - If the only indirect RSD readings for a locomotive were from small samples, then the locomotive was assigned no indirect RSD readings at all.

- **Data Issue #3: Indirect RSD readings with mixed plumes**

  Review of the raw indirect RSD data showed that some of the large samples were in fact mixed plumes from two locomotives: for the 0.5 second that the indirect RSD took a reading, it read from the end of one locomotive's plume and the beginning of the next locomotive in the consist. In each case, the mixed plume sample was replaced with a different large sample for a single locomotive.

- **Data Issue #4: Incorrect Road Numbers**

  ARB staff double-checked the video clips and JPEG photographs, and corrected road numbers as necessary.

Making these corrections to the indirect RSD data was a complex, labor-intensive process that took about five months. ARB staff presented the corrected data to the Advisory Group in January 2009.

[11] Size of sample was determined from maximum $CO_2$ level, reported in units of *percent* $CO_2 \bullet$ *cm of column*. Examination of the data showed that maximum $CO_2$ levels ranged from 10 to about 340: samples with maximum $CO_2$ level below 40 were considered small samples. For the large samples, the average maximum $CO_2$ level was about 140.

The indirect RSD data for each of the three locations are summarized below. Note that the indirect RSD data are available on the ARB website at http://www.arb.ca.gov/msprog/offroad/loco/loco.htm.

**BNSF Cajon**

- Usable data for 834 different locomotives.
- 120 of the 834 locomotives were repeat locomotives, providing indirect RSD data more than once; 4 of the 120 repeat locomotives had four or more indirect RSD readings.
- Including repeat locomotives, there were a total of 997 indirect RSD readings.
- Indirect RSD readings were obtained for 58 percent of the videotaped locomotives. On five of the 17 days, there were indirect RSD data gaps lasting 12 hours or more: many of these data gaps were due to failure of the generator powering the indirect RSD.

**UP Cajon**

- Usable data for 74 different locomotives.
- 2 of the 74 locomotives were repeat locomotives, providing indirect RSD data more than once.
- Including repeat locomotives, there were a total of 76 indirect RSD readings.
- On three of the 14 days, there were no indirect RSD data at all. The data gaps were attributed to generator failure.

**Weimar**

- Usable data for 65 different locomotives.
- None of the 65 locomotives were repeat locomotives, so there were a total of 65 indirect RSD readings from unique locomotives.
- On six of the 18 days, the indirect RSD was non-operational. This was in part due to generator failure, but mostly due to inclement weather.

### *Analysis of Indirect RSD Data for Line Haul Operations*

One of the goals of the RSD study was to investigate whether the measured results could be calibrated to determine whether a locomotive is above or below the applicable federal certification standards. A brief discussion of the U.S. EPA test for compliance determination is presented in Appendix E.

**Calculations with Indirect RSD Data**

The indirect RSD readings were not found to vary significantly among the three testing locations, so the data from BNSF Cajon, UP Cajon, and Weimar were combined into one dataset for analysis. $NO_x$, PM, and CO emissions in grams per brake horsepower-hour were calculated according to the equations in Appendix D.

All locomotives were assumed to be operating in Notch 8. Examination of in-use test data shows Notch 8 to be generally representative of the line-haul duty cycle as a whole (see further discussion and Table 3 below). For the 73 Cajon and Weimar locomotives for which power setting data could be obtained by ARB, 82 percent were found to be in Notch 8, and another 12 percent were found to be in Notch 7. However:

- The indirect RSD cannot read the notch settings of the locomotives passing by, nor can it tell whether a locomotive was transitioning from one notch setting to another. Transitions between notch settings, generally lasting several seconds, can produce significantly higher locomotive emissions.

- While examination of in-use test data shows that Notch 8 emissions are generally representative of the entire line-haul duty cycle, more detailed analysis shows a variation of ±10 percent for $NO_x$, ±20 percent for PM, and ±40 percent for CO as shown in the summary of available in-use test data[12] in Table 3.

**Table 3**
**Notch 8 Emissions, as a Percentage of**
**Line-Haul Duty Cycle Emissions**
In-Use Test Data Range for Locomotives

| Tier | $NO_x$ | PM | CO |
|---|---|---|---|
| Pre-0 | 93% - 100% | 62% - 102% | 63% - 100% |
| 0 | 84% - 100% | 64% - 102% | 80% - 148% |
| 1 | 81% - 101% | 79% - 99% | 91% - 108% |
| 2 | 92% - 95% | 85% - 97% | 61% - 106% |

Furthermore, when in-use testing is performed, the variability in Notch 8 emissions is such that a locomotive can be in exceedance in Notch 8, and still meet federal certification standards when the emissions data are weighted over the line haul duty cycle.

Various other assumptions were made by ARB staff in calculating $NO_x$, PM, and CO emissions in grams per brake horsepower-hour:

- An $NO_2$ to NO ratio of 0.04 was used, based on available published data, which were for Notch 8 for a single Tier 0 EMD SD60 locomotive. For other notch settings, the available published data for the same Tier 0 EMD SD60 locomotive

[12] Fritz, S., *Diesel Fuel Effects on Locomotive Exhaust Emissions*, October 2000.

show the $NO_2$:NO ratio ranging from 0.01 to 0.07[13]. Available internal test data for a single pre-Tier 0 EMD 645E3B engine show a much greater $NO_2$:NO ratio, but within a tighter band, ranging from 0.13 in Notches 2 through 6 to 0.14 in Notches 1, 7, and 8.[14] The available published and internal data give an uncertainty of -3 to +10 percent for the $NO_x$ readings.

- A ratio of grams per gallon to grams per brake horsepower-hour of 19.7 was used, based on an average of in-use test data for Notch 8. Ratios calculated from in-use test data for Notch 8 range from 17.0 to 21.1,[15] giving an uncertainty of -9 to +15 percent for the $NO_x$, PM, and CO readings.

- No $NO_x$ corrections were made for humidity, giving an uncertainty of -7 to +10 percent for the $NO_x$ readings based on published data.[16]

In summary, the various assumptions made introduce the following multiple uncertainties in the calculated data:

- ±10 percent for the Notch 8 to line-haul duty cycle ratio for $NO_x$, ±20 percent for PM, and ±40 percent for CO;
- -3 to +10 percent due to the $NO_2$:NO ratio (applicable to $NO_x$ readings only);
- -9 to +15 percent due to the grams per gallon to grams per brake horsepower-hour ratio; and
- -7 to +10 percent for the $NO_x$ humidity correction.

Simple addition of these uncertainties[17] produces a combined uncertainty of -29 to +45 percent for $NO_x$, -29 to +35 percent for PM, and -49 to +55 percent for CO. More importantly, if these locomotives were operating in a lower notch setting, or transitioning between notch settings, the uncertainty would be much greater.

Due to the lack of notch setting information, there are inherent difficulties with relating the indirect RSD readings to the measurement standard and the assumptions made in calculating emissions data. The indirect readings are either at just one power setting or transitioning between power settings. The federal measurement standard is weighted over the entire line haul duty cycle of eleven power settings. Therefore, ARB staff concludes that the readings taken with the indirect RSD for moving locomotives cannot be used to determine the levels of emissions from locomotives and cannot be related to the U.S. EPA locomotive emissions standards.

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[13] Osborne, D., Fritz, S., Iden, M., and Newburry, D., *Exhaust Emissions from a 2,850 kW EMD SD60M Locomotive Equipped with a Diesel Oxidation Catalyst*, Proceedings of 2007 ASME/IEEE Joint Rail Conference & Internal Combustion Engine Spring Technical Conference, March 2007.
[14] Southwest Research Institute Internal Test Data (2003).
[15] Southwest Research Institute Internal Test Data (2007).
[16] Dodge, L. Callahan, T. and Ryan, T., *Humidity and Temperature Correction Factors for $NO_x$ Emissions from Diesel Engines*, Southwest Research Institute, June 2003.
[17] This is an oversimplification, which nevertheless gives a general idea of the magnitude of the overall uncertainty.

Furthermore, even the regulated locomotives with the highest indirect RSD $NO_x$ readings, which were about twice the federal certification emission standard, could not be identified as “gross” or “excessive” polluters. The highest indirect RSD $NO_x$ readings for unregulated locomotives were within the range of Title 40 CFR Part 92 emission testing results.

Nevertheless, the calculated averages and standard deviations for indirect RSD locomotive emissions data can be analyzed for general trends. Calculated indirect RSD data are summarized in Table 4:

**Table 4**
**Summary of Indirect RSD Data***
**BNSF Cajon, UP Cajon, Weimar**

| Tier | Number of Locomotives | $NO_x$ (g / bhp-hr) | | | PM (g / bhp-hr) | | | CO (g / bhp-hr) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Average | Standard Deviation | Relative Standard Deviation** | Average | Standard Deviation | Relative Standard Deviation | Average | Standard Deviation | Relative Standard Deviation |
| Pre-0 | 60 | 12.6 | 2.8 | 21.8% | 0.25 | 0.20 | 82.3% | 2.06 | 2.05 | 99.4% |
| 0 | 570 | 9.2 | 1.4 | 15.5% | 0.13 | 0.10 | 76.4% | 0.94 | 0.36 | 38.8% |
| 1 | 255 | 8.2 | 1.3 | 15.4% | 0.14 | 0.20 | 139% | 0.87 | 0.35 | 39.9% |
| 2 | 253 | 6.1 | 0.8 | 13.2% | 0.06 | 0.05 | 78.3% | 0.29 | 0.26 | 88.7% |
| Total | 1,138 | | | | | | | | | |

* Includes repeat locomotives
** Relative standard deviation is equal to the sample standard deviation divided by the sample average.

Including duplicates, there were a total of 1,138 locomotives: about 50 percent were Tier 0 (built between 2000 and 2001, or built pre-2000 and remanufactured), about 22 percent were built to Tier 1 emissions standards (built between 2002 and 2004), another 22 percent were built to Tier 2 emissions standards (built after 2004), and the balance were unregulated (pre-Tier 0, built pre-2000 and not remanufactured).

For comparison, U.S. EPA locomotive emissions standards are presented in Table 5.

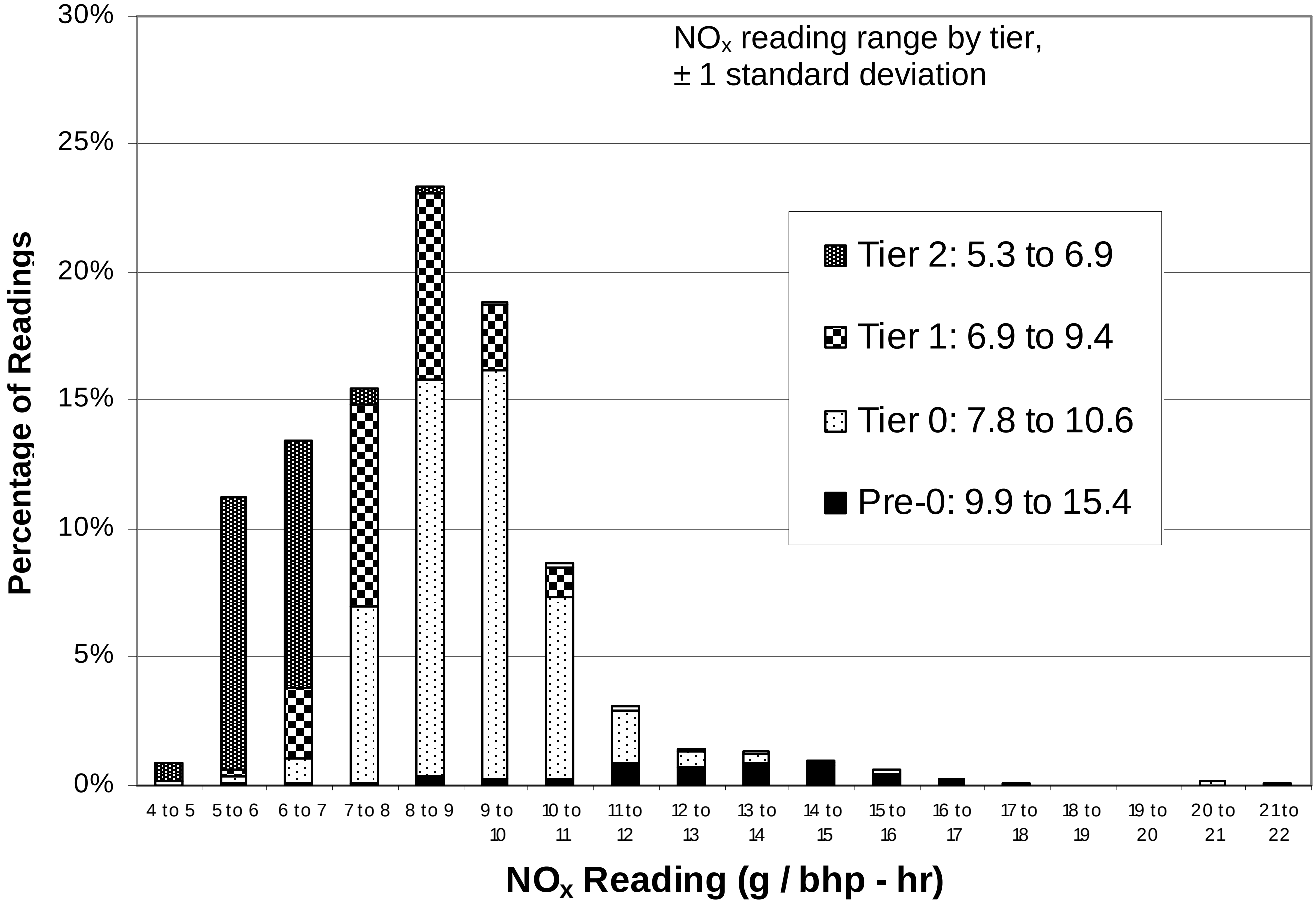
**Table 5**
**U.S. EPA Locomotive Emissions Standards**

| Tier | $NO_x$ (g / bhp-hr) | PM (g / bhp-hr) | CO (g / bhp-hr) |
|---|---|---|---|
| Pre-0 | None | None | None |
| 0 | 9.5 | 0.60 | 5.0 |
| 1 | 7.4 | 0.45 | 2.2 |
| 2 | 5.5 | 0.20 | 1.5 |

As would be expected, the average indirect RSD $NO_x$ readings are lowest for Tier 2 and highest for pre-Tier 0, with relative standard deviations ranging from 13.2 percent for Tier 2 to 21.8 percent for pre-Tier 0. For the regulated locomotives (Tiers 0, 1, and 2), the highest indirect RSD $NO_x$ reading within each tier was about twice the federal certification standard.

The indirect RSD $NO_x$ readings are presented by emissions tier in Figure 7.

**Figure 7: Indirect RSD $NO_x$ Readings by Emissions Tier**




The indirect RSD PM and CO averages are about the same for Tiers 0 and 1, with higher averages for pre-Tier 0 and lower averages for Tier 2. The indirect RSD PM and CO readings have a higher standard deviation than the indirect RSD $NO_x$ readings: for PM, ranging from 76 percent for Tier 0 to 139 percent for Tier 1; and for CO, ranging from 39 percent for Tier 0 to 99 percent for pre-Tier 0. This is consistent with the in-use test data for PM and CO, which show a wider variation in the ratio of Notch 8 emissions to emissions over the entire duty cycle.

Closer examination of the 1999 University of Denver RSD study [Popp, P. et al., 1999] shows that, for the six pre-Tier 0 locomotive emissions measurements measured in Notch 8 three miles north of Northport, Nebraska, the relative standard deviation in NO emissions was 14.4%. This is similar to the relative standard deviation of 21.8% for pre-Tier 0 locomotives determined for the indirect RSD in this study. Popp et al. claimed that their RSD was shown to be effective in measuring NO emissions from locomotives in normal line-haul operation. To support this claim, however, Popp et al. present the $NO_x$ results of only one laboratory test from the Southwest Research Institute (SwRI) for a similar pre-Tier 0 locomotive engine. The University of Denver

RSD study results, when converted to $NO_x$ using the $NO_2$ to NO ratio, average about 25% higher than the SwRI data.

Also, there is no indication of how, or whether, Popp et al. dealt with the effects of exhaust temperature on the NO readings. In Phase 1 of the AB 1222 study, performed at TTCI in February 2007, it was found that locomotive emissions for the direct RSD were significantly affected by the hot exhaust plume temperatures. It was for this reason that subsequent work in the AB 1222 study was all performed using the indirect RSD.

The various deficiencies and limitations noted in measuring $NO_x$, PM, and CO emissions with the indirect RSD make it very challenging to meet the third objective of the AB 1222 pilot program, which is to calibrate the indirect RSD readings to determine whether a given locomotive is above or below the U.S. EPA locomotive emissions standards. Taking a locomotive out of service is a considerable financial expense, one that cannot be justified unless there is a high degree of certainty that the locomotive's emissions are above the U.S. EPA standards.

### Data for Front Locomotives

In the Phase 2a testing at TTCI, it was noted that the front locomotive in the four-locomotive consist had a lower rate of valid readings than the other three locomotives. This was thought to be due to the large wind pressure faced by the front locomotive, which could significantly reduce sample flow and lead to a lower rate of valid indirect RSD readings. Subsequent to the Phase 2a testing, adjustments were made to the accumulator box to increase the overall flow in the sampling system.

The indirect RSD data for BNSF Cajon were further analyzed for differences in front locomotive emissions data. The analysis showed that about a quarter of the locomotives with valid readings at BNSF Cajon were front locomotives. This was approximately equal to the total number of front locomotives, whether their readings were valid or not. Furthermore, the average $NO_x$, PM, and CO emissions for the front locomotives at BNSF Cajon are almost the same as for the entire Phase 2 dataset. The only significant difference noted is for the PM emissions for Tier 1 locomotives, which average about a third higher. Therefore, it cannot be concluded from the BNSF Cajon data that there is any wind pressure effect on front locomotives.

### Data for Repeat Locomotives

Four of the repeat locomotives in the Phase 2 field testing had four or more indirect RSD readings: two were Tier 0, and two were Tier 2. Their RSD data are summarized in Table 6. Analysis of the $NO_x$, PM, and CO data shows that the average and standard deviation values for the two Tier 0 locomotives are generally equal to or slightly lower than for the entire Tier 0 dataset of 570 indirect RSD readings; the PM standard deviations are significantly lower. The average and standard deviation values for the two Tier 2 locomotives are generally slightly higher or slightly lower than for the entire

Tier 2 dataset of 253 indirect RSD readings, although the PM standard deviations are significantly lower, as is the CO standard deviation for one of the Tier 2 locomotives.

**Table 6**
**Summary of Indirect RSD Data**
**For Repeat Locomotives**

| Locomotive | Tier | Number of Readings | $NO_x$ (g / bhp-hr) | | | PM (g / bhp-hr) | | | CO (g / bhp-hr) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Average | Standard Deviation | Relative Standard Deviation | Average | Standard Deviation | Relative Standard Deviation | Average | Standard Deviation | Relative Standard Deviation |
| BNSF 4842 | 0 | 22 | 9.2 | 1.1 | 12.1% | 0.11 | 0.02 | 18.6% | 0.93 | 0.15 | 15.7% |
| BNSF 4888 | 0 | 9 | 7.9 | 0.4 | 4.9% | 0.10 | 0.02 | 22.8% | 0.80 | 0.27 | 33.9% |
| BNSF 7624 | 2 | 4 | 5.6 | 0.5 | 8.1% | 0.06 | 0.01 | 14.1% | 0.24 | 0.04 | 16.7% |
| BNSF 7644 | 2 | 10 | 6.8 | 1.5 | 21.3% | 0.07 | 0.02 | 32.4% | 0.41 | 0.41 | 100.1% |

***Yard Operations***

The Phase 2 testing of line haul locomotives in yard operations was done at the UP Colton Railyard, from October 4 through October 18, 2007.

Since line haul locomotives in yard operation are often operated in idle or in Notch 1, they have very small plumes that exit the locomotive at very low velocities. Therefore, a locomotive's plume blooms out and mixes with the previous locomotive's exhaust, making it impossible to assign gas readings to a particular locomotive with the indirect RSD. The indirect RSD is clearly not suitable for yard locomotive monitoring. A decision was made by the Advisory Group to discontinue UP Colton yard testing after two weeks, and not to proceed with the previously planned northern California yard testing at the UP Roseville Railyard.

## D. Phase 3: Correlation Testing

This final phase was designed to relate indirect RSD emission readings to federal certification standards for locomotives under controlled test conditions. Federal certification testing is done on a stationary locomotive. Plans for Phase 3 testing were made shortly after completion of Phase 2 testing at BNSF Cajon and UP Cajon in October 2008, and took about three months. In January and February 2008, a Tier 0 locomotive and a Tier 2 locomotive were tested at the UP Roseville Railyard. The trailer for federal certification testing was transported by SwRI from its headquarters in San Antonio, Texas; ESP provided the indirect RSD equipment.

Both locomotives cycled three times through idling, dynamic braking, and Notches 1 through 8. Each of the three times, for each setting, indirect RSD readings, performed by ESP, were conducted in parallel with the Federal Test Procedure (FTP) protocol (Title 40, Code of Federal Regulations, Part 92), performed by SwRI.[18] The Phase 3 correlation testing was blind, with ESP and SwRI each providing results separately to CARB.

Indirect RSD and FTP data are presented on the ARB's website at http://www.arb.ca.gov/msprog/offroad/loco/loco.htm. Statistical analyses were performed comparing the locomotive indirect RSD and FTP emissions data for each locomotive over the line haul duty cycle for each locomotive.

**Table 7**
**Summary of Correlation Testing Data**
**Indirect RSD and Federal Test Procedure**

| Tier | Test | $NO_x$ (g / bhp-hr) | | PM (g / bhp-hr) | | CO (g / bhp-hr) | |
|---|---|---|---|---|---|---|---|
| | | Average | Standard Deviation | Average | Standard Deviation | Average | Standard Deviation |
| 0* | Indirect RSD | 8.40 | 0.45 | 0.34 | 0.0045 | 0.41 | 0.065 |
| 0* | FTP | 8.74 | 0.031 | 0.35 | 0.0033 | 0.88 | 0.0076 |
| 2 | Indirect RSD | 5.60 | 0.46 | 0.19 | 0.11 | 0.64 | 0.72 |
| 2 | FTP | 5.32 | 0.020 | 0.12 | 0.0012 | 0.56 | 0.00080 |

* An operational error occurred with the indirect RSD during the third test for the Tier 0 locomotive. The Table 7 data for the Tier 0 locomotive were calculated using the data for the first two tests.

Under the highly controlled conditions of the Phase 3 testing:

- Indirect RSD $NO_x$ readings over the duty cycle are close to the FTP $NO_x$ measurements, with less than 5 percent difference. However, the standard deviations are greater for the indirect RSD.

- The $NO_x$ levels for the cleaner Tier 2 locomotive differed by only 0.3 g/bhp-hr: 5.6 g/bhp-hr for the indirect RSD, versus 5.3 g/bhp-hr for the FTP. Nevertheless, the federal certification standard of 5.5 g/bhp-hr is a not-to-exceed standard, so even with this slight difference in emissions levels, the indirect RSD would have incorrectly identified a complying locomotive as non-complying.

- Indirect RSD PM readings over the duty cycle are very close to the FTP PM measurements for the Tier 0 locomotive, but significantly higher for the Tier 2 locomotive. For the Tier 2 locomotive, two of the three test results were very close; indirect RSD readings during the 2nd test indicated very high occasional

[18] Fritz, S., Osborne, D., *AB1222 Locomotive Remote Emissions Sensing: Phase 3 – FTP Correlation Testing*. March 2008.

PM bursts at low notch conditions.  There was some visual confirmation of puffs of black smoke during the test.  This could indicate that the RSD technology is much more dynamic in its response than FTP sampling instrumentation.

- Indirect RSD CO data are significantly different from the FTP CO data.  For the Tier 0 locomotive, the indirect RSD data average about 50 percent lower. For the Tier 2 locomotive, the indirect RSD data average about 15 percent higher, with a very high standard deviation.

## E. Indirect RSD Program Cost Estimates for Line Haul Operations

Based on an evaluation of the data, ARB staff is not recommending that RSD equipment be deployed for locomotives.  However, as AB 1222 identified a need to provide cost data, ARB staff has providing the following estimates If an indirect RSD monitoring program were implemented at a single high priority line-haul location for one year.  The total estimate cost would be about $460,000 as shown below:

- $200,000: purchase of RSD device;
- $20,000: purchase of other equipment, site permitting, equipment installation and removal; and
- $240,000: labor for flagman, equipment operator, and data reviewer.

## F. Existing Locomotive Emissions Monitoring Programs

Implementation of an indirect RSD monitoring program should also be analyzed in the light of two existing monitoring programs, the visible emissions reduction program and the U.S. EPA in-use test program.  These programs are described below.

### *Visible Emissions Reduction Program*

Since June 2005, as part of the 2005 ARB / Railroad Statewide Agreement, the railroads have been monitoring locomotive emissions under the visible emissions reduction program.  Locomotives operating in California and exceeding a steady opacity measurement of 20 percent must be sent to maintenance facilities to determine whether repairs are needed to comply with applicable visible emission standards as set forth in federal regulations.

Visible emission inspections for both BNSF and UP nationally from June 2005 through March 2008 are compiled in Table 8.  Under the 2005 ARB / Railroad Statewide Agreement, the railroads are required to achieve a 99 percent compliance rate for visible emissions over a calendar year for locomotives operating in California.  For the three types of visible emission inspections performed, the overall compliance rate is 99.4 percent for BNSF and UP nationally.

**Table 8**
**Visible Emissions Reduction Program**
**Summary of National Data for BNSF and UP**
**June 2005 to March 2008**

| | Certified Opacity Meter | Certified U.S. EPA Method 9 | Non-Certified Visible | **Total** |
|---|---|---|---|---|
| Number Inspected | 9,325 | 37,743 | 17,819 | **64,887** |
| Number Passed | 9,324 | 37,463 | 17,732 | **64,519** |
| Compliance Rate | 99.99% | 99.3% | 99.5% | **99.4%** |

The few locomotives that failed were repaired to meet Federal opacity standards. The most likely cause of excessive emissions would be defective fuel injectors. However, every time a locomotive is refueled, all engine systems are checked diagnostically and visually, including fuel injectors. Upon identification of defective injectors, they are replaced before the locomotive is put back in operation. Also, all locomotives have to meet the Federal Railroad Administration 92-day maintenance and inspection requirements.

***U.S. EPA In-Use Test Program***

The U.S. EPA in-use test program for determination of compliance with federal certification standards for locomotive emissions is Title 40 Code of Federal Regulations Part 92 (40 CFR Part 92). Locomotives emissions are monitored under highly controlled laboratory testing conditions, with load testing used to simulate locomotive operation. To date, not one locomotive tested pursuant to 40 CFR Part 92 has failed to meet certification standards.

The visible emissions reduction program shows that less than one percent of locomotives do not comply with the visible emissions standard, and the U.S. EPA in-use test program has not yet shown even one locomotive failing to meet federal certification standards. Even if the indirect RSD readings could be calibrated to determine whether a given locomotive is above or below the U.S. EPA locomotive emissions standards, an indirect RSD program would not be likely to provide a level of exceedance detection above what is already provided by the visible emissions reduction program and the U.S. EPA in-use test program.

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# Appendix A

## Text of Assembly Bill 1222

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## ASSEMBLY BILL 1222

## HEALTH AND SAFETY CODE SECTIONS 39940-39944

39940.

(a) The state board shall implement a pilot program to determine emissions from locomotives, using wayside remote sensing devices. The objectives of the pilot program are to determine whether remote sensing devices can accurately and replicably determine, with a reasonable level of precision:

  (1) The levels of nitrogen oxides, particulate matter, and carbon monoxide emissions from locomotives.
  (2) Whether a locomotive is subject to tier 0, 1, or 2 federal certification standards.
  (3) Whether the measured results can be calibrated to determine whether the locomotive emissions are above or below the applicable federal emissions certification levels.

(b) The state board shall design and implement the pilot program in consultation with the advisory group established pursuant to Section 39941.

(c) The pilot program shall collect sufficient data to ensure that a representative sample of locomotives operating in the state are tested, so that there is a sufficient basis for the state board to meet the objectives and to make the determinations that are set forth in subdivision (a). Data collection shall, at a minimum, be performed under representative conditions in northern and southern California.

39941. The state board shall establish an advisory group to make recommendations to the state board regarding the design and implementation of the pilot program.

(a) The advisory group shall consist of an even number of members, not to exceed 14, as determined by the boards of the South Coast Air Quality Management District and the Sacramento Metropolitan Air Quality Management District.

(b) The advisory group shall consist of recognized experts in the field of remote sensing and locomotive engine technology, and representatives of citizen community groups, representatives of the South Coast Air Quality Management District, and representatives of the Sacramento Metropolitan Air Quality Management District. The advisory committee may also include representatives of the Union Pacific Railroad and the Burlington Northern Santa Fe Railway.

(c) The advisory group shall be appointed by the South Coast Air Quality Management District and the Sacramento Metropolitan Air Quality Management District. If the Union Pacific Railroad and Burlington Northern Santa Fe Railway choose to participate, 50 percent of the members of the advisory group shall be appointed by the Union Pacific Railroad and Burlington Northern Santa Fe Railway and 50 percent shall be appointed by the South Coast Air Quality Management District and the Sacramento Metropolitan Air Quality Management District.

39942. The state board may contract with an independent entity to conduct the pilot program specified in Section 39940, and shall oversee the work of the independent entity. The state board shall implement the pilot program in consultation with the advisory group established pursuant to Section 39941 to review the design of the pilot program and to ensure quality control in collection, reporting, and evaluation of data.

39943.

(a) On or before December 31, 2006, the state board shall submit a report to the Legislature that includes both of the following:

    (1) A summary of data acquired through the pilot program.
    (2) The state board's determination as to whether the remote sensing devices can meet the objectives of the pilot program stated in Section 39940.

(b) If the state board determines that remote sensing devices can be expected to meet objectives of the pilot program stated in Section 39940 to an extent reasonably sufficient to allow the state board to make the following projections and recommendations, the report shall also include both of the following:

    (1) To the extent feasible, a projection of the amount, location, and timing of emission reductions that could be expected from the use of remote sensing devices to identify locomotives to be repaired or maintained.
    (2) A projection of the cost to deploy, maintain, and use data from, a system of remote sensing devices in areas of high priority in the state, as determined by the state board, recommendations regarding the funding of such a program, and the expected cost-effectiveness of such a program compared to other opportunities for air quality improvement in the covered areas.

39944. The South Coast Air Quality Management District, the Union Pacific Railroad, and the Burlington Northern Santa Fe Railway shall each reimburse the state board for its costs of implementing the pilot program established pursuant to this chapter. The Union Pacific Railroad and the Burlington Northern Santa Fe Railway shall reimburse the state board for 25 percent of those costs, but the reimbursement shall not to exceed a total of two hundred thousand dollars ($200,000) for both railroads. The South Coast Air Quality Management District shall reimburse the state board for the balance of the costs of implementing the pilot program, but the reimbursement shall not exceed a total of three hundred thousand dollars ($300,000). Funds provided by the Union Pacific Railroad and Burlington Northern Santa Fe Railway shall be used only to reimburse the state board for the costs of planning, implementing, evaluating, and reporting the results of, the pilot program as it relates to the testing of locomotives operated by those railroads.

# Appendix B

## Remote Sensing of Railroad Locomotive Emissions: A Feasibility Study

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# Remote Sensing of Railroad Locomotive Emissions: A Feasibility Study

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## 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.

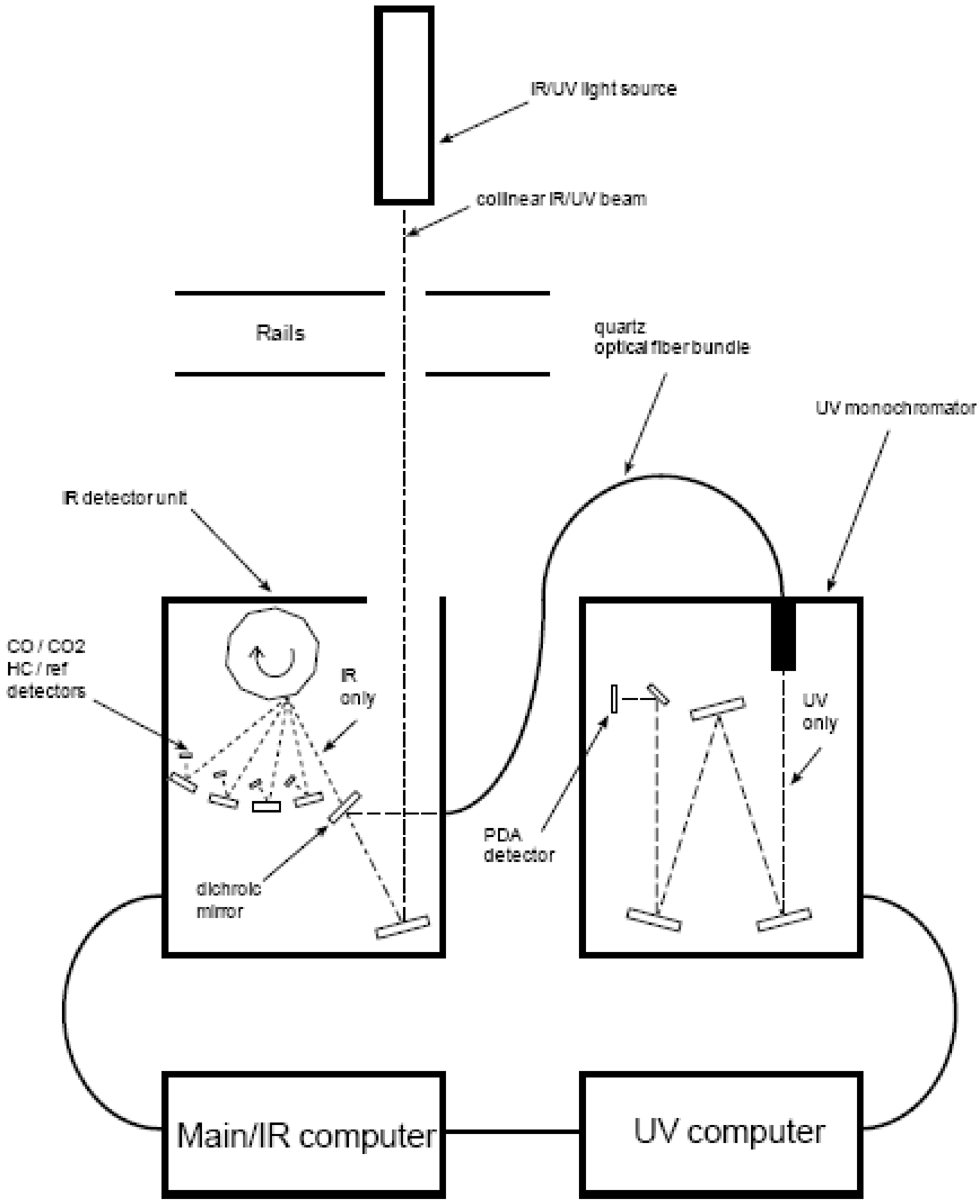


**Figure 1.** University of Denver remote sensing system configured for measuring locomotive emissions.

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.

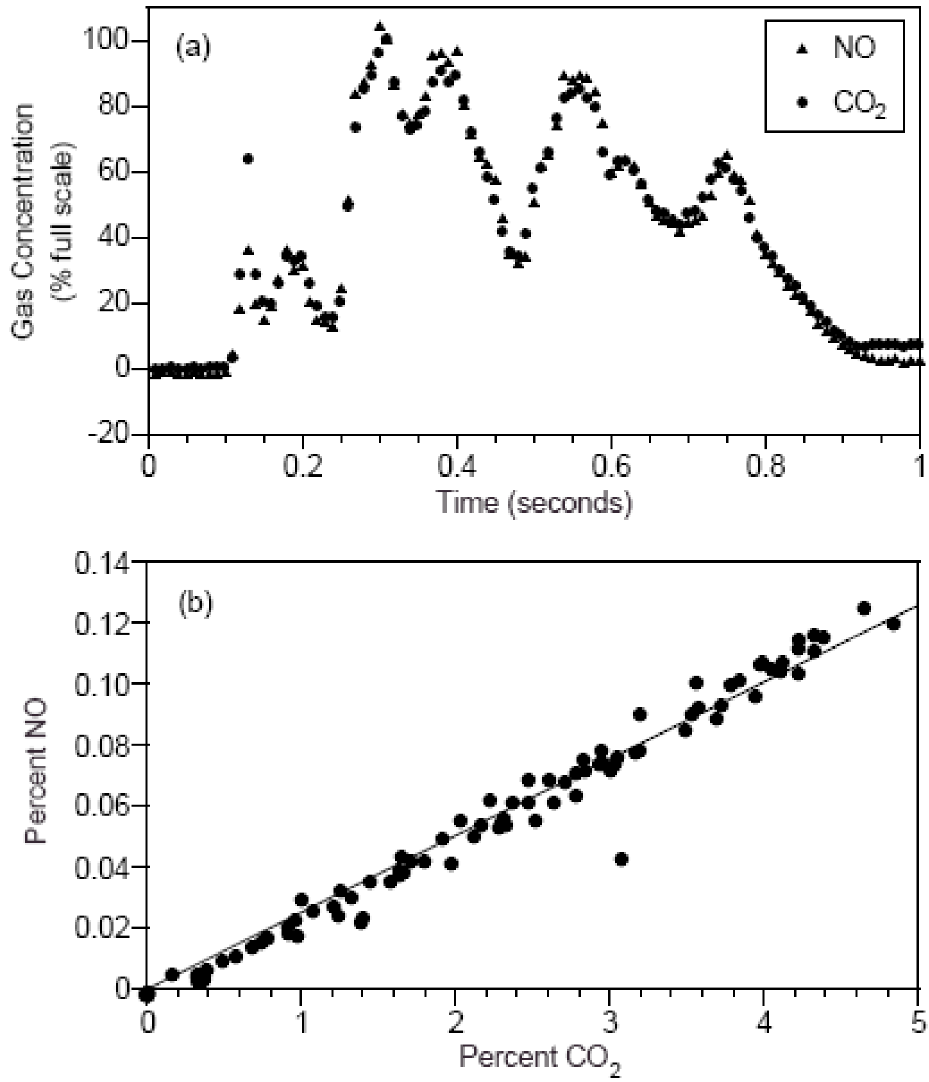


**Figure 2.** Simultaneous NO and $CO_2$ traces observed in the plume of an EMD SD-40-2 (a) and the least squares plot obtained from the same data (b). Data in (a) are represented as a percent of full scale because of the difference in magnitude of the NO and $CO_2$ concentrations.

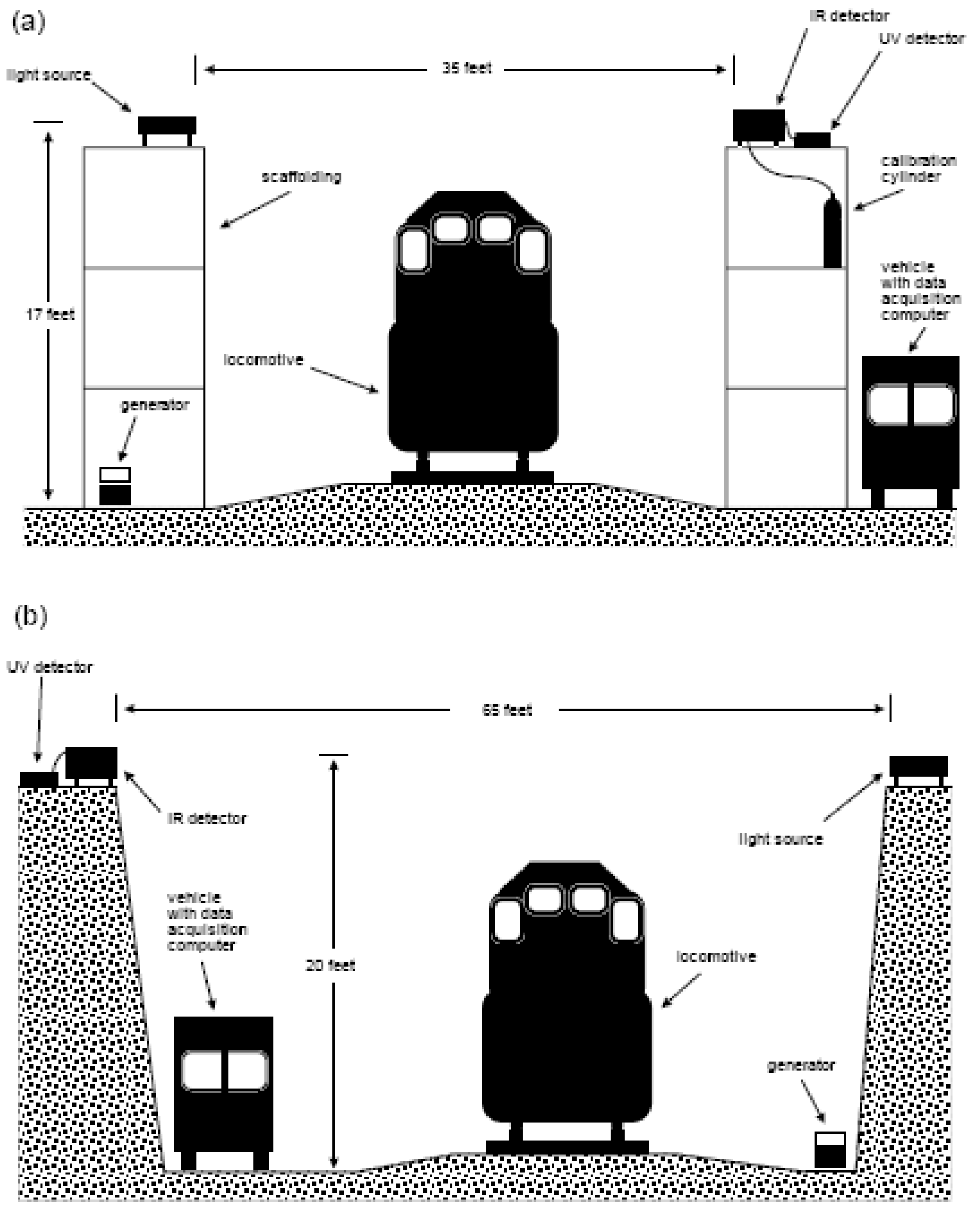


**Figure 3.** Instrument configuration at the BNSF yard (a) and at the cut 3 miles north of Northport, NE (b).

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-

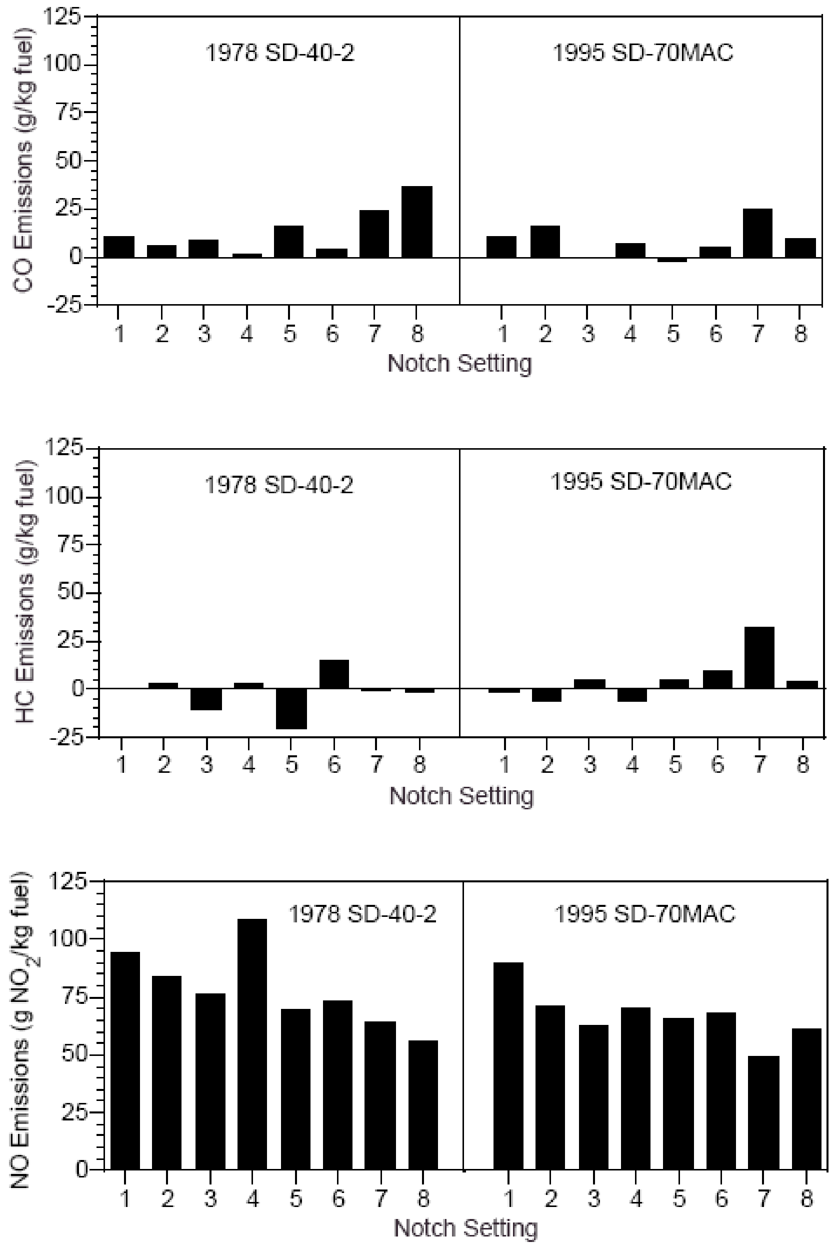


**Figure 4.** Carbon monoxide, hydrocarbon and nitric oxide emissions for the EMD SD-40-2 and SD-70MAC measured at the BNSF yard at Alliance, NE.

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

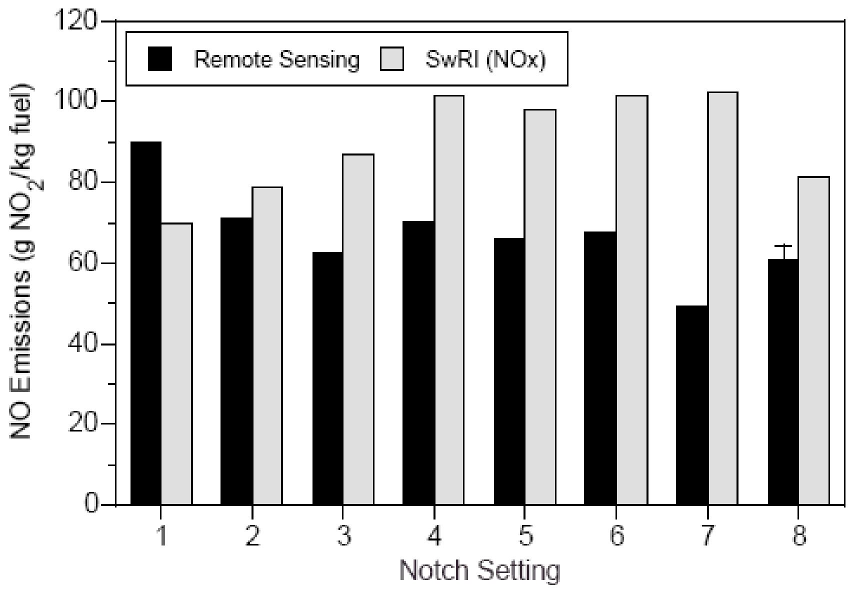


**Figure 5.** Comparison of NO emissions from an EMD SD-70MAC measured by remote sensing at the BNSF yard and $NO_x$ emissions from an EMD SD-75M measured by Southwest Research Institute (SwRI). Both locomotives were equipped with EMD 16-710 series engines. Note that the SwRI data is a measure of total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

The authors would like to thank Burlington Northern Santa Fe Railway for their cooperation and considerable assistance in conducting the field measurements at Alliance, Nebraska.

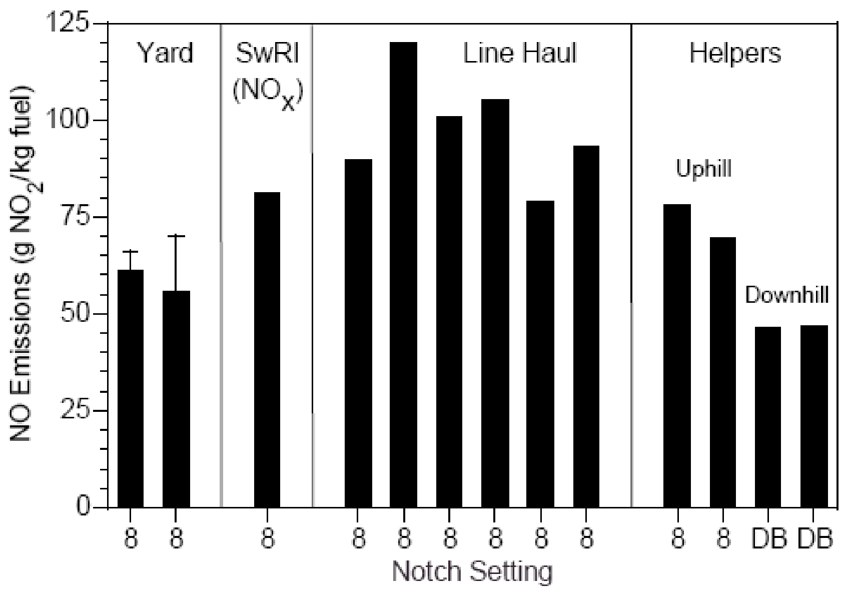


**Figure 6.** Nitric oxide emissions of line-haul locomotives measured at the cut 3 miles north of Northport, NE. Emissions of the helper locomotives are indicated for measurements taken during both uphill and downhill operation. Emissions from the two locomotives measured at notch 8 in the BNSF yard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

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# Appendix C

## Comment Letters from the South Coast Air Quality Management District

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South Coast
Air Quality Management District
21865 E. Copley Drive, Diamond Bar, CA 91765-4182
(909) 396-2000 · http://www.aqmd.gov

April 29, 2009

Mr. Bob Fletcher
Chief, Stationary Source Division
California Air Resources Board
1001 I Street
P.O. Box 2815
Sacramento, CA 95812

Dear Mr. Fletcher:

**Comments on California Air Resources Board**
**Draft Report to the California State Legislation –**
**Pilot Study on Remote Sensing Device to Measure Locomotive Emissions**

The South Coast Air Quality Management District (AQMD) staff is providing comments on the Draft Final Report for the AB 1222 pilot study on remote sensing device technology to measure locomotive emissions. As a member of the AB 1222 Advisory Group, we have been closely involved in the process. The AQMD firmly believes the results of the pilot study show that indirect remote sensing device (RSD) technology is a viable tool in identifying high emitting locomotives, and thereby meets the intent of AB 1222. Because of the success of the pilot study, staff believes that the Advisory Group should recommend that an RSD program be implemented to identify high emitting locomotives in the state, and legislative support for funding such a program be recommended because of the potential health benefits for Californians.

We strongly disagree with the reported conclusion that RSD technology failed and should not be used as part of a locomotive monitoring program. Uncertainties due to lack of locomotive notch settings is reported as the major contributor to the technology's inability to measure emission form locomotives. The Advisory Group as a whole, recognized from the start of this program, the importance of notch setting information to eliminate a major source of uncertainty. The Advisory Group diligently explored various options to obtain locomotive notch settings in concert with RSD measurements, and ultimately decided on testing sites which ensured the highest probability a locomotive would operate in a fixed and known notch setting of notch 8 (steep grades in the Cajon Pass and the Sierra Nevada foothills near Weimar). The choice resulted in over 90% of the locomotives measured operating in the two highest notches and the results clearly showed the expected differences between the tier level emission rates notwithstanding the uncertainty caused by the lack of notch information.

To demonstrate further the technology's successful demonstration, the Phase 3 results clearly show accurate measurements of NOx and PM emissions (see Table 1) and confirm the RSD technology's utility. Staff believes that the technology could be added *today* to the existing locomotive testing currently performed by the railroads. Moreover, with some minor modifications to the field deployment of RSD (e.g. collection of locomotive throttle "notch" setting and humidity measurements), we believe RSD could be used to monitor emissions from in-use locomotives in high priority areas to ensure the cleanest operation of locomotives.

**Table 1 – FTP vs. RSD from Phase 3: Correlation. AB 1222 Pilot Study**

| Tier 0 | FTP | RSD | | Tier 2 | FTP | RSD |
|---|---|---|---|---|---|---|
| NOx (avg) | 8.74 | 8.4 | | NOx (avg) | 5.32 | 5.6 |
| PM (avg) | 0.35 | 0.34 | | PM (avg) | 0.12 | 0.19 |

We strongly urge that CARB staff revise the report to reflect the successful demonstration of the RSD technology and to recommend implementation of an RSD emissions monitoring program for locomotives. This program could be incorporated into the railroads' normal periodic locomotive performance testing routines or other maintenance programs where load testing of a locomotive is required or could be performed. Such a program will benefit the railroads and residents adjacent to railyards. Class I railroads would have a tool to evaluate proper engine operation which could translate into improved engine performance and fuel cost savings. More importantly residents could be ensured that locomotives are performing at their certified levels of emissions.

In summary, staff believes the results of Phase 2 (field measurements on moving locomotives) and Phase 3 (stationary, load test locomotive measurements) strongly suggest that RSD, with knowledge of the locomotive's notch setting, could be used in high priority areas to determine compliance with locomotive emission standards.

We recommend that the report provide recommendations to implement an RSD emissions monitoring program to identify high emitting locomotives and a follow-on study to develop methods that report proper notch setting during an RSD measurement campaign. With this improvement, RSD could be used at many locations in California to ensure the cleanest operation of locomotives.

We appreciate the opportunity to comment on the draft report. If you have any questions, please contact me at (909) 396-2647.

Sincerely,

Dean Saito, Manager
On-Road Division, Mobile Source Section
Science & Technology Advancement Office

CSL: HH: DKS: RJP: PMB

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*Office of the Executive Officer*
*Barry R. Wallerstein, D.Env.*
*909.396.2100, fax 909.396.3340*

December 3, 2009

Mr. James Goldstene, Executive Officer
California Air Resources Board
1001 I Street
P.O. Box 2815
Sacramento, CA 95812

Dear Mr. Goldstene:

Comments on California Air Resources Board Draft Report to the California State Legislature – Pilot Study on Remote Sensing Device to Measure Locomotive Emissions

The South Coast Air Quality Management District (AQMD) staff is providing comments on the revised Draft Final Report titled Remote Sensing Device to Measure Locomotive Emissions: Report to the California Legislature. As a member of the AB 1222 Advisory Group, we have been closely involved in the process and have provided comments on the draft report. At that time, we indicated several areas of concern relative to the findings of the draft report. We are extremely disappointed that our comments were not addressed in the final report. We firmly believe the results of the pilot study show that indirect remote sensing device (RSD) technology married with locomotive notch information is a viable tool *today* for identifying high emitting locomotives, and thereby meets the intent of AB 1222. We further believe that with additional demonstration, the technology would likely be able to identify locomotives that do not meet applicable NOx certification standards. The AQMD staff, therefore, urges the Advisory Group to recommend that the RSD study be expanded to identify high emitting locomotives in the state, with the proviso that the Railroads be required to supply the needed notch information. The Final Report's conclusion of the failure of RSD technology to meet the objectives of the Pilot Program is based mainly on the uncertainty from not knowing the notch setting of the locomotive. This can easily be corrected by simply requiring the notch level be recorded and reported.

Furthermore, we recommend that that further study be conducted to improve the technology to determine compliance the certification levels of locomotives. Given the health risk assessment findings from CARB's railyard assessment, it is imperative that CARB seek every opportunity to quantify and identify potentially higher emitting locomotives.

Other uncertainties identified in the Report can also be easily corrected (e.g., perform humidity measurements as part of the program). In addition, other assumptions should be studied further to determine exactly how much they contribute to the uncertainty of the RSD measurements. It is not clear from the report whether the data sets used are robust enough to calculate the uncertainties associated with the assumptions. Yet these uncertainties are added together (an over-simplistic and most likely incorrect methodology to quantify the uncertainty) and used as one of the major reasons in CARB's conclusion relative to the failure of the RSD technology. AQMD staff believes that additional study is warranted and should ultimately show that the uncertainties are sufficiently small such that RSD can be deployed as early as possible to identify non-compliant locomotives (at least for NOx and possibly PM).

In addition to our general comments above we offer the following more specific comments.

***Accuracy of the RSD Program***

On Page 2 of the Executive Summary, the federal test procedure (FTP) and RSD are described and compared. We believe that the FTP and a properly performed RSD program will result in more similar test results than is implied in the Executive Summary. RSD is described as being influenced by a large number of additional variables such as wind speed turbulence, ambient temperature, humidity and lack of knowledge of the notch setting. While we agree that the FTP is performed in a more controlled environment, we believe that proper modifications to the RSD test methods (including recording and reporting notch level, temperature, and humidity measurements) and measurement location (to ensure the locomotive is likely operating under steady state conditions – i.e., Cajon Pass) can eliminate much of the uncertainties associated with these environmental variables. We recommend revising the paragraph to indicate that with these improvements to the RSD measurement methodology, agreement between FTP and RSD would be sufficient for RSD use at the very least as a method for identifying gross emitting locomotives and most likely for determining a locomotive's compliance status.

***Overall Uncertainty Analysis Needs More Detail and Justification***

On Page 6 and Pages 32 and 33, a description is provided of the uncertainties associated with the assumptions used by CARB staff to convert the RSD readings to common units for comparison to the FTP results. We believe that the uncertainty analysis needs further refinement and as reported is flawed. First, more information and description of the data used to generate the uncertainty values for each of the assumptions (e.g., NO/NO2 ratio, humidity corrections, etc.) is needed to justify the values used in the analysis. As mentioned above, the robustness of the data and analysis is not clear from what is presented (e.g., the NO/NO2 ratio is based on testing results from only two locomotives, none of which were a Tier 2 locomotive) and needs to be further explained. Second, simply adding the uncertainties to yield an overall uncertainty needs more justification. AQMD staff believes this approach is not appropriate as it is not clear that all of the variables are independent. If the variables are correlated, a more sophisticated analysis is warranted. Finally, including the uncertainty for the Notch 8 to line-haul duty cycle ratio is not appropriate. While the ratio may vary, as shown in Table 3 on Page 32, it is almost always less than one for NOx and PM (meaning that the Notch 8 measurement underestimates the actual value) and as RSD is being used to identify high emitters, this will make the RSD value a conservative estimate of the actual emission, and its uncertainty is not practically relevant.

***Comparison of Locomotive RSD program to Automotive RSD Program***
On Page 34, we do not agree that the RSD report for automobiles be used to buttress the arguments that RSD should not be used to identify high-emitting locomotives. Not only do we not agree with the conclusions of the study as we relayed to your staff in our previous comment letter, but we note that RSD measurements for locomotives are inherently much easier to relate to the certification standards because of the format of the locomotive certification test cycle. Since the locomotive test cycle is based on 11 weighted steady state measurements and not a complex variable test cycle as that used for automobiles, it is much simpler to correlate the RSD information with the locomotive certification standard. Therefore, RSD should be more effective at identifying high emitting locomotives. We believe that referencing the RSD automobile report is not informative or appropriate and recommend it be deleted from the report.

***Reliance on Existing In-Use Testing Programs***
On Pages 40 and 41, the results of the visible emissions reduction program and the in-use testing program are described and show a less than 1% failure rate (high emitter identification rate). This low failure rate along with the federally mandated 92-day maintenance and inspection requirements are used to conclude that RSD would not be likely to identify additional high emitting locomotives. While we agree that the testing and routine maintenance does help in maintaining clean locomotive operations in the Basin, we note that the visible emissions test is only for PM emissions and does not provide any assurance that the NOx certification levels are being met. In addition, we understand that very few locomotives are tested under the in-use testing program. While having no locomotives fail this test to date is encouraging, more information about the number of locomotives tested is needed for the reader to determine the importance of this result. Overall, we do not agree that these tests and the federally required maintenance are suffi-

cient or eliminate the need of an RSD program, especially considering forthcoming changes in emission standards.

In summary, staff believes the results of the Pilot Program clearly demonstrate that RSD, with knowledge of the locomotive's notch setting, could be used *today* to identify gross emitting locomotives, and with additional study, ultimately be able to determine if a locomotive is meeting the required certification standards. We recommend that the report provide recommendations to implement an RSD emissions monitoring program to identify high emitting locomotives, that the Railroads be required to supply the needed notch information, and that a follow-on study be initiated to better understand the uncertainties associated with the assumptions used to compare the RSD measurements with the locomotive certification measurements. With these improvements, RSD could be used at many locations in California to ensure the cleanest operation of locomotives.

We appreciate the opportunity to comment on the draft report. We urge CARB staff to reconsider its findings and provide constructive steps to further developing RSD technologies to identify higher-emitting locomotives. If you have questions regarding the AQMD staff's comments, please feel free to call me at (909) 396-2100.

Sincerely,

Barry R. Wallerstein, D.Env.
Executive Officer

CSL:HH:RJP
cc: Bob Fletcher

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# Appendix D

## Equations and Constants for Calculated Data

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## Equations and Constants for Calculated Data

These are the equations that were used to calculate the indirect RSD $NO_x$, PM, and CO emissions:

$$NO_x\left(\tfrac{g}{gallon}\right) = \frac{[10^{-4}\,NO(ppm)]}{[CO_2(\%)] + [CO(\%)] + 3HC_{coefficient}\,10^{-4}[HC(ppm)]}\,MW_{NO_2}\,\frac{\rho_{diesel}}{MW_{diesel}}\left[1 + Ratio_{NO_2:NO}\right]$$

$$PM\left(\tfrac{g}{gallon}\right) = 10^{-2}\,uvSmoke(\%)\;\;\rho_{diesel}$$

$$CO\left(\tfrac{g}{gallon}\right) = \frac{[CO_2(\%)]}{[CO_2(\%)] + [CO(\%)] + 3HC_{coefficient}\,10^{-4}[HC(ppm)]}\,MW_{CO}\,\frac{\rho_{diesel}}{MW_{diesel}}$$

The following values were used for the various constants appearing in the above equations:

| | | |
|---|---|---|
| $MW_{CO}$ | 28 | g / mole |
| $MW_{NO2}$ | 46 | g / mole |
| $MW_{diesel}$ | 13.9 | g / mole |
| $\rho_{diesel}$ | 3217.6 | g / gallon |
| $HC_{coefficient}$ | 2 | |
| $Ratio_{NO2:NO}$ | 0.04 | |

CO, $NO_x$, and PM readings in grams per gallon were converted to grams per brake horsepower hour using a conversion factor of $\frac{0.051\,\frac{g}{bhp-hr}}{\frac{g}{gallon}}$ , which was determined from an average of in-use test data for Notch 8.

The $NO_2$:NO ratio of 0.04 was determined from published data for Notch 8.[19]

The $HC_{coefficent}$ value of 2 was empirically determined by Environmental Systems Products, Inc.

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[19] Osborne, D., Fritz, S., Iden, M., and Newburry, D., *Exhaust Emissions from a 2,850 kW EMD SD60M Locomotive Equipped with a Diesel Oxidation Catalyst*, Proceedings of 2007 ASME/IEEE Joint Rail Conference & Internal Combustion Engine Spring Technical Conference, March 2007.

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## Appendix E

## Title 40 CFR Part 92

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## U.S. EPA Test for Determination of Compliance with Federal Locomotive Emission Standards:

The U.S. EPA test method used for determination of compliance with federal certification standards, Title 40 Code of Federal Regulations Part 92 (40 CFR Part 92),[20] is for stationary locomotives under highly controlled laboratory testing conditions. Load testing is used to simulate locomotive operation. The locomotive is run through eleven test modes: low idle and normal idle, dynamic brake, and Notches 1 through 8. For each test mode, the gross horsepower is recorded, and the locomotive emissions ($NO_x$, PM, CO, HC, $O_2$, and smoke opacity) are measured, with $NO_x$ corrected for humidity (published data indicate that temperature effects are negligible[21].

Each test mode is proportionately weighted over the line-haul duty cycle. The line-haul duty cycle emissions are calculated as follows:

1. For each test mode, the gross horsepower and the measured emissions (in grams per hour, with $NO_x$ corrected for humidity) are multiplied by the test mode weighting factor to give the weighted horsepower and the weighted emissions in grams per hour, respectively.
2. The weighted horsepower values (from Step 1) are summed over all eleven test modes to give the total weighted horsepower.
3. The weighted emissions in grams per hour (from Step 1) are then summed over all eleven test modes to give the total weighted emissions in grams per hour.
4. The weighted emissions in grams per hour (from Step 1) are divided by the weighted horsepower (from Step 2) to give the emissions in grams per brake horsepower-hour for each test mode.
5. Finally, the total weighted emissions in grams per hour (from Step 3) are divided by the total weighted horsepower (from Step 2) to give the line-haul duty cycle locomotive emissions in grams per brake horsepower-hour.

[20] http://www.access.gpo.gov/nara/cfr/waisidx_07/40cfr92_07.html and http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?c=ecfr&tpl=/ecfrbrowse/Title40/40cfr1033_main_02.tpl

[21] Dodge, L. Callahan, T. and Ryan, T., *Humidity and Temperature Correction Factors for $NO_x$ Emissions from Diesel Engines*, Southwest Research Institute, June 2003.

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