MBTA Bus Fleet Emissions Screening Using Remote Sensing Technology

Dana Lowell
M.J. Bradley & Associates
Manchester, NH

Anne Herzenberg
Chief Operating Officer
Massachusetts Bay Transportation Authority
Boston, MA

ABSTRACT

Exhaust emissions from transit buses has been a hot topic for years. In order to improve local air quality, many agencies have invested millions of dollars in advanced and clean fuel technologies to reduce emissions from their bus fleets. Generally, the only information available about the emission characteristics of these vehicles comes from expensive engine- and chassis-dynomometer tests. Relatively little is known about actual on-road performance, especially as vehicles age.

While virtually all states have emissions inspection and maintenance (I/M) programs for light-duty vehicles, only sixteen have I/M programs for heavy-duty vehicles that evaluate exhaust emissions on a regular basis. The purpose of any emissions I/M program is to identify "high emitters" that require maintenance to reduce their emissions back to normal and expected levels. Virtually all of these heavy-duty I/M programs use opacity meters to evaluate exhaust smoke levels as a proxy for particulate emissions.

Massachusetts is one of the states with a heavy-duty I/M program, but it has not proven very effective at evaluating actual in-use emissions performance of the buses operated by the Massachusetts Bay Transportation Authority (MBTA) in Boston. In 2003, the MBTA developed a comprehensive plan to reduce bus fleet emissions, which includes use of ultra low sulfur diesel fuel fleet-wide, engine upgrades and retrofit of diesel particulate filters on older buses, as well as purchase of new emission-controlled diesel (ECD) and compressed natural gas buses. As part of their overall commitment to ensure that their revitalized fleet will continue to have low emissions throughout its life, the MBTA also decided to implement an enhanced I/M program specifically focused on measurement of in-use emissions to identify and correct high emitters.

M.J. Bradley and Associates has worked with the MBTA and a citizen's advisory committee to identify and test various technologies that could be used as fleet emissions screening tools for it's enhanced I/M program. The two most promising technologies evaluated are Portable Emissions Monitoring Systems (PEMS) and Remote Sensing Devices (RSD).

This paper will discuss the technology evaluation process, including descriptions of each technology, the results of in-use emissions evaluations of the MBTA fleet using both PEMS and RSD, and current plans for the MBTA's new enhanced I/M program.

INTRODUCTION

In addition to operating extensive subway and trolley systems, the MBTA operates a fleet of 980 urban transit buses in fixed-route service throughout the Boston metropolitan area. Historically, the MBTA fleet looked like most U.S. bus fleets, with standard diesel engines predominating. In 2003, the MBTA began an aggressive program to transform its fleet by incorporating emissions reduction technologies on every bus.

Since then, 535 pre-1994 buses (57% of the fleet) have been retired and replaced with new compressed natural gas and "emissions-controlled diesel" (ECD) buses, reducing the average fleet age from 14 to 4 years. The ECD buses are equipped with Caterpillar ACERT^{TM} engines certified to 2.4 g/bhp-hr NOx emissions, plus a first-fit diesel particulate filter (DPF) that reduces PM emissions by more than 90%. The engines in the remaining 1994-1995 vintage diesel buses have been overhauled and upgraded to meet 1998 emission standards, and have been retrofit with DPFs. In addition, all diesel buses in the fleet now operate on cleaner, ultra-low sulfur diesel (ULSD) fuel, with no more than 30 ppm sulfur.

Together, these actions have resulted in a 92% reduction in PM emissions and a 44% reduction in NOx emissions from the bus fleet.

MBTA currently tests the emissions of its buses bi-annually, under a state mandated emissions inspection and maintenance program. This program uses an SAE J1667 snap-acceleration procedure and a traditional green-light opacimeter to measure smoke opacity of the exhaust. As discussed below, this program has proved ineffective at evaluating the MBTA fleet, particularly the new, cleaner buses.

As part of its over-all environmental commitment, the MBTA decided to develop and implement an "enhanced" emission I/M program. The intent of this program is to ensure that MBTA's new technology buses remain clean throughout their life, by regularly testing every bus in the fleet to identify buses with "excess" emissions, which can then be scheduled for maintenance action.

As part of a project team that includes Environmental Systems Products, Inc (ESP), Drucker Communications, and Causemedia, M.J. Bradley & Associates has been helping the MBTA to evaluate the available options for emissions testing and to design the enhanced I/M program. This project has included significant community outreach, and has been overseen by a Project Advisory Committee composed of representatives from federal and Massachusetts state government, as well as interested environmental, community, and health groups.

CURRENT I/M PROGRAM

Current Massachusetts state law mandates that every heavy-duty diesel vehicle in the state, including MBTA buses, be tested bi-annually for exhaust smoke emissions. Like most other state I/M programs for diesel vehicles, the Massachusetts program uses green-light opacimeters, in conjunction with the snap-acceleration procedure outlined in SAE J1667.

An opacimeter (or opacity meter) is a device that measures the density of the smoke in a vehicle's exhaust by shining a light of a particular frequency through the exhaust plume and measuring what percentage of the light energy is blocked by the smoke particles. The more smoke, the more light is blocked, and the higher the opacity.

The J1667 snap-acceleration procedure requires measurement of the maximum opacity registered while the engine of a stationary vehicle in park is quickly ramped up from idle to maximum governed engine RPM. This procedure is repeated three times, and the results averaged to give a single value of % opacity.

Under Massachusetts law, a vehicle with more than 40% measured opacity "fails" the test. Failed vehicles must be scheduled for maintenance and re-tested.

The current opacity testing program costs MBTA approximately $100/year/bus, including capital and operating costs.

Opacity testing has significant limitations as an emissions inspection and maintenance tool. First, it can measure only one of four criteria pollutants, and cannot give any information about NOx, CO, or HC emissions. Second, while smoke density is related to PM emissions, the correlation to regulated PM mass is not robust, particularly for modern, clean diesel and CNG engines. One problem is that traditional opacity meters use a green light with a wavelength of approximately 550 nm, which is much longer than the diameter of the most numerous particles from modern engines. As a result, the light is not blocked by these particles.

Another problem is that the mandated test limits have not kept up with modern engine technology. Out of 344 opacity tests conducted by the MBTA in 2004, 75% of the tested buses measured less than 5% opacity, compared to the failure limit of 40%.

DEVELOPMENT OF AN ENHANCED I/M PROGRAM

Because the current opacity testing program is considered to be ineffective for identifying excess emissions from MBTA's new clean buses, the enhanced I/M program requires a new testing methodology. The first task of the current project was to identify, and evaluate, all available test methods.

The project team identified four goals for the new program, as follows:

- Test for all criteria pollutants: PM, NOx, CO, HC
- Increase testing frequency for each bus
- Cost less than $500/year/bus, including amortization of capital costs and incremental operating costs
- Minimize impacts on bus operations

With the above goals in mind, the project team identified the following parameters as evaluation criteria for each testing option:

- Capital cost
- Fixed operating costs
- Variable operating costs
- Parametric vs. direct measurement capabilities
- Accuracy and Repeatability
- Capability for frequency of measurements
- Pollutant capabilities

Evaluation of Testing Technologies

The project team's first task was to determine which technologies or techniques could potentially be used for fleet emissions screening, and then evaluate each one against the above criteria. The team identified a wide range of possible options, including the use of engine or chassis dynamometer testing, continued use of opacity testing, parametric emissions measurement using on-board diagnostic systems or maintenance data analysis, and direct emissions measurement using portable emissions monitoring systems (PEMS) or remote sensing devices (RSD).

For certification purposes, emissions from heavy-duty diesel engines are tested with the engine mounted on an engine dynamometer. Large chassis dynamometers are also available that can be used to test emissions with the engine mounted in a vehicle. In either case, the engine or vehicle is operated over a "typical" duty cycle and the exhaust is routed to a dilution tunnel, where it is sampled and the emissions are analyzed using various laboratory grade "bench" analyzers.

Either of these approaches could theoretically be used to test emissions as part of an I/M program. However, the project team determined that neither approach is practical or feasible due to the very high cost of the equipment, the specialized staff required to operate it, and the time required for testing. With respect to the enhanced I/M project goals noted above, neither approach would allow frequent, cost-effective testing of an entire fleet.

The project team considered the continued use of opacity testing as the primary emissions screening tool. As discussed above, while relatively cost effective and capable of being used for more frequent testing, opacity testing has very limited utility for identifying "excess" emissions of criteria pollutants from modern diesel and CNG vehicles. The project team therefore determined that opacity testing would not be useful as part of the enhanced I/M program.

The team also evaluated two parametric methods of testing vehicle emissions: On-board Diagnostics (OBD) and Data Analysis. Neither of these methods measure emissions directly, but rather infer vehicle emissions performance based on review of related information.

OBD uses on-board sensors to determine whether or not the engine is operating in a way that will ensure low emissions. If a condition exists that is likely to result in increased emissions, the engine diagnostic system can relay this information to the operator or to maintenance personnel via warning lights in the operator's compartment or via a diagnostic reader. This approach is used with light-duty vehicles, with specific emissions-related engine failures triggering a "check engine" light on the dash.

Like all modern engines, the diesel and CNG engines in MBTA's buses are equipped with electronic diagnostic systems. However, the use of these systems for emissions OBD with heavy-duty engines is not as advanced as it is with light-duty engines. A review of the available diagnostic data shows that there is little specifically related to emission failures. In fact, several buses that were identified as having excess emissions using other test methods showed indication of an intermittent problem, but no active codes for emissions failures, in the engine diagnostic data. The project team therefore determined that OBD would not be a useful method of emissions screening, at least without additional development work by the engine manufacturers.

All fleet operators collect, or potentially could collect, various operating and maintenance data on their vehicles, including such information as fuel economy and oil usage. Because engine problems that can negatively affect emissions performance can also affect vehicle fuel economy and oil usage, analysis of this collected data could potentially identify high emitting buses without the need to directly measure vehicle emissions. By looking for trends, or deviations from the fleet average from individual buses, Data Analysis techniques seek to identify potential problem buses using existing information.

Unfortunately, this kind of data is typically neither readily available, nor accurate enough for the purpose of identifying high emitting vehicles. Though fleet averages can easily be calculated based on purchase quantities of fuel and oil, this data does not help in determining individual problem buses. In order to get vehicle-specific fuel consumption and oil consumption results, both mileage and fluid amounts must be accurately documented every time a vehicle refuels or receives an oil change. While seemingly simple, this process can actually be very difficult and potentially time consuming for a fleet as large as the MBTA.

Even if data collection is executed flawlessly, the utility of the data to identifying high emitting buses is questionable. Unfortunately, there are simply too many variables that affect fuel economy and oil consumption for this system to be used as a means of flagging buses for repair. For example, it's entirely possible that two properly functioning, identical buses will achieve fuel economies that differ by over 100%, because of their greatly varying duty cycles (arterial operation versus operation in stop-and go city traffic). Monitoring individual bus duty cycles could provide more accurate results, but would require the installation of new equipment on every bus, and would occupy considerable personnel time to collect, analyze, and review this data. The project team therefore determined that Data Analysis would not be a practical method of emissions fleet screening.

The project team also evaluated two additional methods of direct emissions measurement from vehicles:

the use of a Portable Emissions Monitoring System (PEMS) and the use of Remote Sensing Devices (RSD). As described further below, each of these methods was judged to have the potential to provide relevant, cost effective emissions results as part of a fleet screening program. The project team therefore decided to demonstrate each test method on the MBTA fleet.

DESCRIPTION OF PEMS & RSD

A PEMS device uses the same technologies typically used in bench exhaust gas analyzers to measure and record continuous time-series emissions data. However, the device is small enough to be installed on a bus, to collect data while the vehicle is operated in actual or simulated service, rather than being operated on a chassis dynamometer.

Figure 1. PEMS Unit Installed on MBTA Bus

PEMS units can accurately measure concentrations of carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxide (NO), nitrogen dioxide (NO_2), total hydrocarbons (THC), methane (CH_4), and oxygen (O_2) in the vehicle's exhaust, in units of parts per million. Current PEMS units cannot measure PM emissions. Via a connection to the engine's electronic control module, engine operating conditions such as torque, exhaust temperature, exhaust flow, engine speed, acceleration, boost pressure, fuel rate and vehicle speed are also recorded simultaneously. A separate flow meter can also measure the total volumetric flow of the exhaust. With this data, the device is able to calculate instantaneous emission levels of the various aforementioned pollutants in practical quantities such as grams/second (g/s), grams/gallon of fuel (g/gal), and grams/brake horse-power-hour (g/bhp-hr).

When charted against pertinent operational data such as engine speed or torque, this time series data will give a complete and accurate picture of vehicle emissions and performance. Because instantaneous values can vary widely depending on engine operating parameters (speed, torque), PEMS data is also often viewed in the aggregate, to give a single number for each pollutant for g/gallon, g/mile, or g/bhp-hr over the entire measured drive cycle, for comparison to emissions certification standards and laboratory test results. Figure 1 shows the Semtech D^{TM} PEMS device used in this project installed on an MBTA bus.

RSD uses principles of spectroscopy to take an approximately ½ second "snap shot" of the exhaust emission concentrations from vehicles as they drive by a fixed sensor. The sensor passes a beam of infrared and ultraviolet light through the exhaust plume. This light is reflected off a mirror on the other side of the roadway back to the sensing unit, which reads how much of the light was absorbed. Based on the relative absorption at different frequencies, the concentration of different

Figure 2.RSD Deployment at MBTA Bus Depot

substances in the plume can be measured.

The RSD unit measures concentrations of NO, CO, HC, and CO_2 in units of parts per million (ppm). By themselves these numbers are not very meaningful. However, because the carbon content of typical vehicle fuel is known, these numbers can be translated, using simple mathematics, into values of g/bhp-hr or g/gal by comparing the measured concentration of each pollutant to the measured concentration of CO_2, the major byproduct of combustion in an engine.

In addition to the gaseous pollutants, the RSD unit measures "smoke factor" as a proxy for PM emissions. Smoke factor is similar to a measure of opacity, except that the RSD unit uses a shorter wavelength of light than typical opacimeters, which is better matched to the size of PM particles from modern diesel and CNG vehicles. The measured opacity is also divided by the measured concentration of CO_2 in the exhaust plume, so that smoke factor is proportional to PM mass per unit of fuel burned.

The RSD device used for this program is able to take readings at a rate of 1.2 Hz – just greater than one reading every second. Therefore, if placed in an area of heavy traffic, a single RSD system could capture emissions data on over 3,000 vehicles per hour.

An RSD unit is typically deployed in conjunction with a device to measure the speed and acceleration of vehicles as they pass the sensor, as well as a camera to take an identifying photo. Figure 2 shows RSD set up at an MBTA bus depot, to measure emissions from buses as they enter the yard. The sending/receiving unit in shown on the right on top of a tower and the mirror unit is on the left.

RSD & PEMS Demonstration Program

In November 2004, the project team conducted emissions tests on various MBTA buses using a Semtech D™ portable emissions monitoring system (PEMS).

Typical PEMS setup time is about 60 to 90 minutes for each bus. PEMS setup involves securing the gas analyzer in the back of the bus, installation of a sensor in the bus exhaust stack, connection to the vehicle interface, and installation of a flow meter on the exhaust stack. The PEMS device must be powered during setup. While the vehicle's batteries can be used to power the PEMS device for short periods, because setup time is significant a separate 12-volt marine-grade battery is used to power the device during setup. Once all connections have been made, the system undergoes a series of calibrations, a process that requires three separate gas mixtures. Once the device is calibrated, the power is switched from the marine battery to the bus batteries, and the bus is driven through a route. Since the device is large and requires that lines and cables be run across the interior of the bus, no passengers were picked up during testing. Instead, each bus was driven over a typical route for approximately one hour, but did not make passenger stops.

PEMS testing took place over a nine-day period, during which buses with each engine type in the MBTA fleet were tested (older two-stroke diesel, mid-age four-stroke diesel, new emission-controlled diesel, and CNG) at the Charlestown, Cabot and Southampton facilities. Over nine days, a total of 15 buses were tested, but due to various equipment problems, only five buses yielded valid, useful data.

RSD data was collected from the MBTA fleet during two two-week periods, one in June 2004, and the other in September 2004. During each test period, RSD devices were deployed for one week at the Charlestown depot, and then at the Cabot depot the following week.

Reading and recording of RSD data is automatic, and requires no operator intervention. The RSD unit that was used for this project requires a technician to calibrate the machine every hour or two, a process that takes only seconds using a bottle of reference gas. Newer RSD models contain a calibration gas cell, which the device uses to automatically calibrate itself as needed. For a demonstration program such as that at the MBTA, it also takes a few hours to set up the equipment each day, and periodically the sending unit and mirror can move out of alignment due to vibration from passing vehicles. When this happens, the unit alerts the operator that signal strength is low, and the operator must re-align the units. In a permanent or semi-permanent installation for an on-going testing program, fixed mounts could be installed for both the sending unit and mirror unit to retain alignment. In this situation, the RSD unit could theoretically operate for days at a time virtually unmanned.

The RSD unit is a "line of sight" device, and must be aligned vertically with the location that the exhaust plume exits the vehicle tail pipe. Since the MBTA currently has buses with both low-stack exhaust exiting at street level and high-stack exhaust exiting at roof level, two RSD units were deployed during the demonstration program, one high and one low. The MBTA is currently phasing out all of the older low-stack buses, and future testing would require only a single RSD unit.

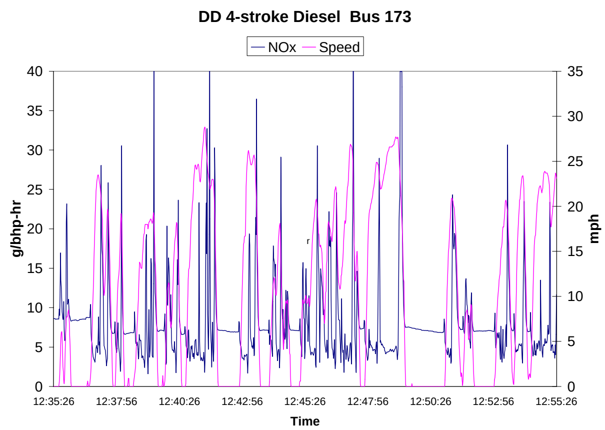
The equipment was set up outside of the main gate at Charlestown Depot and data was collected as buses entered the facility. The RSD unit was active from 7:30 AM until 2:30 PM each day. During the first week of testing a total of 826 valid RSD readings were taken from 226 buses. Valid readings were taken from every bus assigned to the depot, plus a few additional buses from other depots that entered the yard for fueling.

At the Cabot facility the following week, the RSD devices were set up behind the service garage, at the entrance to the rear parking lot and refueling area, and measurements were taken from buses as they returned from their routes. The equipment was typically set up from 9:00 AM until 4:00 PM at Cabot, though sometimes testing continued until 6:00 PM. The device was operational at different times at the different depots so that hours of peak bus traffic were captured at each. A total of 765 valid readings were taken at the Cabot depot, from 202 buses. Again, valid readings were taken from every bus assigned to Cabot plus additional buses from other facilities that entered the yard.

The RSD testing was repeated in September 2004. Again, testing occurred over a two-week period, one week at Charlestown and the other at Cabot, during the same peak traffic hours as in June. An additional 1,055 valid RSD readings were recorded during this test period. In total, the RSD captured valid data for over 90% of the buses that passed through its sensors.

PEMS Test Results

A sample of the results of PEMS testing at the MBTA can be seen in Figures 3-5. Figures 3 and 4 show a 20-minute PEMS trace of NOx emissions from bus number 0173, a 1994 model year diesel bus with an engine certified to 4 g/bhp-hr NOx emissions. Figure 3 shows the NOx emissions of the vehicle in units of grams per brake horsepower-hour (g/bhp-hr) plotted against vehicle speed. Figure 4 shows the NOx emissions of the same vehicle, over the same time period, in units of grams per second (g/s) plotted against vehicle speed.



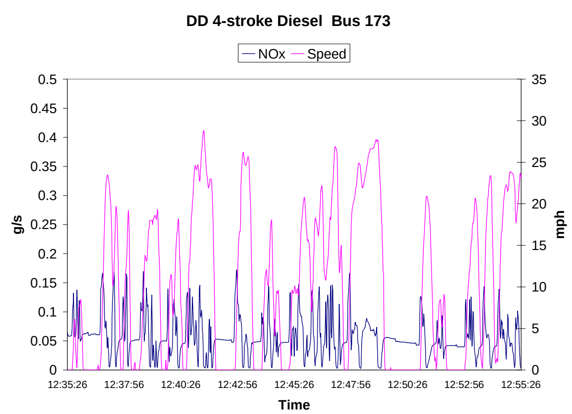


Figure 4. PEMS NOx Emissions from Bus 0173(g/s)

As shown, g/second NOx emissions are low at idle and tend to increase as vehicle speed increases (i.e. as the engine load increases). This is expected behavior from a diesel engine. NOx emissions expressed in units of g/bhp-hr (i.e. grams per unit of work done by the engine) are quite different. As shown, NOx g/bhp-hr values are lowest while the engine is under load, but are very high when the vehicle just starts to decelerate. Again, this is expected.

When analyzing PEMS data, it is important to look for these trends (spikes in g/s data during acceleration, and dips in g/bhp-hr). It is also important to note the maximum and minimum values of each, as well as the values during idle, and the averages over the entire measured cycle.

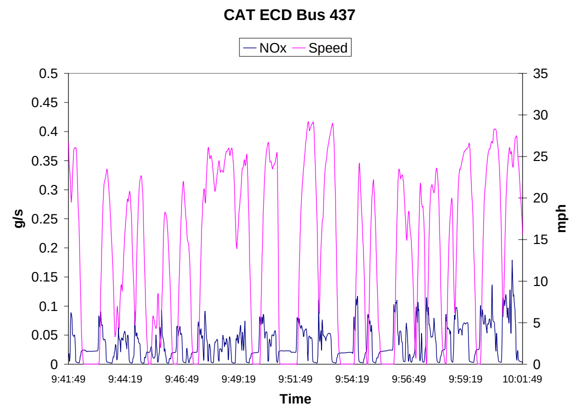


Figure 5. PEMS NOx Emissions from Bus 437(g/s)

Over the 20-minute cycle shown in Figures 3 and 4, bus 0173 averaged 10.38 mph and produced 5.0 g/bhp-hr average NOx (19.9 g/mile). The fact that the average measured NOx does not exactly match the certification value of 4 g/bhp-hr is not a concern, since the cycle measured by the PEMS unit is not exactly the same as that used for certification testing. From the PEMS data gathered on bus 0173, it was determined that this bus was functioning properly.

Figure 5 shows the NOx emissions from bus number 437, a 2004 ECD diesel bus, with an engine certified to 2.5 g/bhp-hr NOx. In this figure NOx is shown in units of grams per second (g/s) plotted against vehicle speed. As you can see, the NOx emissions from this bus were significantly lower that those from bus 0173, as expected based on the engine certification. Over the 20-minute cycle shown in Figure 5, bus 437 averaged 13.9 mph and produced 2.7 g/bhp-hr average NOx (9.3 g/mile). From the PEMS data gathered on bus 437, it was determined that this bus was also functioning properly.

Comparison of the data from these two buses indicates the benefit derived from the MBTA's decision to replace older buses with new, cleaner ECD buses. As shown the ECD bus produces about 10 g/mi less NOx than the older bus. For a bus that operates 30,000 miles/year, this will result in an annual savings of 0.3 tons NOx.

RSD Fleet Screening Results

The MBTA fleet data collected by the RSD unit during the demonstration program indicates promising fleet emission trends. Figures 6 - 8 display the gaseous emissions data gathered at the Charlestown and Cabot facilities, with the data separated into groups by engine type. Within each group, results are plotted along the horizontal axis in increasing bus number order, and multiple readings from the same bus are plotted stacked vertically above each other.

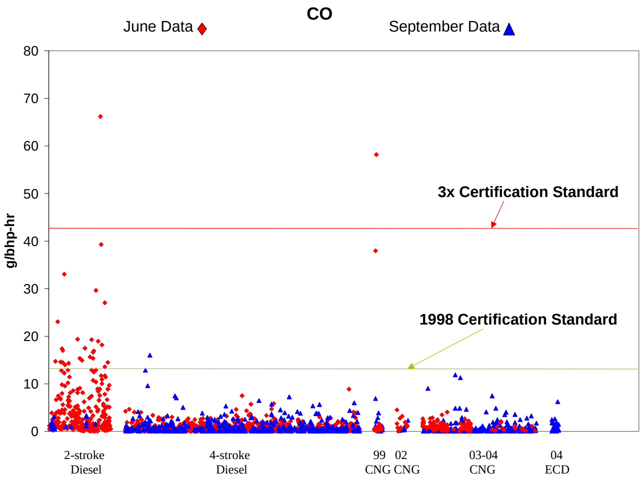


Figure 6. RSD Fleet Screening Results CO

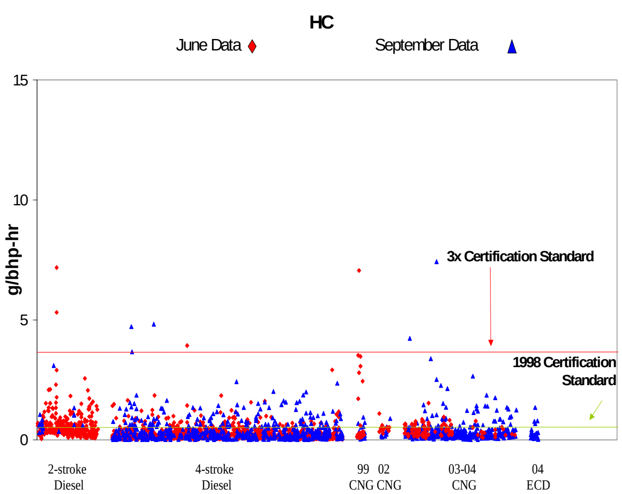


Figure 7. RSD Fleet Screening Results HC

The lower (green) lines in the graphs represent the 1998 EPA certification standard for urban bus engines for each pollutant. The 4-stroke diesel buses were designed to meet these emission standards. The older 2-stroke diesels were designed to meet less stringent standards, while the CNG and ECD diesels were designed to meet more stringent standards. The upper (red) line represents three times the 1998 emission standard, which is the level above which many state light-duty I/M programs declare a vehicle a "high emitter".

The general trend observed in these graphs indicates that the newer buses that contain more advanced emission controls are cleaner than the older buses, as expected.

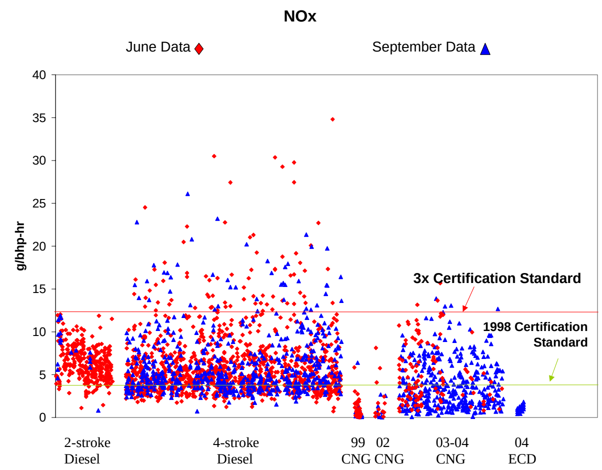


Figure 8. RSD Fleet Screening Results NOx

This data also illustrates how RSD fleet screening can be used to identify high emitters in an I/M program. Several of the CNG buses were shown to emit significantly more HC and CO than the rest of the fleet, as seen by a few data points well above the red line in the graphs. In a CNG engine, this indicates incomplete combustion due to lean misfire. Typically, this is caused by an oxygen sensor malfunction, which causes the engine to operate lean.

Several of the high emitters identified by RSD in June had new oxygen sensors installed. Figure 9 shows the results of one such replacement. While an OBD scan indicated no oxygen sensor malfunction, the vehicle's HC emissions after the sensor was replaced were less than 1/5 of what they were in the original test, and average NOx emissions were also cut in half. This decrease in emissions indicates an increase in combustion efficiency and an increase in fuel economy. Note that after replacement of the oxygen sensors in June, these high HC and CO readings were not repeated during the September testing.

In Figure 8, one can see that the majority of RSD NOx readings from both diesel and CNG buses were well below the "expected" value based on engine certification levels. However, with both engine types, there is also a fair amount of scatter above the mass of readings. At least some of this scatter is likely due to vehicles that were decelerating while passing the RSD sensor. As shown above in the PEMS data, NOx values denoted in g/bhp-hr tend to spike during deceleration, even though the engine is not actually producing a lot of NOx.

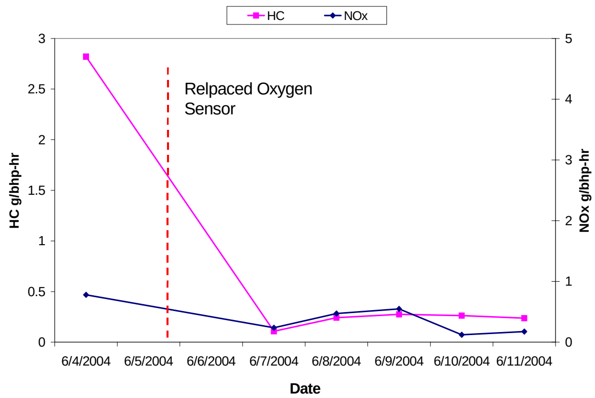


Figure 9. Effect of Maintenance

To a certain extent this can be controlled based on the RSD set-up, by deploying RSD in a location where most vehicles will be accelerating through the sensor. Even so, some readings will probably always be taken at idle or deceleration. For this reason, it is probably not appropriate to designate a "high emitter" based on a single RSD reading, especially for NOx.

One should also note that Figure 8 plots values for "NOx", which for diesel and CNG vehicles is primarily NO plus NO_2. Because the RSD unit measures NO only, these values were adjusted using a multiplication factor to account for the un-measured NO_2. These factors were determined by averaging the NO/NO_2 ratio as measured by PEMS for each bus type. For older 2-stroke diesel and CNG buses, RSD measured NO was multiplied by 1.3 to get the plotted values for NOx. For mid-age 4-stroke diesel and new ECD diesel buses, RSD measured NO was multiplied by 1.85. The difference is due to the diesel particulate filters installed on the mid-age and new diesels. These filters convert some of the NO to NO_2, which then helps to oxidize the collected carbon PM out of the filter.

As noted previously, the RSD device also measures an opacity-based "smoke factor" as a proxy for PM emissions. The MBTA fleet results for smoke factor are shown in figure 10. As shown, the older 2-stroke diesels exhibit higher smoke factor values than the newer diesel buses (that are equipped with particulate filters) and CNG buses, as expected. Also as expected, the new DPF-equipped diesels and CNG buses have virtually the same, low, smoke factor values, which is consistent with other emissions test results which shows roughly equivalent PM emissions from DPF-equipped diesel and CNG engines.

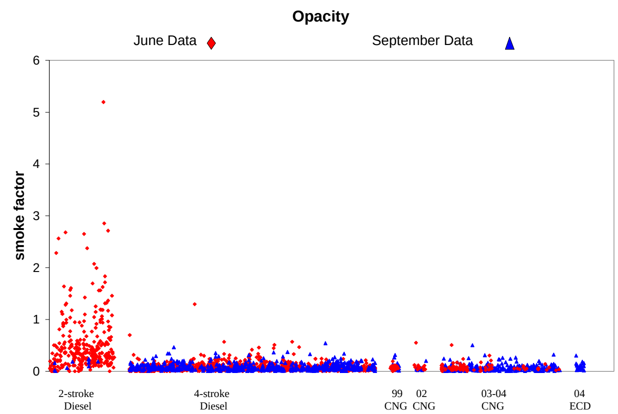


Figure 10. RSD Fleet Screening Results PM

The bus with the highest measured smoke factor was Bus number 8750. This bus exhibited a smoke factor of 5.19, 1.8 times the second highest smoke factor reading measured during the testing. When this bus was subsequently given a snap-acceleration opacity test using an opacimeter, the measured opacity was 2.0%. The state mandated value to designate a "failure" is 40.0% opacity. It is clear that as a test to indicate vehicles that are exhibiting excess emissions, the standard snap-acceleration opacimeter test is less than robust.

RELATIONSHIP OF PEMS AND RSD DATA

Because RSD only takes a "snapshot" of a vehicle's emissions, a relevant question is: how does this snapshot compare to other emissions measurements such as PEMS and engine certification data, and how should the RSD results be interpreted?

Figure 11 highlights a small portion of the PEMS NOx dataset from a 4-stroke diesel bus. This data shows NOx g/bhp-hr over a single acceleration event from 0 to just over 20 mph, and then deceleration to approximately 15 mph. As shown, during acceleration NOx g/bhp-hr is very flat, and is well representative of the engine certification value of 4 g/bhp-hr. As noted previously, NOx g/bhp-hr is significantly higher during deceleration. However, since the engine is not doing much work during deceleration, actual total NOx emission rates (g/s) are low at this time. During a typical acceleration/deceleration cycle, a vast majority of NOx is produced during acceleration. Also, since a typical transit bus duty cycle has a very high number of accelerations from a stop, this is an important reference point in the over-all duty cycle.

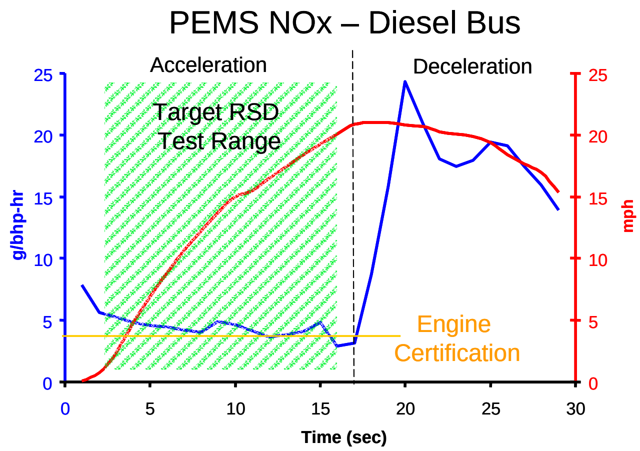


Figure 11. PEMS NOx During Acceleration

All of this is very relevant to interpretation of RSD results. As long as the RSD "snapshot" was taken while the vehicle was accelerating, the measured value should correspond to the point of peak NOx production throughout the entire drive cycle. It should also correspond well to the "expected" value based on engine certification data. Because NOx g/bhp-hr is quite flat throughout the full acceleration event, it is less important how hard the vehicle was accelerating or how fast it was going. It is more important just that it was accelerating through the sensor at some rate, as opposed to cruising or decelerating.

It should be clear from the above discussion that an RSD deployment should enforce data collection during acceleration only. This can be partially controlled with the physical set up. It can also be controlled by accurately measuring vehicle speed and acceleration, and ignoring data taken below some threshold value of acceleration and/or speed.

During the RSD demonstration at the MBTA, these conditions were not as well controlled as one would prefer, and undoubtedly some of the high NOx readings from every bus type shown in Figure 8 are due to snapshots taken during deceleration.

It should also be clear from a review of Figures 6 - 11 that there are two relevant starting points for designation of a high emitting bus based on RSD testing. The first is whether the bus has consistently higher readings than the majority of buses with the same engine/fuel type. In this type of analysis, it is critically important to separate the buses into groups, since it is clear that different engine types have very different RSD "signatures", as one would expect based on differences in technology. This type of analysis must also take account of the fact that no matter how well data collection is controlled, any individual RSD snapshot may have been taken during a point of engine operation for which g/bhp-hr values would be expected to be high, even from a properly functioning vehicle. This implies that single high readings can probably be ignored. One should be looking for a pattern of high readings.

The other relevant starting point for designation of high emitters is the engine certification value. As shown in Figure 11, as long as consideration is given to expected variability in g/bhp-hr values throughout the target test range, this single value is a good yardstick for expected RSD results from a well-functioning vehicle. In light-duty I/M programs, this variability is typically accommodated by setting the "failure" criteria 2 or 3 times the certification value. Consistent RSD readings greater than this value would be considered indicative of a high emitter that required maintenance action.

PROPOSED ENHANCED I/M PROGRAM

During the technology demonstration phase, both PEMS and RSD were shown to be able to collect valid and relevant emissions data that could be used to designate "high emitting" buses in an emission I/M program.

Of the two technologies, PEMS provides the most detailed information on gaseous pollutants. While PEMS cannot at this time measure PM directly, in many cases increased PM emissions will be accompanied by increased HC and CO emissions, which can be detected by PEMS. Within the next few years, PM measurement capability is likely to be added to some PEMS, although at significantly increased capital cost. The most significant drawback to PEMS is its high operating cost, and therefore its inability to provide frequent, cost-effective measurements. Because PEMS testing takes approximately three and a half hours per bus, a program to measure emissions from each bus in the MBTA fleet annually using PEMS would require a minimum of three PEMS devices, and seven full-time-equivalent employees. This would cost approximately $800/bus/year, just for annual testing. Quarterly testing would cost at least $3,000/bus/year and would require each bus in the fleet to be removed from service for two days per year just for this testing.

Like PEMS, RSD can directly measure all gaseous pollutants, and can also measure smoke factor, which appears to be a reasonable proxy for PM emissions. While the emissions "snap shot" taken by RSD is not as detailed as the emissions data provided by PEMS, it was demonstrated to be accurate and repeatable enough to provide a robust screening method in the context of an emissions I/M program. In fact, the data provided by PEMS is really much more than is required for this screening function.

While the capital cost of RSD devices are virtually identical to those of PEMS devices ($100,000-150,000 per device), operating costs are much lower because vehicles can be tested while in service, and the device can operate virtually un-manned. This also increases the practical frequency of measurement significantly.

Quarterly testing of each bus in the MBTA fleet would require only one RSD device, and one full-time equivalent employee. This would cost substantially less than PEMS testing and would not require the vehicles to be removed from service in order to complete the testing.

Based on the above analysis, the project team recommends that the MBTA use RSD as the primary emissions screening tool to identify high emitting buses for its enhanced I/M program

As explained above, the choice to recommend the use of RSD technology is due to the system's ability to gather data on emissions of all criteria pollutants from a large number of vehicles in a short time, and at a low cost. Multiple RSD readings can be used to identify high emitters for maintenance. The RSD technology can then be used to evaluate the effect of maintenance. All of this can be done with minimal incremental labor cost, and without interfering with normal fleet operations in any way.

The more detailed emissions data that can be collected using PEMS is likely to prove very useful in diagnosing certain types of engine problems that are initially identified using the RSD screening. For this reason, the project team recommends that the MBTA should acquire the capability to conduct PEMS testing as needed on high emitting buses. This PEMS testing capability will be used to enhance the maintenance aspect of the I/M program, and will ultimately save money by reducing diagnostic effort.

As discussed above, since RSD only takes a snap shot of a vehicle's emissions, and the actual engine operating state at the time of measurement are not known exactly, the project team recommends that the designation of a "high emitter" be based on multiple RSD readings as opposed to a single reading. This can be accomplished by conducting multiple, consecutive days of testing at each depot.

On any particular day, at least 85% of the vehicles assigned at each depot are needed for peak service. Also, many vehicles tend to enter and leave the depot several times during the day, as vehicles are dispatched to meet both morning and evening peak service requirements. To maximize the number of vehicles tested, the daily hours of testing should coincide with peak pull-in periods. Pull-ins are preferred to pull-outs so that the engines and after-treatment systems will be fully warmed up when emissions readings are taken. On diesel vehicles, "cold-start" emissions are known to be higher than normal in-use emissions after the engine has warmed up. Regular testing of cold buses might increase the incidence of "false positive" high emitter designations. A minimum of six hours of testing per day will be required to cover two peak pull-in periods.

The project team recommends that for each test period, five consecutive days of testing be conducted at each depot. This will yield 5-10 readings for each bus, if the daily testing covers both peak pull-in periods.

For each pollutant (NOx, HC, CO, Smoke Factor) designation of a high emitter would be based on review of all of the readings from each bus during each test period. The readings would be compared to each other and to a pre-determined "cut point" for each type of engine. Multiple readings above the cut point would indicate a "failure" that would require remedial maintenance action. One single high reading would not indicate a failure.

Designation of appropriate cut points to denote failures is an issue that requires further discussion between the MBTA and the Project Advisory Committee. The Project Team believes that for the pollutants NOx, HC, and CO, an appropriate starting point for consideration is three times the achieved certification value (in g/bhp-hr) for the engine. This is consistent with light-duty emissions I/M programs. Since smoke factor does not relate directly to PM certification values, more work is required to evaluate the appropriate smoke factor cut points.

As to testing frequency, the project team recommends that at each depot, testing be conducted for one week per quarter. This recommendation is based on a preliminary analysis of the cost and benefits of different testing frequencies using RSD.

In this analysis, it was assumed that emissions related failures from a diesel bus would result in NOx emissions three times the engine certification value. With an assumed 2,500 average miles per bus per month, an uncorrected failure would result in 62.5 pounds of excess NOx emissions per month. It was also assumed that the MBTA fleet would experience such emissions failures at a rate of 1.0% per month, which is a very conservative assumption based on the observed incidence of high emitters during the recently completed RSD fleet screening.

Beginning with an annual test requirement, and moving to semi-annual, quarterly, monthly, and weekly, the incremental cost of more frequent testing was compared to the incremental benefit from identifying and correcting emissions failures earlier than would otherwise happen with the less frequent testing. The "excess" NOx emissions saved by more frequent testing were valued at $10,000 per ton, consistent with peak values under existing NOx credit trading schemes over the last several years.

This analysis indicates that quarterly testing frequency is optimal, in that the incremental costs most closely balance the incremental benefits. The cost of more frequent testing would outweigh the benefit significantly. Sensitivity analysis shows that this result is true even if you assume a 5% failure rate, or if you assume that NOx is valued at $30,000/ton. A similar analysis for PM gives an equivalent result, even if you assume an arbitrarily high value for PM of $150,000/ton (there is currently no market value for PM based on trading, as there is with NOx). Sensitivity analysis also shows that if you assume a more realistic failure rate of 0.5% per month, semi-annual testing is optimal because the incremental cost of quarterly testing is significantly greater than the incremental benefit.

Since the actual failure rate is not known, the project team recommends taking a conservative approach and instituting quarterly testing to begin with. During the first year of testing, the actual failure rate will be determined with greater certainty (the number of high emitters identified each month). If this actual rate is less than 0.5% per month, the MBTA could move toward semi-annual testing in future years.

A complete RSD system consists of a "Source/Detector Module" (SDM), which transmits the infrared/ultraviolet light and conducts the emission level measurements, a "Transfer Mirror Module" (TMM), a simple setup of angled mirrors that reflect the light back to the SDM, a camera or other method of vehicle identification, and a computer for system monitoring, data recording and storage.

Assuming quarterly testing, one RSD system would be more than adequate to handle the testing required at each of the seven major MBTA depots, including expected down time. Since the SDM and computer system are the most expensive components of the system, the project team proposes that, rather than install these components permanently at each location, a single SDM unit and computer be moved between depots as required.

Nonetheless, in order to minimize labor costs for installation and set-up at each location, as well as to ensure that the SDM and TMM maintain adequate alignment, the project team recommends that the MBTA install a permanent, covered tower for mounting the TMM and a small building for housing the SDM and computer equipment during testing at each depot.

During testing, a system is also required to identify each bus that passes the sensor. As with the demonstration program, a camera system could be used for this purpose. However, this requires someone to review each photo and manually record the bus number in the database.

The project team recommends that in lieu of a camera system, the MBTA install an inexpensive, passive radio frequency ID tag (RFID) on each bus. A tag reader could then be integrated with the RSD equipment, to automatically record a bus number in the database based on the unique RFID tag identifier.

In the scenario proposed above, the RSD testing at each depot can proceed virtually automatically, with very little labor required. An RSD technician will be required to move the SDM and computer equipment between depots weekly, and to periodically check to ensure that each unit is functioning properly during testing. In addition, the RSD technician will be required to produce test reports at the end of each weeks testing, including lists of high emitters. Most of the analysis required to create these reports can be automated.

In addition to the RSD testing, the project team recommends that the MBTA acquire the capability to conduct testing using PEMS, as required for diagnosing engine problems. Since it is impossible to determine how often PEMS testing will be required, and PEMS equipment is very expensive, the most cost-effective method for the MBTA to acquire PEMS testing capability will probably be to contract for testing services rather than to purchase equipment themselves.

The above program is expected to cost significantly less, and to be much more effective, than a program using any of the currently available alternative approaches. The net cost of the program will be even less if current opacity testing can be discontinued.

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