TECHNOLOGY DIGEST

Timely Technology Transfer

Water Vapor Effects on Engine Exhaust NO_x Measurements

by

Steven Fritz, Vernon Markworth and Dan Steeples

TD94-004

Summary

The Association of American Railroads (AAR) and Southwest Research Institute (SwRI) are conducting a series of field and laboratory exhaust emission tests on locomotive diesel engines. These tests will determine the effects that different fuels, lubricants, and engine configuration changes have on gaseous and particulate emissions. This program supports the rail industry in negotiations with state and federal regulators.

Recently, SwRI discovered a measurement discrepancy in NO_x emission values for locomotive engines tested between 1989 and early 1993. The instrumentation used claimed to give correct NO_x measurements independent of exhaust water vapor concentrations. This claim turned out to be false.

SwRI recently tested four locomotives, along with laboratory bench tests, to quantify the water vapor effect on the measurement instrumentation used between 1989 and 1993. Standard statistical methods showed that a two-variable regression model fit the resulting data very well and that the old data could easily be corrected. Also, these NO_x measurement errors are independent of engine type. The regression model was used to correct previously collected NO_x emissions data studying the effect of two engine modifications: 1) re-tarding the fuel injection timing, and 2) installing 4-pass aftercoolers to increase inlet air cooling. The original conclusions, indicating statistically significant NO_x emission reductions for both modifications, remained unchanged.

Association of American Railroads
Research and Test Department

February 1994

INTRODUCTION AND CONCLUSIONS

SwRI has performed exhaust emissions tests on locomotive engines for the AAR since 1989 and has developed a 3-mode test cycle to characterize typical locomotive duty cycles. NO_x emissions in the SwRI system (and most commercial systems) are measured with a chemiluminescent (CL) analyzer.

It is well known that NO_x reactions are quenched in the presence of water vapor. Early CL instrument users circumvented the water vapor effect by analyzing only dry exhaust samples. Several years ago Beckman, now Rosemont Analytical, introduced their Model 955 CL, a heated analyzer advertised as being, "designed for analysis of sample streams containing high concentrations of water." The Model 955 CL became the most commonly used NO_x instrument by engine manufacturers and laboratories, based on the manufacturer's claim, to measure wet exhaust samples.

Despite the manufacturer's claim, SwRI determined that the Model 955 CL analyzer did not provide correct NO_x measurements in wet exhaust samples. To quantify the water vapor effect on NO_x measurements from locomotive engine exhaust, SwRI conducted a special set of tests where both "wet" and "dry" exhaust samples were tested.

The test results verified that a water interference problem existed with the Model 955 CL NO_x instrument. The wet exhaust data consistently underestimated NO_x. The data showed a consistent linear measurement error over the range of water vapor concentrations traditionally encountered in locomotive engine exhaust. The adjusted "dry" NO_x values have a positive linear relationship with both water vapor % and the "wet" NO_x measurements. The model developed from these test results was used to correct data collected on 13 locomotives tested in late 1992 and early 1993. These tests were conducted to estimate the NO_x emission effects of two engine modifications: 1) retarding the fuel injection timing, and 2) installing 4-pass aftercoolers to increase inlet air cooling. An analysis of the corrected data supported the original conclusions that both modifications yielded statistically significant reductions in NO_x emissions. The absolute NO_x values for the standard and revised engine configurations experienced a linear shift upwards with no variability adjustment as a result of the corrections to the original "wet" data. In general, the "wet" measurement underestimated the "dry" measurement by about 11%.

SwRI developed a system to eliminate the water vapor effect by installing an ice-bath water trap between the converter and reaction chamber within the CL instrument. This trap design is now used in all SwRI NO_x measurements and recommended for all other NO_x measurement systems. This program clearly shows that the US Environmental Protection Agency needs to specify standard testing procedures on locomotive exhaust emissions. This will ensure that all organizations reporting locomotive emissions data use the same data collection and analysis methods.

TEST RESULTS

Characterizing the Water Concentration Effect on NO_x Measurements

SwRI performed this series of experiments from late October through early December 1993, using the same Model 955 CL NO_x instrument used in recent locomotive field test programs. This instrument was modified with an SwRI-designed ice-bath water trap to condense the water vapor in the exhaust sample. Also, it incorporated a trap bypass to document the instrument response changes with the "dry" (dry to 32° F dew point) exhaust versus "wet" exhaust.

Initial evaluations were performed on SP 2706, an EMD MP-15 switcher equipped with a 1500 hp Roots-blown 645E 12-cylinder engine. This was the first locomotive tested at the new AAR locomotive exhaust emissions test site located at the former Southern Pacific diesel mechanical shops in San Antonio. The three additional locomotives tested included: 1) Amtrak 514, a GE DASH8-32BWH passenger locomotive equipped with a 3275 hp 12-cylinder 7FDL12J8 engine, 2) Amtrak 229, an EMD F40-PH locomotive equipped with a recently overhauled 3300 hp 16-645E3B engine, and 3) a new GE AMD-103 4100 hp locomotive equipped with a 16-cylinder 7FDL engine. SwRI tested each locomotive at three or four different throttle notch settings. Table 1 displays the actual data. The following two-variable regression model provided the best fit to the data:

$$NO_x(dry) = -1.05 + 1.00(NO_x(wet)) + .018(NO_x(wet))*(H_2O\%\ volume)$$

Table 1. Summary of Locomotive Evaluations Used to Determine Effect of Water Vapor on NO_x Measurements

Loco-motive	Notch	Measured* "dry" NO_x (ppm)	Measured "wet" NO_x (ppm)	Exhaust water (%volume)
SP 2706	1	209	199	2.88
SP 2706	3	374	350	3.90
SP 2706	5	611	562	5.02
SP 2706	8	882	791	6.59
Amtrak 514	Low idle	275	261	3.13
Amtrak 514	idle	480	446	4.30
Amtrak 514	2	950	862	5.66
Amtrak 514	3	1,055	942	6.60
Amtrak 514	5	1,175	1,042	7.09
Amtrak 229	4	625	576	4.64
Amtrak 229	6	950	852	6.21
Amtrak 229	8	1,163	1,052	5.97
Amtrak 806	1	735	672	5.37
Amtrak 806	5	975	869	6.84
Amtrak 806	8	1,210	1,082	6.49

Note: SP 2706 - 1,500 hp EMD 12-645 NA engine
Amtrak 514 - 3,275 hp GE 7FDL12J8 engine
Amtrak 229 - 3,300 hp EMD 16-645 E3B engine
Amtrak 806 - 4,100 hp GE 7FDL 16L16 engine
* - Dry to 32°F dew point

This model yielded an R-squared coefficient of nearly .999, meaning that virtually all of the variability in the "dry" NO_x measurement is explained by knowing the "wet" NO_x measurement and the water vapor % volume in the engine exhaust. There's also a significant interaction effect between the wet NO_x measurement and the water vapor % volume.

These data (which include the total quench and volume effects) confirm that water vapor concentrations have a significant effect on measured NO_x emissions and are independent of locomotive engine type. An analysis of variance indicated that measured NO_x (wet) explains most of the variability in NO_x (dry). Finally, the measurement error is essentially linear over the range of water concentration and NO_x parts-per-million levels encountered in locomotive engine exhaust. A separate report providing additional information on this water effect is forthcoming from SwRI.

Effect on Existing Data

The regression model described above can be used to correct the "wet" NO_x exhaust measurements to their respective "dry" measurements. All necessary information is readily available. The "wet" exhaust measurement is already recorded and the water vapor % volume is obtained by a known relationship with 4 other factors: i) fuel hydrogen-to-carbon ratio, ii) measured CO_2, iii) measured CO, and iv) the ambient air humidity. The process yields the corrected NO_x measurement.

Several AAR studies have been released where "wet" exhaust emissions were used in the analysis. The statistical interpretations should remain the same but the mean and confidence interval locations will shift upwards. A complete list of the affected reports is available from the third author.

Case Study #1 - 4° Timing Retard Test Data:
Table 2 presents the summary data analyses from 13 locomotives tested in late 1992 and early 1993 to assess the wet-to-dry NO_x correction effects. For all types of locomotives tested, retarding the fuel injection timing by 4° still produces a statistically significant reduction in NO_x emissions. Accounting for the variability in the data, in % terms this reduction could range from roughly 10% to 30%.

Case Study #2 - EMD Retrofit Aftercooler Data
Table 3 presents the effects of retrofitting the SwRI test engine with an aftercooler. The retrofit 4-pass aftercooler leads to a statistically significant reduction in measured NO_x values. Accounting for the variability in the data, in % terms this reduction could range from roughly 2% to 13%.

Table 2

Configuration	AAR 3-Mode Corrected NO_x (g/hp-hr)					
	4-GE 7FDL Engines		5-EMD 645E3B Engines		4-EMD 645 E3 Engines	
	"Wet"	"Dry"	"Wet"	"Dry"	"Wet"	"Dry"
Std. Fuel Inj. Timing	11.0 (10.5 to 11.6)	12.4 (11.9 to 12.9)	11.0 (10.4 to 11.6)	12.2 (11.6 to 12.8)	10.1 (9.9 to 10.4)	11.1 (10.8 to 11.3)
4° Retard	8.6 (7.8 to 9.5)	9.7 (8.8 to 10.5)	8.4 (7.9 to 8.9)	9.2 (8.7 to 9.8)	7.6 (7.3 to 7.9)	8.3 (8.0 to 8.6)
Difference (NO_x Red.)	(1.5 to 3.4)	(1.8 to 3.7)	(1.8 to 3.3)	(2.2 to 3.8)	(2.2 to 2.9)	(2.4 to 3.1)

Note: The scalars represent 3-cycle weighted averages. In the first two data rows the numbers in parentheses represent 95% confidence intervals for the estimated weighted averages. In the last row they are 95% confidence intervals for the difference in the weighted averages and if these intervals do not contain 0 then there is a statistically significant difference.

Table 3
The Effect of Water Vapor Correction on Laboratory
Engine EMD Retrofit Aftercooler NO_x Test Results

Configuration	AAR 3-Mode Composite Corrected [a,b] NO_x (g/hp-hr)	
	As Measured "Wet"	If Measured "Dry"
Baseline EMD 12-645E3B	11.5 (11.1 to 12.0)	12.7 (12.3 to 13.1)
With Retrofit Aftercoolers	10.6 (10.3 to 10.9)	11.7 (11.4 to 12.1)
Difference (i.e. NO_x reduction)	(0.37 to 1.41)	(0.37 to 1.51)

Note: a- AAR 3-mode weighted composite average based on multiple tests at each notch
b- Corrected for ambient air temperature and humidity

Note: Contact Dan Steeples at (202) 639-2260 with questions or comments about this document.