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"Locomotive Exhaust Emissions: Combined Effects of Low-Sulfur, Low-Aromatic, High-Cetane Fuel; Retarded Injection Timing; and Increased Aftercooling,"

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Summary

The Association of American Railroads (AAR) and Southwest Research Institute (SwRI) are conducting a series of tests on locomotive diesel engines to determine the effects on gaseous and particulate emissions of different fuels and lubricants and of changes in engine configuration. The testing program supports the rail industry in dealing with both state and federal regulators.

Low-sulfur, low-aromatic, and high-cetane fuel; retarded fuel-injection timing; and increased intake-air aftercooling have all previously been found to reduce emissions of either particulates or oxides of nitrogen (NO_x) *in some smaller engines. Their emissions impact on General Motors Electro-Motive Division (EMD) and General Electric (GE) locomotive-type engines was measured at SwRI. The results of these tests indicate that the combination of these three techniques can result in reduced* NO_x *emissions for some existing locomotive engines without a major redesign of the engine or of the fueling system. These tests showed* No_x *reductions in the range of 30 percent. These reductions could come at a cost in fuel consumption of one percent or more, however, and such fuels could be considerably more expensive. Retarded injection timing and/or different fuels could also lead to increased engine maintenance frequency and cost.*

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INTRODUCTION AND CONCLUSIONS

The California Air Resources Board (CARB) is studying several fuel and engine retrofit options for locomotive engines in connection with the development of locomotive exhaust emissions standards that would apply to the current fleet of locomotives. Among the options being considered by CARB are retarding injection timing by 4° on all existing engines; requiring the use of low-sulfur, low-aromatic, high-cetane fuel; and requiring increased aftercooling of intake air.

In order to evaluate the effects of these potential requirements, tests were conducted at the diesel engine laboratory at San Antonio, Texas. This facility is jointly owned by AAR and Southwest Research Institute (SwRI). The laboratory's principal engines are 12-cylinder turbocharged EMD 645E3B and GE 7FDL engines.

The test program included comparing emissions using an alternative fuel to emissions using standard diesel fuel; mapping the emissions as a function of injection timing; mapping the emissions as a function of inlet air temperature; and measuring the effects of combining 4°- retarded timing with lower inlet air temperature and low-sulfur, low-aromatic, high-cetane fuel.

The test results indicate that it is possible to reduce NO_x by a measurable amount using such combinations of fuel and engine modifications. NO_x reductions in the range of 30 percent were measured. Engine models other than the two tested may not produce the same level of reductions. While retarded injection timing appears to be a promising method for reducing NO_x, its impact on costs and smoke are unknown. Increased aftercooling would probably reduce NO_x and improve fuel efficiency on any engine, but it may or may not be feasible to increase the aftercooling on existing locomotives. While fuel properties may affect emissions levels, the fuel tested did not show any clear improvement in emissions other than reduced SO_2. A lower-cost alternative to reduce SO_2 would be to simply use a low-sulfur fuel.

APPROACH

Each emission value presented is based on the averages of three readings at each of three throttle positions (idle, notch 5, and notch 8) which are then normalized for a typical engine duty cycle. In each case, statistical tests were performed to verify that the differences between the base and test cases were statistically significant. It should be kept in mind that the findings presented in this report are based on a small number of tests on only one EMD and one GE engine. There can be substantial variability in emissions among engines of the same design, or within the same engine over time, which could affect the conclusions presented in this report.

EFFECT OF FUEL SPECIFICATION ON EMISSIONS

Fuel sulfur content, aromatic content, and cetane number are all thought to affect engine emissions in some way. Lower sulfur content results in lower sulfur dioxide (SO_2) emissions and is thought to contribute to reducing particulate matter (PM). Lower aromatic content often leads to reduced PM in smaller engines. Higher cetane numbers produce better combustion in small, high- speed, diesel engines and are thought to lower some emissions as a result.

A low-sulfur, low-aromatic, high-cetane fuel was compared with a typical diesel fuel in the two 12-cylinder test engines. Table 1 summarizes the results. The small differences in the readings obtained with these two fuels are more likely the result of measurement variability than fuel-caused emissions reductions. Note the only statistically significant difference between the base fuel and test fuel emissions was for NO_x in the GE engine.

The low-aromatic, high-cetane, low-sulfur fuel is lighter than the base fuel and results in about a 3.5% increase in fuel consumption. This fuel is not now commercially available, and the premium over the cost of regular No. 2-D fuel is unknown. The cost premium of fuel with less than 10%

aromatics has been estimated to be as high as $0.25 per gallon. A regular No. 2-D fuel that has less than 0.05% sulfur (the EPA highway fuel specification starting in 1993) may cost $0.01-0.02 extra per gallon. Sulfur is a good lubrication agent, so fuel injectors could have a shorter life with low-sulfur fuel.

EFFECT OF ENGINE INJECTION TIMING ON EMISSIONS

Injection timing was varied on both engines to determine the effect on emissions, especially NO_x and PM, when compared with standard timing. The results appear in Table 2.

As expected, as timing is retarded, NO_x decreases and PM increases. On the two engines tested, the deleterious effects of retarded timing do not seem especially bad at 4°. There is a fuel penalty of approximately 1%.

These tests did not include measurements of smoke opacity. If retarding the timing increases smoke appreciably, railroads could be fined for violating smoke ordinances.

EFFECT OF INLET AIR AFTERCOOLING ON EMISSIONS

A well-known way to reduce NO_x emissions while also improving fuel efficiency is to cool the intake air after it has been compressed by the turbocharger. Most, if not all, turbocharged locomotive engines already have aftercooling equipment; however, it might be possible to reduce the inlet air temperature even more, at least on some locomotives.

Table 1. Brake Specific Engine Emissions – Low-Sulfur, Low-Aromatic, High-Cetane Fuel versus Base Fuel

		Fuel Characteristics			*Brake-Specific Emissions (g/bhp-hr)*			
Engine	*Fuel*	*Sulfur (wt %)*	*Aromatics (vol %)*	*Cetane Number*	*PM*	*NO_x*	*HC*	*CO*
EMD	*Base*	*0.29*	*30.8*	*44.2*	*0.15*	*10.5*	*0.29*	*0.81*
645E3B	*Test*	*0.04*	*15.6*	*54.5*	*0.17*	*10.4*	*0.33*	*0.83*
GE	*Base*	*0.29*	*30.8*	*44.2*	*0.19*	*11.2*	*0.42*	*1.98*
7FDL	*Test*	*0.04*	*15.6*	*54.5*	*0.18*	*9.9**	*0.36*	*1.87*

** Significant difference at the .05 level.*

Table 2. Brake-Specific Engine Emissions as a Function of Fuel Injection Timing Retardation

		Brake-Specific Emissions (g/bhp-hr)			
Engine	*Fuel Injection Timing Retardation*	*PM*	*NO_x*	*HC*	*CO*
EMD	*0°*	*0.15*	*10.5*	*0.29*	*0.81*
645E3B	*2°*	*0.25**	*9.5**	*0.33*	*0.77*
	4°	*0.24**	*8.9**	*0.40**	*0.85*
	6°	*0.25**	*8.0**	*0.40**	*0.95**
GE	*0°*	*0.19*	*11.2*	*0.42*	*1.98*
7FDL	*4°*	*0.26*	*9.2**	*0.41*	*1.91*
	8°	*0.39**	*7.2**	*0.49*	*2.21*
	12°	*0.58**	*5.8**	*0.72**	*2.60**

* *Significant difference from 0°* at the .05 level.

With the injection timing retarded 4° on each engine, the emissions were mapped as a function of inlet air temperature. The results are presented in Table 3. . The aftercooling already in place on these engines is fairly effective; the advantage of increased aftercooling is not large but could still be significant.

COMBINED EFFECTS

The combination of 4° of retarded injection timing; increased aftercooling of the compressed intake air; and low-aromatic, high-cetane fuel was tested to see how these changes work together. Table 4 shows the results.

The three changes seem to work well together in reducing NO_x with little or no increase in particulates. Apparently the reduced inlet air temperature serves to minimize the increase in PM normally associated with retarded injector timing. It is not clear whether or not the effect of the fuel is significant.

Table 3. Brake-Specific Engine Emissions as a Function of Inlet Air Temperature (Injector Timing Retarded 4°)

Engine	Inlet Air Temperature (°F)	Brake-Specific Emissions (g/bhp-hr) PM	NO_x	HC	CO
EMD	210	0.24	8.9	0.40	0.85
645E3B	195	0.25	8.1*	0.38	0.95
	180	0.23	8.0*	0.38	0.92
	165	0.23	7.9*	0.39	0.93
GE	185	0.26	9.2	0.41	1.91
7FDL	170	0.25	8.7	0.42	1.94
	155	0.25	8.7	0.41	2.01
	140	0.28	8.7	0.46	2.04

** Significant reduction compared with 210° F at the .05 level.*

Table 4. Brake-Specific Engine Emissions Resulting from a Combination of 4° Retarded Injection Timing; Increased Aftercooling; and Low-Aromatic, High-Cetane Fuel

Engine	4° Retarded Injection Timing	Inlet Air Temp (°F)	Low-Aromatic High-Cetane Fuel	Brake-Specific Emissions (g/bhp-hr) PM	NO_x	HC	CO	Ref.
EMD 645E3B	No	210	No	0.15	10.5	0.29	0.81	Table 1
	No	210	Yes	0.17	10.4	0.33	0.83	Table 1
	Yes	210	No	0.24	8.9	0.40	0.85	Table 2
	Yes	180	No	0.23	8.0	0.38	0.92	Table 3
	Yes	180	Yes	0.19*	7.2*	0.33	1.02*	-
GE 7FDL	No	185	No	0.19	11.2	0.42	1.98	Table 1
	No	185	Yes	0.18	9.9	0.36	1.87	Table 1
	Yes	185	No	0.26	9.2	0.41	1.91	Table 2
	Yes	140	No	0.28	8.7	0.46	2.04	Table 3
	Yes	140	Yes	0.20	7.6*	0.36*	2.04	-

** Significant change from the base case (no retarded injection timing, no additional inlet air cooling, no low-aromatic, high-cetane fuel).*

Note: Contact G. Richard Cataldi at (202) 639-2261 with questions or comments about this document.

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