Development of the Low-Emission GE-7FDL High-Power Medium-Speed Locomotive Diesel Engine

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This paper summarizes the technical development of the low-emission GE-7FDL series locomotive diesel engine. The development focused on reducing the engine exhaust NO_x *emission significantly while reducing and curbing other visible and nonvisible emissions with minimal adverse impact on the engine fuel efficiency and minimal changes to the engine system and components. Concepts were analyzed, and were investigated using a single-cylinder 7FDL research engine. A low-emission 16-cylinder 7FDL engine and a GE locomotive prototype were built and tested for performance demonstration, function evaluation, and design optimization. The GE low-emission 7FDL engines and locomotives have been in production. The newly developed low-emission locomotive engine meets the EPA Tier-0 levels without fuel efficiency penalty. This was accomplished with minimal changes to the engine system and components. The desired engine reliability performance is retained. The engines are interchangeable with the preceding 7FDL baseline models, and the upgrade of the existing baseline engines to the low-emission version is facilitated.* [DOI: 10.1115/1.1563241]

Introduction

Medium-speed heavy-duty diesel engines are used as the motive power for present diesel electric locomotives. The Clean Air Amendments of 1990 directed the U.S. Environmental Protection Agency (EPA) to establish regulations on previously unregulated non-road mobile sources including rail locomotives. The EPA's final rule for locomotive exhaust emissions requires future manufactured or remanufactured domestic locomotives to meet standards at different stringency levels for both line-haul and switch locomotive duty cycles. This includes remanufactured locomotives to meet Tier-0 standards from 2001, newly manufactured locomotives to meet Tier-1 from 2002 through 2004, and newly produced locomotives to meet Tier-2 in 2005 and later, as shown by the regulation, [1]. The standards for the locomotive line-haul duty cycle shown by EPA [2] are given in Table 1. The regulations require locomotives to meet the standards over a wide range of environmental conditions. For instance, the standards of each Tier shown in Table 1 must be met from sea level up to 1219 meter (4000 ft) altitude by testing and up to 2134 meter (7000 ft) altitude by engineering analysis verification, as required by EPA [1].

The GE 7FDL series is one of the main engines for heavy duty locomotives in North America and worldwide. The engine's predecessor was designed by Cooper Bessemer and was adopted by GE in the late 1950s for entry into the heavy-duty locomotive market as a complete vehicle supplier. The 16-cylinder version was introduced at 1864 kW (2500 hp) in 1963 in the classic U25 locomotive. Over the next three decades the power grew successively to 2237, 2461, 2685, 2908, 3057, and 3356 kW (4500 hp) on the same bore and stroke format. This growth was made possible by the constant development of turbocharger, fuel injection, manifolds, power assemblies, and all other stressed components. The engine is the highest production medium speed diesel engine in the world, with over 1200 engines produced annually. The operating fleet numbers near 10,000 engines.

The engine has retained its original cross-section layout, as shown in Fig. 1, in spite of an almost 100% power growth. The individual power assemblies are carried on a low deck crankcase. The camshafts are driven by single reduction gears and are accessible through the crankcase doors. No separate camshaft openings and a deep skirt give the crankcase high bending and torsional rigidity. The crankshaft is supported in underslung, side bolted steel bearing caps. The connecting rod is a master-slave design which reveals its Cooper Bessemer heritage. This design provides one bearing for the full width of the crankpin for modest bearing loads. The piston pins are bolted to the rod ends which also provide full-width bearings. Pistons are composed of steel crowns bolted to aluminum skirts.

The electronic fuel injection system uses a solenoid-controlled pump mounted high on the cylinder and coupled by a short stiff fuel line to a low sac injector. The four-valve cross-flow head provides very little swirl to the quiescent combustion chamber. Two modular pulse converter exhaust manifolds feed a single turbocharger mounted on the free end of the engine. The turbo has been highly developed over the years in conjunction with GE Aircraft Engine and its high efficiency is largely responsible for the high power density and low fuel consumption of the engine. The basic specifications of the 7FDL engine baseline can be found in Table 2.

General levels of the exhaust gaseous emissions of the noncompliant 7FDL 16-cylinder engine equipped with an electronic fuel injection (EFI) system and split-intercooling system are included in Fig. 2 for comparison. This shows oxides of nitrogen (NO_x) is

Table 1 EPA Standards for line-haul locomotive duty cycle

	NO_x	CO	HC	PM	SMOKE (%OPACITY) Steady state	30-sec peak	3-sec peak
	(g/hp-hr)						
Tier 0	9.5	5.0	1.0	0.60	30	40	50
Tier 1	7.4	2.2	0.55	0.45	25	40	50
Tier 2	5.5	1.5	0.30	0.20	20	40	50

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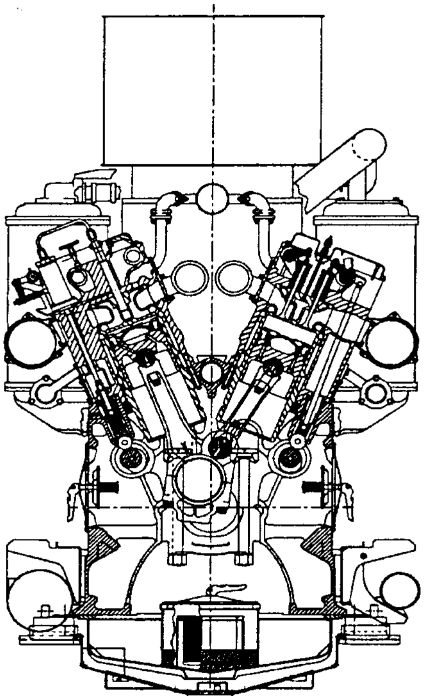


Fig. 1 Cross section of 7FDL engine baseline

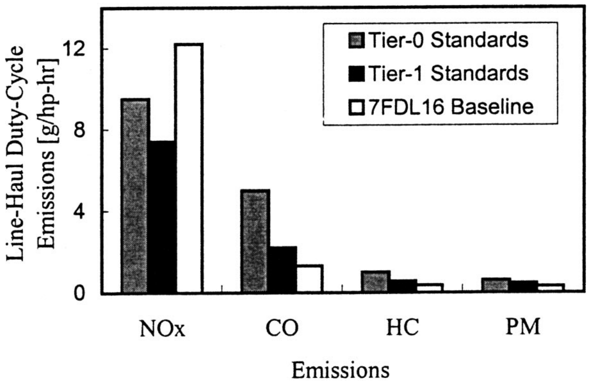


Fig. 2 Locomotive baseline emissions and comparison

a primary concern among the exhaust gaseous emissions of the baseline locomotive engine. The NO_x emission needed to be significantly reduced to meet the Tier-0 and further Tier-1 regulation standards while reducing and curbing other exhaust emissions such as smoke, particulate matters (PM) and carbon monoxide (CO). The adverse impact on the engine fuel efficiency needed to be avoided and minimized in the engine emission-reduction development. All of this needed to be realized with minimal changes to the existing baseline engine system and components in consideration of the interchangeability and upgrade from the baseline engines to the low-emission configuration.

Basic Technical Approach

The basic technical approach in the development was to meet the following objectives: (a) reduction in NO_x emission while reducing and curbing other visible and nonvisible emissions to comply with the regulations to meet the Tier-0 and further Tier-1 standards; (b) no or minimal loss in the engine fuel efficiency compared to the non-compliant baseline; (c) minimal changes in engine system and components; and (d) no adverse impact on any other desirable performance characteristics.

For NO_x reduction, one of the conventional effective means is to retard fuel injection timing. Nevertheless, using retarded injection timing to reduce NO_x results in lowering the cycle efficiency and deteriorating the engine fuel efficiency. The mechanism can well be described by the low relative efficiency concept by Hsu [3]. The trend of change in the specific fuel consumption (SFC) of the 7FDL16 engine baseline in full load condition versus the NO_x reduction by only retarding fuel injection timing is shown in Fig. 3. Also, while the major noncompliant gaseous emission of the 7FDL16 baseline engine was NO_x, the additional concerns were on the exhaust emissions of smoke, CO, and PM. It was worth attention for the following reasons: (a) smoke, particularly transient smoke, of a turbocharged locomotive diesel engine may become a concern at some notch or notch-change operations; (b) retarding fuel injection timing to reduce NO_x would increase the fuel late burning and thus would usually increase CO, PM, and smoke; and (c) smoke and PM emissions may increase with time as the engine wears.

Table 2 Specifications of GE-7FDL16 locomotive engine baseline configuration

Item	Specification
Configuration	V16, DI diesel, turbocharged, intercooled
Operating cycle	4-stroke
Bore	228.6 mm
Stroke	266.7 mm
Displacement volume	10.95 liter
Compression ratio (static)	12.2:1
Type of fuel injection system	Electronic fuel injection
Rated speed	1,050 rpm
Normal rated power	3,356 kW (4500 hp)

One of the measures to address the above concerns in this development was to increase the absolute cycle efficiency by raising the cylinder compression ratio (CR). Normally in a high-power medium-speed diesel engine, raising compression ratio is limited by the structurally allowable peak cylinder pressure. When injection timing is retarded, the engine peak cylinder pressure will decrease. Thus, coupled with retarding fuel injection timing, the CR can be increased to compensate for the efficiency loss brought by the timing retardation, while utilizing the maximum allowable structure capability without exceeding the peak firing pressure limit. For reducing NO_x without loss in the fuel efficiency, lowering intake manifold air temperature (MAT) can be effective as well. Lowering MAT reduces the initial combustion air temperature and therefore the peak cycle temperature is lower. The capability of lowering MAT in a diesel engine is generally limited by the intercooling system design and capacity. In addition, the late burning can be reduced with higher fuel injection rate due to the

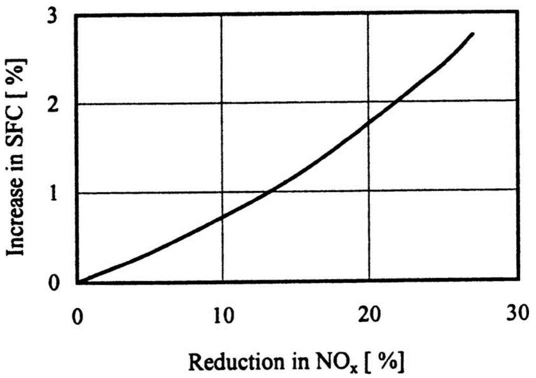
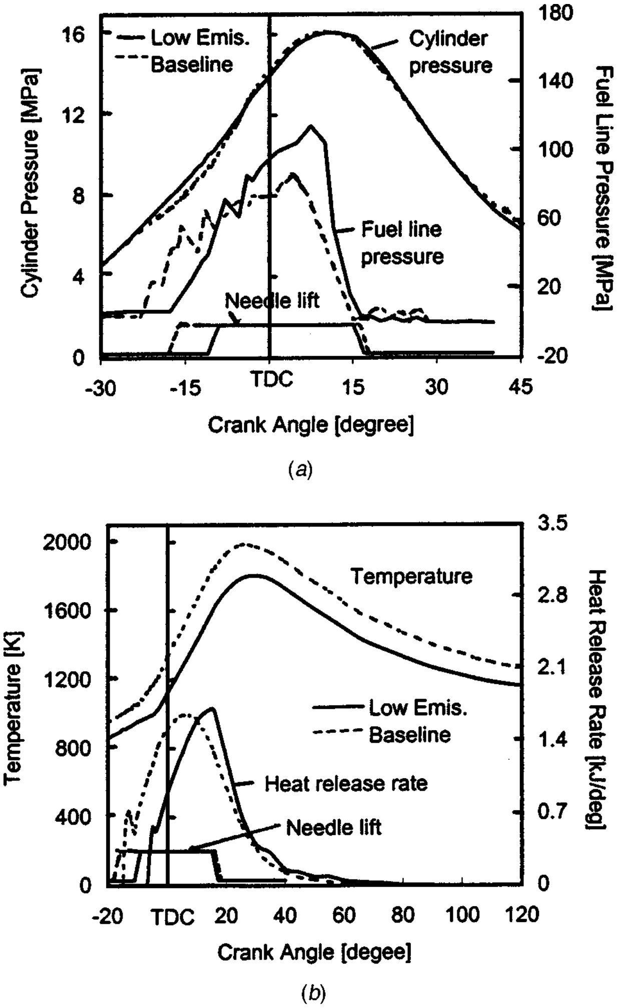


Fig. 3 Efficiency affected by solely retarding injection timing to reduce NO_x (estimated for 7FDL16 engine, full load)



(*a*)

(*b*)

Fig. 4 Engine combustion analysis for the emission-reduction approach development; (*a*) cylinder pressure and fuel injection and (*b*) temperature and heat release

combined effect of increased timely heat release and shortened injection duration. Thus, sufficient soot burnoff time is maintained and the related emissions can be controlled. Higher fuel injection rates with higher injection pressures also have the added advantage of providing smaller fuel droplet size and higher fuel-air relative velocity for fast evaporation. In such case, the soot generation becomes less also.

Therefore, the technical approach to achieving the development objectives and the required emission reduction for the 7FDL locomotive engines is summarized as follows: modify fuel injection timing; increase compression ratio; increase fuel injection rate; optimize intake manifold air temperature based on the intercooling system capacity; improve turbocharger match and air boost; and optimize individual notch and duty-cycle operations.

The following underlying guidelines were followed in the development: maintain the baseline peak cylinder pressure, and the thermal loading on the engine components are not to exceed the previous production system. It is anticipated that much time can be saved for reliability development due to the consideration of these guidelines.

The in-cylinder combustion comparison analyzed using a set of test results is illustrated in Fig. 4. Relative to the nonsplit cooling 7FDL engine baseline (shown as baseline), the low-emission configuration (shown as low emis.) has a retarded fuel injection timing, raised compression ratio, increased injection pressure and lowered manifold air temperature. When the needle-lift start indicating the fuel injection-start timing, is retarded from the baseline, the peak cycle temperature becomes lower. By lowering MAT, the cycle temperature is further reduced. As CR is raised with fuel injection timing retarded, the peak cylinder pressure can be maintained at the same level, as shown in the top part of Fig. 4. The higher injection rate due to the higher injection pressure in the low emission configuration results in the fuel injection ending earlier and thus injection duration is shorter. This means that for the 7FDL engine, by modifying the designs of a limited amount of engine components, the Tier-0 and possibly Tier-1 emissions requirements can be met by changing the combustion process.

Components Development and Design

In order to increase the compression ratio of the GE-7FDL engine with minimal impact on the overall engine configuration and with the interchangeability of the power-assembly components retained, the following engine components were investigated and redesigned, with the fundamental system consideration shown by Hsu and Chen [4] and by Hsu et al. [5].

Piston Crawn Bowl Shape. Raising compression ratio was accomplished by simply reducing the top dead center (TDC) piston-to-cylinder head clearance volume. The piston crown with its top bowl contour was redesigned to reduce the TDC clearance volume, and to retain the required fuel injection jet flow behavior and combustion performance.

Cylinder Head Port Flow and Valve Event. The valve cam lift profiles for both the intake and exhaust valves were modified to accommodate the consequent smaller piston-to-valve bumping clearance when compression ratio was raised. With the high level of brake mean effective pressure (BMEP) at which medium-speed diesel engines operate, sufficient scavenging flow is necessary. The cylinder head of the engine was redesigned on the valve port throat bore for both intake and exhaust without changes to the valve seats. Thus, the required scavenging flow will be maintained or even improved while physically allowing sufficient piston-to-valve clearance after changing to the high compression ratio configuration.

Fuel Cam Profile. The fuel cam lift profile was changed from the baseline to obtain a higher cam lift velocity and consequently higher injection pressure. Achieving suitable match in phase between the cam lift velocity and injector needle lift duration was also included in the investigation and design. The higher-rate fuel cam, when used with the current EFI pump, is capable of delivering both the higher maximum and mean injection pressures. Analysis and experimental validation has shown that the cam loading is within the desired range and the desired reliability of the cam and driving components should be maintained.

Fuel Injector. As part of the combustion chamber design refinement and combustion process optimization, fuel injectors with different spray included angles were investigated in the development in response to the piston crown bowl shape change. As a result, the injector nozzle with a suitable spray included angle was determined.

Development With Single-Cylinder Research Engine

A single-cylinder 7FDL research engine was configured to verify the concepts and technical feasibility and capability. The engine has similar configuration parameters as the GE-7FDL series engine. The engine was supercharged with its intake manifold air pressure (MAP) and temperature (MAT) externally controlled. The exhaust back pressure could also be manually adjusted. A digital data acquisition and processing system, described in more detail by Hsu and Hoffman [6], was used to acquire and store outputs from transducers sensing the required parameters such as pressures, temperatures, speed, torque, and injector needle lift. The in-cylinder combustion analysis and heat release

Table 3 Changes in emissions and efficiency with HCR crown design (single-cylinder engine, full load)

	Baseline	HCR Crown A	HCR Crown B
NO_x	+0%	−42.5%	−40.9%
SFC	+0%	+0.7%	+1.9%
Smoke (BSU)	+0	+0.02	+0.21

information were obtained through the computerized analysis and calculation based on the acquired data. The exhaust gaseous emissions and smoke were also measured.

Preliminary Investigation of Emission Reduction Capability At the initial stage of investigation, various designs of the piston crown top contour were used to raise compression ratio, and tested to verify the desired emission reduction and performance capability. All test runs were at full load and compared at the same peak cylinder firing pressure. The comparison of two crowns to form the same increased compression ratio with the same level of MAT is shown in Table 3. The injection timing was retarded and the injection rate was modified from the baseline. For the reduction in NO_x, the fuel efficiency loss is considerably reduced with the HCR single-cylinder engine, compared to the engine solely retarding fuel injection timing. It is seen from Table 3 that the piston crown A is better in terms of NO_x reduction and fuel consumption, as well as smoke. It was chosen for the further development based on its better combustion results.

In the high-compression-ratio (HCR) configuration with the MAT unchanged and injection timing retarded without injection rate modification from a baseline, the NO_x reduction was the result of both lowering the peak cycle temperature and the smaller amount of fuel burned in the initial premixed stage immediately following fuel ignition. This is shown in the Fig. 5.

Intake Manifold Air Temperature Effect. The effect of MAT on the cylinder temperature of the 7FDL engine was investigated. The cylinder temperature history analyzed from the single-cylinder engine test results is shown in Fig. 6. As the MAT is decreased, the cylinder cycle temperature becomes lower, contributing to the NO_x reduction. This indicates if the HCR engine is run at a lower MAT, then the NO_x can be further reduced due to the further decreased cycle temperature. The comparison of the analyzed combustion process parameters is included in Fig. 4.

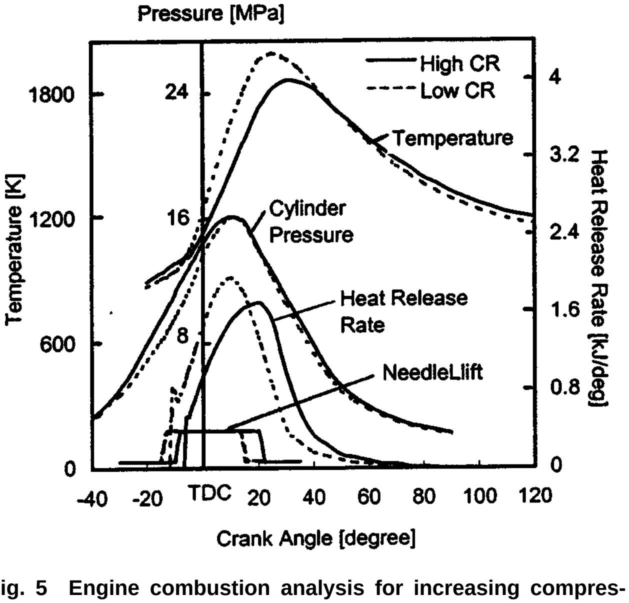


Fig. 5 Engine combustion analysis for increasing compression ratio coupled with modifying injection timing (single-cylinder engine)

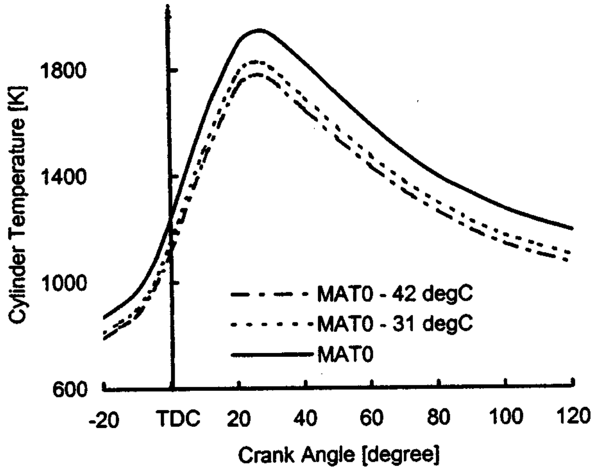


Fig. 6 Intake manifold air temperature effect on cylinder temperature

Fuel Injection Rate. The test was also conducted on the single-cylinder engine to verify that a higher fuel injection rate can be achieved with the modification in the fuel system. This is presented by the injection pressure trace shown in Fig. 7 from the single-cylinder research engine tested at the full load condition. With the modification, both the maximum and mean injection pressures are higher, and the injection duration is shortened.

Injector Tip Spray Included Angle Development. As part of the combustion chamber design refinement, injector tips with different spray included angles were experimentally investigated on the HCR single-cylinder engine. The spray included angle is illustrated in Fig. 8. The single-cylinder engine tests focused on the injectors with the spray angles ($\theta°$, θ+5°, θ+10°) for the detailed effect-on-combustion analysis, since the preliminary engine tests and analysis indicated a lower overall performance by injectors in the angle smaller than $\theta°$. Tests were run at full load. The $\theta°$ spray included angle injector tip had the best fuel efficiency, highest NO_x emissions and lowest smoke level. All these indicators are summarized in Table 4. A typical cylinder firing pressure and heat release comparison of the $\theta°$ and θ+5° injectors is shown in Fig. 9. The cylinder pressure history of the θ+5° injector tip drops down after the peak faster than the $\theta°$ tip, as shown in the top part of the figure. The heat release comparison at the bottom depicts the initial heat release rates for the two injectors are about the same. Later the heat release of the θ+5° tip

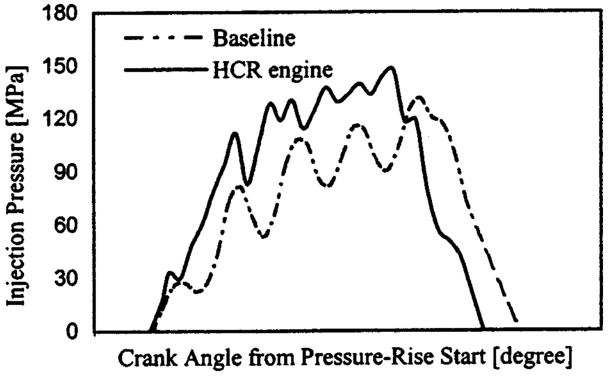


Fig. 7 Fuel injection pressure modification in the HCR engine configuration

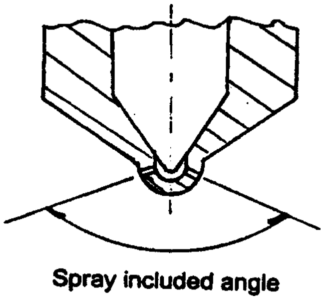


Fig. 8 Illustration of injector tip spray included angle

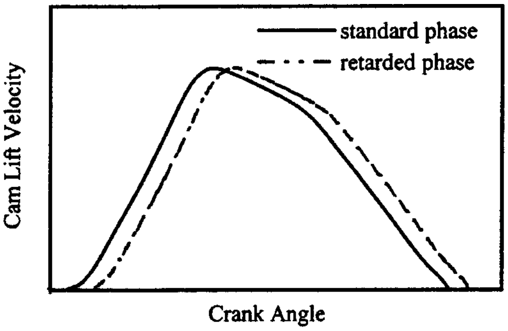


Fig. 10 Illustration of the fuel cam phase shift

becomes slower and arrives at a lower peak value. Some degrees after TDC, the heat release rate for the $\theta+5°$ tip becomes higher, signifying more late burning. The fuel efficiency loss is a direct consequence of this kind of untimely burning. The late burning shortens the time for soot burn off period and higher smoke emissions are the consequences. The $\theta°$ spray included angle injector tip was chosen.

Fuel Cam Phase Investigation. With retarding the fuel injection timing and modifying the fuel cam profile, the investigation and optimization of the fuel cam phase was needed. A shift in the phase of cam profile is illustrated in Fig. 10. Following preliminary analysis, two fuel cams with the modified profile and three-deg difference in the cam phase were tested and compared at about the same brake power. The measured engine performance results are summarized in Table 5. From Table 5, the phase-retarded cam has higher injection pressure and slightly lower indicated fuel consumption (ISFC) than the standard-phase cam. However, the higher injection pressure and lower ISFC did not yield lower brake fuel consumption (BSFC). Further data analysis had shown that, although the two cams were tested at about the same brake horsepower, the indicated power (IkW) for the phase retarded cam was higher than the standard-phase cam. The energy needed to drive the retarded cam was higher due to the higher mean injection pressure. However, the more efficient combustion with the phase-retarded cam cannot compensate for the greater amount of work needed to drive the fuel injection system, and consequently, the brake efficiency was lower. The change from the standard to the retarded phase may increase loading on the fuel injection components. In summary, the retarded-phase cam did not show much advantage over the standard-phase cam.

Table 4 Injector tip spray included angle comparison (single-cylinder engine, full load)

	$\theta°$ Angle	$\theta+5°$ Angle	$\theta+10°$ Angle
BSFC change	+0%	+2.1%	+2.4%
NO_x change	+0%	−10%	−8.4%
Smoke change (BSU)	+0	+0.28	+0.13

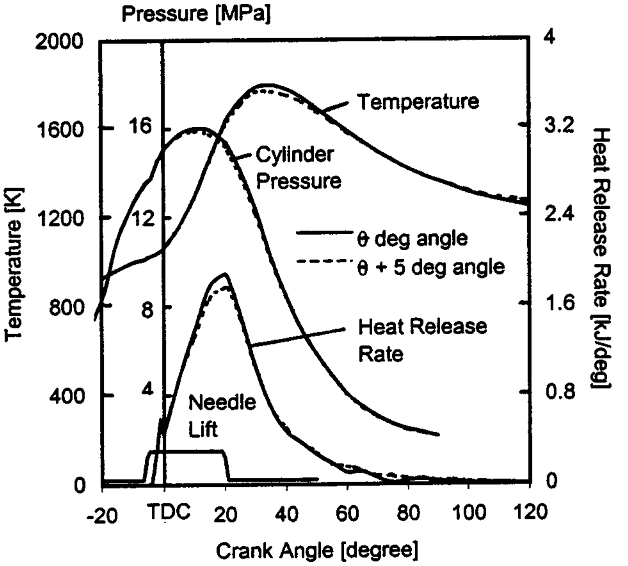


Fig. 9 Comparison of in-cylinder efficiency between two spray angle injector tips

Development of 16-Cylinder Locomotive Engine

Following the single-cylinder engine testing, a 16-cylinder 7FDL locomotive engine (GE-7FDL16) in the HCR configuration was built and tested for design verification and optimization. Compared to the single-cylinder engine, the full-size engine was turbocharged and thus the turbocharger effect to the engine operation was included. During the full-size engine development, the compression ratio was incrementally changed from the engine baseline. The engine in various compression ratios was tested to optimize the engine design and performance.

The engine exhaust species measured during the tests included: CO_2, CO, NO_x, HC, smoke opacity, and PM. The exhaust emissions were measured by the equipment as follows: NO_x by a chemiluminescence analyzer, CO by a nondispersive infrared analyzer, HC by a heated flame ionization analyzer, PM by a split particulate tunnel, and smoke opacity by a full-flow opacity meter. For the purpose of evaluation and comparison, the measured NO_x emissions were corrected for inlet air temperature and humidity to a standard condition. The engine specific fuel consumption measured was also corrected to standard reference conditions of inlet air temperature and barometric pressure including the AAR reference condition. Results of the multi-cylinder engine development and investigation are summarized as follows.

Evaluation of Valve Overlap Flow. As one of the engine components changed to form the low-emission engine configuration, the cylinder heads were tested for comparison. The test was conducted on the 7FDL16 engine prior to raising the compression ratio. The difference between MAP and pre-turbine pressure

Table 5 Test results of fuel cam phase difference (single-cylinder engine, full load)

	Standard HCR Cam	Phase-Retarded HCR Cam
Inj. pressure change	+0%	+1.2%
BSFC change	+0%	+0.6%
BkW	196.6	196.8
IkW	228.8	230.2
ISFC change	0%	−0.1%
Smoke change (BSU)	+0	−0.02

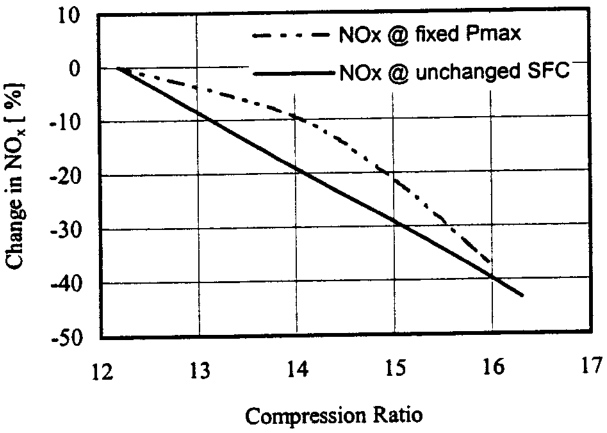


Fig. 11 Reduction in NO_x versus compression ratio (7FDL16 engine, full load)

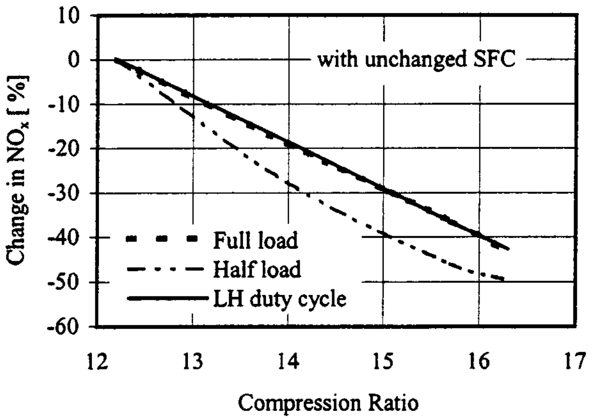


Fig. 12 NO_x reduction versus compression ratio with unchanged SFC (7FDL16 engine)

(Δp_{ov}) was monitored as an indication of the valve flow efficiency during the valve overlap. The results compared with the baseline configuration and indicate that the Δp_{ov} became smaller as the modified head was applied. When both the modified cylinder heads and modified valve cam shafts were used, the Δp_{ov} was about the same as that of the engine baseline, meaning the required scavenge flow during the valve overlap was retained.

NO_x Reduction and Efficiency With Raising Compression Ratio at Full Load. Full-load operation of a locomotive engine generally consumes a major part of the total duty-cycle fuel and contributes a major part to the production of the duty-cycle NO_x and other gaseous emissions. The measured NO_x emissions versus compression ratio in the 16-cylinder engine full load condition are plotted in Fig. 11. As shown in the figure, with the averaged peak cylinder pressure remaining about the same, the NO_x emission decreases rapidly as the compression ratio increases from the baseline while the specific fuel consumption (SFC) remains below or the same as that of the baseline. The decrease in the NO_x emission was mainly due to the fuel injection timing retardation, and the retained engine fuel efficiency was mainly due to raising the compression ratio. The NO_x reduction versus raising compression ratio with SFC remaining unchanged is also shown in Fig. 11. All of this indicates, increasing compression ratio up to a certain level, coupled with retarding fuel injection timing allows the engine to achieve the NO_x reduction at full load condition without loss in the fuel efficiency within the allowable structure capability.

NO_x Reduction and Efficiency at Partial Load. The HCR engine test results showed the advantage of NO_x reduction at partial loads as well. Unlike the full-load operation at which the pressure $p_{\max}$ is dominating, partial load operation usually does not have a concern on the peak cylinder pressure limit. In partial loads, the peak cylinder pressure is always lower than the maximum allowable $p_{\max}$ and thus fuel injection timing may freely be set to achieve desired performance such as the exhaust emissions and the fuel efficiency. Figure 12 shows the reduction in NO_x of the tested 7FDL16 engine versus compression ratio without change in the fuel consumption at a half-load condition. As CR increases, the engine NO_x emission at the half-rated power also becomes lower under no penalty in SFC.

Duty-Cycle NO_x Reduction and Efficiency. In addition, the engine was also tested and evaluated through all of the locomotive notch conditions. Using the EPA defined locomotive line-haul duty-cycle weighting factors with the measured emissions, the line-haul duty-cycle NO_x reduction without sacrifice in the fuel efficiency compared to the baseline along with raising compression ratio is shown in Fig. 12 as well. The desired reduction in the duty-cycle NO_x emissions with retaining the desired fuel efficiency was achieved and demonstrated.

Effect of Manifold Air Temperature on NO_x Production. The full-size multicylinder locomotive engine was also tested under the full load condition over various intake MAT to investigate its effect on the NO_x generation. The MAT is the temperature of air in the intake manifolds after theturbocharger compressor and intercooler before the engine cylinders, and is different from the ambient temperature. The measured NO_x emission versus MAT is shown in Fig. 13. The main effect of MAT change was on NO_x, and the NO_x generation became lower as MAT was lowered.

Combustion and Heat Release Enhancement. The higher fuel injection rate accompanied with the higher compression ratio reduces the in-cylinder untimely combustion caused by retarding fuel injection timing. Thus the engine thermal loading and the exhaust emissions such as PM, smoke, and CO can be reduced. As a proper indication for the magnitude of late burning and untimely combustion, the temperature of exhaust gas at the location before the turbocharger-turbine entrance, usually called pre-turbine temperature, was measured. The full load results can be found in Fig. 14 in contrast with those from the engine baseline only retarding fuel injection timing to reduce NO_x. It is indicated that, as the fuel injection system with a higher injection pressure and improved atomization is applied to the engine with the raised compression ratio while injection timing is retarded, the increase in pre-turbine temperature compared to the engine baseline can be avoided and minimized.

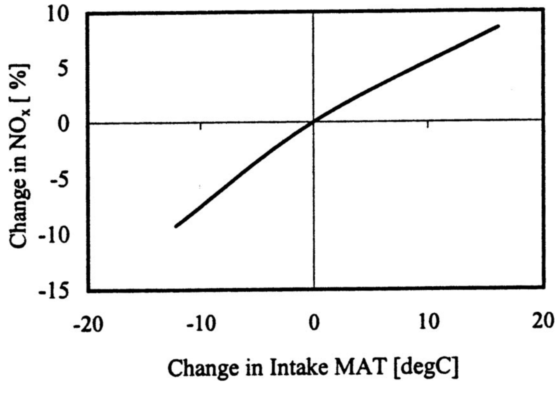


Fig. 13 Effect of MAT on HCR 7FDL16 engine NO_x

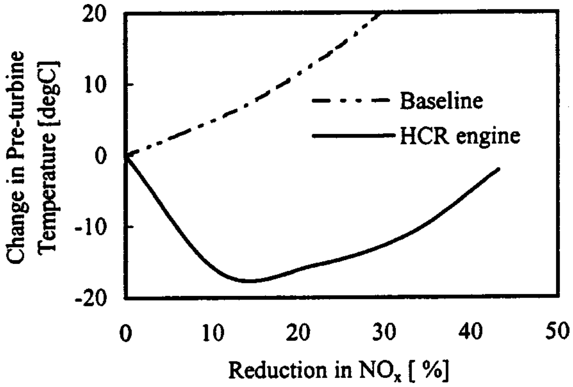


Fig. 14 Change in engine pre-turbine temperature (full load)

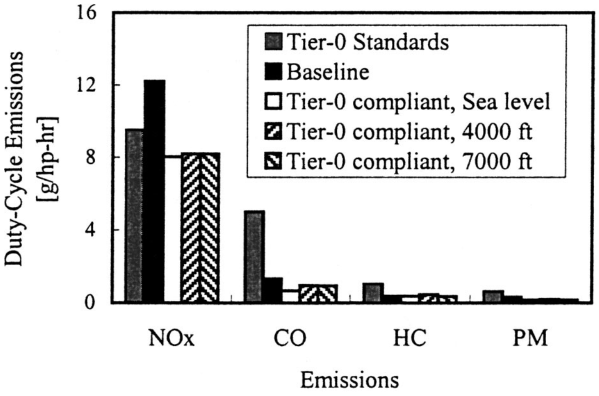


Fig. 16 Low-emission GE-AC4400 locomotive meeting Tier-0 standards (line-haul duty cycle)

Fuel Cam Phase Optimization on 7FDL16 Engine. The fuel cam phase optimization was also verified on the HCR 7FDL16 engine. The results of performance comparison tests are shown in Fig. 15, which shows the differences in NO$_x$ and SFC between the standard-phase and retarded-phase cam. It can be seen from Fig. 15 that the engine brake fuel efficiency with the standard-phase cam is better than that with the phase-retarded cam for the notches shown. The NO$_x$ emission in the full-load condition with the standard-phase cam is also lower. The results confirm the indication from the single-cylinder research engine test. The fuel cam phase needs to be located to obtain a superior overall performance regarding the engine exhaust emissions and brake efficiency. The standard-phase cam provided better performance in the NO$_x$ emissions and fuel efficiency.

Engine Operation Optimization and Smoke Control. With the engine configuration given, engine operation at each individual notch can be optimized to obtain the required duty-cycle NO$_x$ reduction with reducing or curbing other visible and nonvisible exhaust emissions. Steady-state and transient smoke during locomotive duty-cycle operation may become a concern. The exhaust emissions such as smoke, PM, and CO become higher as altitude increases. Thus, control of the exhaust emissions of smoke, PM, and CO caused by incomplete combustion was studied together with the NO$_x$ reduction in the engine testing. Additional methods such as shown by Chen and Hsu [7] and by Chen et al. [8] for controlling engine operating parameters to reduce those emissions while achieving the desired duty-cycle NO$_x$ reduction and maintaining the fuel efficiency were developed. During the investigation, the involved engine operating parameters affecting the formation of smoke and the other incomplete-combustion related emissions were experimentally verified and studied.

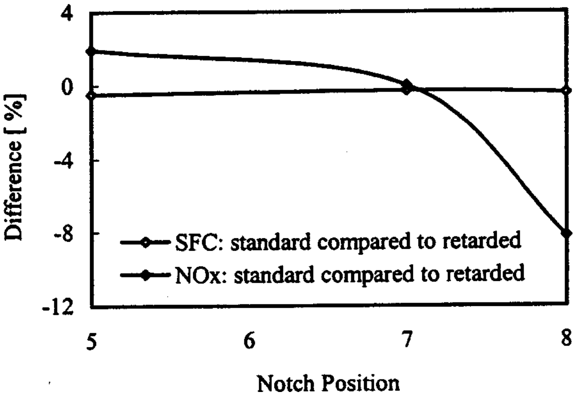


Fig. 15 Performance comparison over fuel cam phase (HCR 7FDL16 engine)

Locomotive Test and Control System Optimization

Following the successful engine development, a GE low-emission locomotive prototype was then built and tested for demonstration and complete function and performance evaluation. The locomotive demonstrated and tested was a GE-AC4400 locomotive using a 7FDL16 low-emission engine with the compression ratio determined based on the engine development results to achieve the Tier-0 emission reduction without loss in fuel efficiency versus the noncompliant baseline.

Exhaust Emissions and Performance. The locomotive was operated through all locomotive throttle notches during the demonstration and evaluation test. The exhaust emissions, operating parameters, and output performances were measured. The test followed the locomotive emissions test procedures by EPA [9]. The duty-cycle emissions were obtained by following the EPA locomotive throttle notch weighting factors. The emission results obtained are summarized in Fig. 16 versus the Tier-0 regulation standards. While achieving the duty-cycle emission reductions to comply with the regulations, no loss in the duty-cycle fuel efficiency compared to the locomotive baseline was demonstrated by the low-emission locomotive in the locomotive evaluation.

Control System Optimization and Smoke Reduction. Retarding fuel injection timing may contribute to an increase in smoke, especially the transient smoke during some notch changes. The engine control system optimization was investigated during the locomotive testing and development. The optimization focused on modifying the control strategies to achieve the desired duty-cycle NO$_x$ reduction and fuel efficiency with the smoke opacity reduced to meet the EPA emissions standards.

The preceding engine development and initial locomotive investigation showed that transient smoke can be reduced through both load application delay and timing advance during a notch increase without affecting the overall load rate. The optimization of the load application and the transient timing advance was tested on the locomotive over a wide range of environmental conditions. A new speed schedule was developed at high altitude to raise the engine speed in lower notches. This reduced the steady-state smoke as well as reducing the transient smoke. The fundamental approach of these methods can be found in [7,8] and [10]. The locomotive was also tested with the new speed schedule to confirm the desired reduction in smoke and emissions. Finally, to further improve the transient smoke for low notch transitions at high altitude, the load rate at low notches was optimized. Figure 17 illustrates the 3-sec transient smoke reduction by the operation

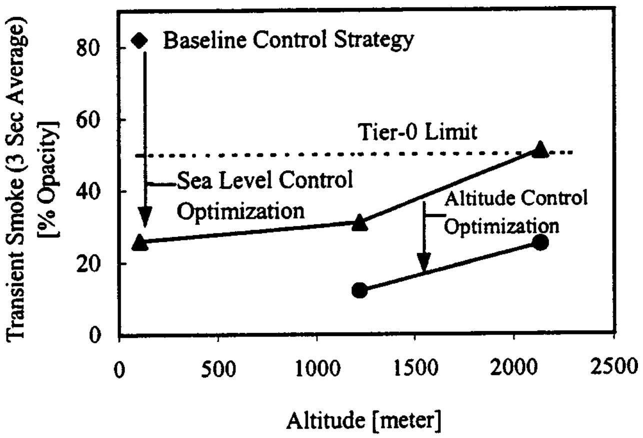


Fig. 17 Transient smoke optimization on tier-0 compliant locomotive

and control optimization developed for the emission-reduction locomotive during low notch transition. Applying these optimization strategies, the locomotive also demonstrated its ability to meet the steady state and transient smoke standards over a wide range of environmental conditions.

A "skip firing" control strategy as shown by Patel and Volpe [11] was also further developed to be implemented at idle notches to further reduce the steady-state smoke and optimize other gaseous emissions. Skip firing systematically skips cylinders from the normal firing sequence. The purpose is to raise injection pressure in the cylinders that are firing. Fuel injected at higher pressures atomizes better as it enters the combustion chamber, fostering complete burning and low smoke production. Applying the skip firing control strategy to the low-emission engine and locomotive, a significant reduction in smoke at idle notches was achieved. The skip firing mode was also validated by measuring smoke and emissions at various environmental and altitude conditions to ensure compliance.

Conclusions

The technical development of the low-emission GE 7FDL medium-speed locomotive diesel engine has been conducted. Conclusions drawn from the development described in this paper are summarized as follows.

1. High-power medium-speed diesel engines are used as the motive power for present diesel-electric locomotives. To comply with the EPA Tier-0 and further Tier-1 locomotive emission regulations, the exhaust NO_x emissions of the baseline locomotive engine needed to be significantly reduced while reducing and curbing other visible and non-visible exhaust emissions. The adverse impact on the engine efficiency needed to be avoided and minimized. All of this needed to be realized with minimal changes to the existing baseline engine system and components in consideration of the reliability, interchangeability and upgrade from the baseline engines to the low-emission configuration.

2. The low-emission GE-7FDL series locomotive engine has been successfully developed and produced. The main technical approach included increasing engine compression ratio coupled with modifying fuel injection timing, increasing fuel injection rate, and optimizing the notch and duty-cycle operations. The concepts were analyzed, and were investigated using the single-cylinder 7FDL research engine. The low-emission GE-7FDL16 engine and locomotive prototype were built and tested for performance and function evaluation and design optimization. The low-emission GE 7FDL engines and locomotives have been in production.

3. The development results have demonstrated that the newly developed low-emission GE-7FDL locomotive engine meets the EPA Tier-0 standards without fuel efficiency penalty versus the noncompliant baseline. The engine mechanical loading such as the peak cylinder firing pressure and thermal loading such as the cylinder exhaust temperature are maintained about the same as those of the engine baseline. The desired engine reliability performance can be retained. This was accomplished with the minimal changes to the engine system and components. The engine has been developed to be interchangeable with the preceding 7FDL baseline, and the upgrade of the baseline engines to the low-emission configuration is facilitated.

4. The development has established a base for the further engine development required for the locomotive diesel engines in accordance with further Tiers of regulation compliance.

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Nomenclature

BSU = Bosch smoke number
CO = exhaust carbon monoxide
CR = compression ratio
HC = exhaust hydrocarbon
HCR = high compression ratio
MAP = intake manifold air pressure
MAT = intake manifold air temperature
NO_x = exhaust nitrogen oxides
PM = exhaust particulate matters emission
$p_{\max}$ = peak cylinder pressure
SFC = specific fuel consumption
TDC = top dead center
T_{prt} = pre-turbine temperature
Δp_{ov} = difference between MAP and pre-turbine pressure

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