TP 14124E

TECHNOLOGY TO MEET EPA LOCOMOTIVE EMISSIONS STANDARDS WITHOUT FUEL PENALTIES

Prepared for
Transportation Development Centre
Transport Canada

by

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NOTICES

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Since the report deals with the North American railway sector as a whole, units of measure are a mixture of imperial and metric units (as per current Canadian railway convention) and American units (as per current railway convention in the U.S.A.).

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16. Abstract

Examined were emissions reduction technologies that have the potential to permit Canadian railway diesel locomotives to comply with the Emission Standards for Locomotives and Locomotive Engines promulgated in April 1998 by the U.S. Environmental Protection Agency (EPA). Of particular interest were those technologies and techniques that are currently available or under development to permit compliance without an increase in fuel consumption to obviate an economic penalty for railway operators.

While no legislated emission standards exist for locomotives operating on Canadian railways, the EPA standards have become the technical reference for Canadian railways when considering the purchase of new locomotives or when rebuilding existing locomotives. Starting January 1, 2002, for the first and subsequent overhauls, locomotives originally manufactured between 1973 and 2001 have to meet EPA Tier 0 standards for hydrocarbons, carbon monoxide, oxides of nitrogen and particulate matter. Their emissions have to be cleaner than when they were first built. This will be accomplished by fitting EPA-certified kits supplied by the U.S. original equipment manufacturers and third-party manufacturers. After January 1, 2002, newly built locomotives must meet more stringent Tier 1 limits and, starting January 1, 2005, even lower Tier 2 limits. Ever more stringent Tier 3 and Tier 4 standards are being drafted by the EPA.

This report provides a reference as to the candidate technologies being pursued and their characteristics. It also contains a scenario for, and suggested content of, a Canadian-side participation in the U.S. railway sector's "Energy Efficient Technology within a Regulated Environment" initiative, the object of which is to tap into Canadian technical capabilities to undertake complementary activities.

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16. Résumé

Le projet vise à étudier les technologies de réduction des émissions qui pourraient vraisemblablement permettre aux locomotives diesel des compagnies de chemin de fer canadiennes de respecter la réglementation relative aux émissions des locomotives et des moteurs de locomotives promulguée par l'Environmental Protection Agency (EPA) des États-Unis en avril 1998. Une attention particulière a été accordée aux techniques et aux technologies présentement utilisées, ou en cours d'élaboration, qui respectent ces normes et qui n'entraînent pas un accroissement de la consommation de carburant. Les compagnies de chemin de fer pourraient alors éviter cette contrainte économique additionnelle.

Puisqu'il n'existe aucune norme législative visant les locomotives utilisées sur le réseau ferroviaire canadien, la réglementation de l'EPA est devenue la réglementation de référence technique en matière d'acquisition de nouvelles locomotives ou de remise à neuf de celles déjà en exploitation par les compagnies de chemin de fer canadiennes. À compter du 1er janvier 2002, toutes les locomotives fabriquées entre 1973 et 2001 qui seront remises à neuf devront respecter les normes du palier 0 de l'EPA relativement aux hydrocarbures, au monoxyde de carbone, aux oxydes d'azote et aux matières particulaires. Les locomotives doivent donc être moins polluantes que lors de leur première mise en service. Pour y parvenir, il faut installer sur les locomotives des pièces certifiées par l'EPA et fournies par le fabriquant d'origine et par des tierces parties. Après le 1er janvier 2002, les locomotives nouvellement construites devront respecter les normes plus rigoureuses du palier 1 et, dès le 1er janvier 2005, les normes du palier 2. L'EPA procède actuellement à l'élaboration des normes préliminaires encore plus strictes des paliers 3 et 4.

Le présent rapport sert de référence relativement aux technologies envisagées et leurs caractéristiques. On y retrouve un scénario éventuel prévoyant une participation du Canada à l'initiative du secteur ferroviaire américain visant à mettre au point des «technologies à haut rendement énergétique dans le cadre d'un environnement réglementé». L'objectif de cette démarche est d'exploiter les capacités techniques du Canada à entreprendre des activités complémentaires.

17. Mots clés Chemin de fer, locomotive, moteur diesel, efficacité énergétique, émission de gaz d'échappement, oxydes d'azote, matières particulaires, gaz carbonique, gaz à effet de serre, normes écologiques, technologie de réduction des émissions	18. Diffusion Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.

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EXECUTIVE SUMMARY

The technologists addressing the increasingly stringent emission standards for railway diesel locomotives while at the same time maintaining or reducing their fuel consumption face a major challenge. Progress in one area can easily lead to backsliding in another. The medium-speed diesel engines in Canadian locomotives produce significant amounts of oxides of nitrogen (NOx) and particulate matter (PM), which are harmful to human health. The reduction of NOx and PM simultaneously presents a unique control challenge: some techniques used to control one of these pollutants increase the production of the other. Unfortunately, most emissions reduction technologies and techniques result in an increase in fuel consumption, thus having a significant impact on the railway sector's operating costs. The challenge is to develop the technology without a fuel penalty – a goal of obvious interest to Canadian railways as fuel is about 10 percent of overall operating costs.

In 1995 the Railway Association of Canada initiated a voluntary monitoring action to cap locomotive emissions at the 1989 annual level of 155,000 tonnes through 2005. In 1998 the U.S. Environmental Protection Agency (EPA) promulgated a rule-making concerning emissions standards for categories of locomotives and locomotive engines operating in the U.S.A. While no legislated standards exist in Canada for locomotive emissions, it is a fact that the equipment and operating context of Canadian railways are highly integrated with those of their American counterparts. As a result, the EPA standards listed below also affect the Canadian railway sector, albeit not in a jurisdictional sense.

- **Tier 0** (1973-2001 locomotives): 34% NO_x reduction, caps on other pollutants
- **Tier 1** (2002-2004 locomotives): 49% NO_x reduction, caps on other pollutants
- **Tier 2** (2005+ locomotives): 62% NO_x reduction, 50% PM and hydrocarbon reductions

(Note: percentages are relative to a 1997 baseline.)

A concomitant event for the Canadian railways is the Canadian government's ratification in December 2002 of the Kyoto Protocol on Climate Change that aims to reduce by 2012 greenhouse gas emissions, particularly CO_2, by 6 percent below 1990 levels. The EPA standards and the Kyoto Protocol are, in effect, technology enablers that are pushing the technological frontier of engine combustion, particularly the medium-speed diesel engine, which is ubiquitous in North American railway locomotives. The emissions reduction technology advances reviewed include:

- lowering temperature of air entering the combustion cylinder
- electronic control of high-pressure fuel injection, including adaptive control
- redesign of piston and cylinder assembly
- hybrid turbocharging
- modifying intake air composition
- exhaust gas recirculation
- after-treatment technologies such as use of particulate traps and catalysts
- diesel fuel parameters and use of alternate fuels and prime movers

The current status in the industry is that the two principal manufacturers – General Motors Electro-Motive Division (GM EMD) and General Electric Transportation Systems (GETS) – are offering EPA-certified technical solutions for selected locomotive models manufactured prior to 2001 to meet Tier 0 emissions standards. There are two categories of kits: those achieving Tier 0 with a fuel penalty and those achieving Tier 0 without a fuel penalty. Both GM EMD and GETS are supplying post-2000 locomotives achieving Tier 1 without a fuel penalty. There was earlier pessimism as to whether these levels could be achieved within the EPA timeframe. However, in January 2003 GETS announced it had achieved Tier 2 on its 12-cylinder 4,500 hp GEVO™ engine model a full two years before the EPA 2005 requirement date, and with a 3 percent improvement in fuel consumption. It is the prime mover for the GETS "Evolution Series" locomotives.

The GM EMD solution to meet Tier 0 standards on its model 710 two-cycle diesel engines is to retard the fuel injection timing by 4 degrees of crankshaft angle. This lowers the peak combustion temperature, resulting in lower NOx formed and, hence, meeting EPA standards, but increasing the fuel consumption by 2 to 4 percent. GETS was able to meet Tier 0 standards without a fuel penalty on its four-cycle FDL engine by lowering the air intake temperature and making incremental improvements to power assembly components. Its strategy for achieving Tier 1 on the same engine without a fuel penalty was through an electronic adaptive control strategy that offsets the NOx increase by retarding fuel injection timing as the intake air temperature rises within the capacity limits of the intercooler, thus optimizing fuel consumption for any operating condition. Two third-party re-manufacturers, Hatch & Kirk U.S.A. Inc. and the CSX Railroad, as well as GETS have obtained EPA compliance for proprietary retrofit Tier 0 kits applicable when GM EMD locomotives with two-stroke EMD model 645 series engines are re-manufactured. They are able to do this because the patents on the GM EMD 645 engine have expired. GM EMD also offers an emissions kit that meets Tier 0 with no negative effects on fuel efficiency for its two-cycle model 645 E3B engine.

Analyses indicate that NOx emissions would be reduced by 20,000 tonnes annually if the approximately 1,000 GM EMD locomotives in service in Canada equipped with the 645 engine model were retrofitted to EPA Tier 0 standards when rebuilt. An additional 18,380 tonnes would be reduced if the other 700 older model locomotives were also retrofitted to Tier 0. Analyses also indicate that for mainline operation, the additional cost of Tier 0 kits offering no fuel penalty could be amortized within two years.

Regarding the future, the EPA is drafting more stringent Tier 3 and Tier 4 emissions standards to come into effect later this decade. Also, the mandating of ultra-low sulfur diesel fuel is foreseen so as to permit adoption of certain advanced emissions reduction technologies. It is recommended that competence be maintained in Canada to ensure Canadian-side complementarity with developments in the U.S.A. In this regard, the study suggests a "Locomotive Emissions Reduction Program for the Canadian Railway Sector" and includes a scenario for Canadian-side collaboration with the U.S. Department of Energy's initiative with the U.S. railway sector to develop "Energy Efficient Technology within a Regulated Environment".

SOMMAIRE

Les technologues chargés de la conception de locomotives diesel respectant des normes de plus en plus rigoureuses en matière d'émissions, tout en maintenant ou en réduisant la consommation en carburant, doivent relever un défi de taille. Les progrès réalisés dans un domaine peuvent facilement entraîner un recul dans un autre. Les moteurs diesel à régime moyen des locomotives canadiennes produisent d'importantes quantités d'oxydes d'azote (NO_x) et de particules, tous deux nocifs pour la santé. La réduction simultanée des émissions de NO_x et de particules constitue un défi unique en ce qui a trait au contrôle des émissions. Certaines techniques employées pour contrôler ces polluants produisent d'autres polluants. Malheureusement, la plupart des techniques et des technologies de réduction des émissions entraînent une consommation accrue de carburant, ce qui a un impact important sur les coûts d'exploitation du secteur ferroviaire. Le défi qui se pose consiste à mettre au point une technologie qui permettrait de réduire les émissions de gaz d'échappement tout en évitant d'accroître la consommation de carburant. Il s'agit d'un objectif important pour les compagnies canadiennes de chemin de fer canadiennes puisque le carburant compte pour environ 10 p. 100 des frais généraux que ces dernières doivent assumer.

En 1995, l'Association des chemins de fer du Canada a entrepris un contrôle volontaire visant à limiter les émissions des locomotives au niveau de 1989, soit 155 000 tonnes d'ici 2005. En 1998, l'Environmental Protection Agency (EPA) des États-Unis a adopté une réglementation concernant les normes d'émissions pour certains types de locomotives et de moteurs de locomotives en exploitation aux États-Unis. Même si aucune norme législative n'existe au Canada relativement aux émissions des locomotives, nous savons tous que l'équipement et le contexte d'exploitation des chemins de fer canadiens sont fortement intégrés à leurs contreparties américaines. Ainsi, les normes de l'EPA, présentées ci-dessous, ont une incidence sur le secteur ferroviaire canadien, non sous l'angle juridique toutefois.

- **Palier 0** (1973-2001) : réduction des NO_x de 34 p. 100, aucune augmentation des autres polluants
- **Palier 1** (2002-2004) : réduction des NO_x de 49 p. 100, aucune augmentation des autres polluants
- **Palier 2** (2005 et après) : réduction des NO_x de 62 p. 100, réduction des particules en suspension et des HC de 50 p. 100

(Nota : les valeurs s'appuient sur les données de 1997.)

Parallèlement à l'application de ces normes, le gouvernement du Canada a ratifié, en décembre 2002, le Protocole de Kyoto sur les changements climatiques qui vise à réduire de 6 p. 100 les émissions de gaz à effet de serre (particulièrement le CO_2) d'ici 2012, par rapport aux niveaux de 1990. Les normes de l'EPA et le protocole de Kyoto sont des outils technologiques qui visent à repousser les frontières technologiques de la combustion des moteurs, particulièrement en ce qui concerne les moteurs diesel à régime moyen, très répandus dans le réseau ferroviaire nord-américain. Voici quelques-unes des technologies de réduction des émissions des locomotives qui sont à l'étude :

- réduction de la température de l'air entrant dans la chambre de combustion
- régulation électronique de l'injection de carburant sous haute pression, y compris le contrôle adaptatif
- reprise de la conception de l'assemblage pistons-cylindres
- turbocompression hybride
- modification du mélange d'air d'admission
- recirculation des gaz d'échappement
- mise au point de technologies permettant le traitement ultérieur des gaz d'échappement, notamment le recours à la réduction catalytique sélective et aux pièges à particules
- modification des paramètres de combustion du diesel et utilisation de carburants de remplacement ainsi que d'appareils moteurs

La situation qui prévaut actuellement dans l'industrie est la suivante : les deux principaux fabricants, soit General Motors Electro-Motive Division (GM EMD) et General Electric Transportation Systems (GETS), offrent des solutions techniques certifiées par l'EPA afin que les locomotives fabriquées avant 2001 puissent satisfaire aux normes de palier 0 en matière d'émissions. Deux trousses de modification sont offertes : celles qui permettent de respecter les normes de palier 0 et qui entraînent un accroissement de la consommation de carburant et celles qui permettent de respecter les normes de palier 0 sans accroître la consommation de carburant. Les deux fabricants (GM EMD et GETS) fournissent des trousses de modification destinées aux locomotives construites après 2000 pour que ces dernières puissent respecter les normes de palier 1 et ce, sans accroître la consommation de carburant. On doutait qu'il soit possible d'atteindre ces objectifs à l'intérieur du délais fixé par l'EPA. En janvier 2003, l'entreprise GETS a même annoncé que son moteur GEVO™ 12 cylindres de 4 500 hp respectait les normes de palier 2 et ce, deux ans avant la date butoir établie par l'EPA, soit 2005. Ce moteur permet même une économie de 3 p. 100 de carburant par rapport aux autres modèles. Il s'agit de l'appareil moteur pour les locomotives «Evolution Series» de GETS.

Pour que ses moteurs diesel à deux temps de type 710 puissent respecter les normes de palier 0, GM EMD a modifié de quatre degrés l'angle du vilebrequin afin que l'injection de carburant dans le moteur soit retardée. Ainsi, la température maximale de combustion se trouve à être réduite, ce qui entraîne une réduction des émissions de NO_x et permet de se conformer aux normes du palier 0 de l'EPA. Cependant, cette modification s'accompagne d'un accroissement de la consommation de carburant de 2 à 4 p. 100. L'entreprise GETS a été en mesure de se conformer aux normes de palier 0 sans accroître la consommation de carburant de son moteur FDL à quatre temps en réduisant la température de l'air entrant dans le moteur et en améliorant graduellement les éléments du moteur. La stratégie de GETS pour l'atteinte des normes du palier 1, sans accroître la consommation de carburant, pour ce même moteur, a été d'avoir recours à un système de contrôle électronique adaptatif permettant de réduire la quantité de NO_x produit en retardant la cadence d'injection de carburant, ce qui permet à l'air entrant dans le moteur de se réchauffer à la limite du refroidisseur intermédiaire. Cela permet une économie de carburant et ce, sans égard aux conditions d'exploitation. Deux tierces parties spécialisées en remise à neuf de moteurs, soit Hatch & Kirk U.S.A. Inc. et CSX Railroad, fabriquent des trousses de modification conformes aux spécifications de l'EPA, à l'instar de GETS. Ces trousses de modification conformes aux normes du palier 0 peuvent être utilisées sur les moteurs EMD modèle 645 à deux temps au moment de leur remise à neuf. Ces parties ont le droit d'apporter ces modifications puisque les brevets du moteur sont expirés. L'entreprise GM EMD offre également des trousses de modification visant à moderniser les moteurs 645 E3B à deux temps pour qu'ils soient conformes aux normes du palier 0 et ce, sans accroître la consommation de carburant.

Des analyses indiquent qu'il serait possible de réduire les émissions de NO_x de 20 000 tonnes par année si les quelques 1 000 locomotives de GM EMD en service au Canada et équipées d'un moteur de type 645, étaient modifiées au moyen de la trousse respectant les normes du palier 0 de l'EPA. On pourrait réduire à nouveau ces émissions de 18 380 tonnes en appliquant la même trousse aux 700 autres locomotives construites antérieurement. Ces mêmes analyses indiquent qu'en ce qui concerne l'exploitation des principales lignes de chemins de fer, le coût d'exploitation additionnel pour la trousse de modernisation conforme aux normes du palier 0 pourrait être amorti sur deux ans.

À l'heure actuelle, l'EPA élabore des normes de palier 3 et 4 encore plus rigoureuses en matière de réduction des émissions. Celles-ci doivent entrer en vigueur au cours de la décennie. De plus, on prévoit utiliser du carburant diesel à faible teneur en souffre afin de faciliter l'adoption de certaines technologies de pointe axées sur la réduction des émissions néfastes pour la santé et l'environnement. On recommande de maintenir le niveau de compétence du Canada dans ce domaine afin d'assurer la complémentarité du Canada vis-à-vis les développement américains. À cet égard, l'étude propose un «Programme de réduction des émissions de locomotives pour l'industrie ferroviaire canadienne» et prévoit également la collaboration du Canada à l'initiative du département de l'Énergie des États-Unis et du secteur ferroviaire américain qui vise à mettre au point des «technologies à haut rendement énergétique dans le cadre d'un environnement réglementé».

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GLOSSARY

Terminology Used in Locomotive Diesel Combustion and Emissions

Medium-speed Diesel Engine: This engine, operating at approximately 900 rpm, is the dominant motive power source for locomotives operating in Canadian and American railway services. It has found its niche as a result of its fuel-efficiency, ruggedness, reliability and installation flexibility. It has a thermal efficiency of at least 40 percent and a power output ranging from 1,000 to 6,000 hp. The two dominant U.S. suppliers, known as Original Equipment Manufacturers (OEMs), are the General Motors Electro-Motive Division (GM EMD) and General Electric Transportation Systems (GETS).

Diesel Combustion: This is the process by which a mixture of fuel and air is compressed in the cylinder of a diesel engine until it auto-ignites (in contrast to using a spark plug or glow plug to trigger ignition). Most diesel engines have a compression ratio of 15 to 20, which creates an ignition temperature of 700 to 900°C.

Diesel Emissions: The principal pollutants emitted by diesel engines are oxides of nitrogen (NOx), particulate matter (PM), unburned hydrocarbons (HC), and carbon monoxide (CO). NOx formation is a function of the peak combustion temperature. NOx has implications for the health of humans, animals and the ecology. If the combustion temperature is decreased to reduce NOx, there is a corresponding increase in the amount of uncombusted fuel emitted as particulate matter (PM) and gaseous hydrocarbons (HC). HC react with NOx and other pollutants in the presence of sunlight to form ground-level ozone (smog). Ozone and PM are associated with many adverse health and welfare effects, including respiratory illness, environmental damage and visibility problems.

Emissions Factors: The emissions factors of a locomotive are calculations based on data from test measurements of specific emissions, the operational duty cycle and the specific fuel consumption of the engine.

1) Principal components from diesel exhaust emissions that are of concern:

NOx (Oxides of Nitrogen): These are the products of nitrogen and oxygen that result from a high combustion temperature. The NOx emission level can be lowered by reducing peak combustion temperatures. One way to effect this is to retard the injection timing. Another technique is exhaust gas recirculation. Both result in higher fuel consumption and lower total power from the engine.

HC (Hydrocarbons): These are the result of incomplete combustion and the lubrication oil that is not oxidized during the combustion process. HC are the products of partial combustion, which is caused by short combustion time and low combustion temperatures (as when operating engines at low power levels or when excessive idling occurs).

PM (Particulate Matter): This is the residue of combustion consisting of soot formed during combustion, heavy hydrocarbons condensed on or absorbed by the soot, and sulfates. This residue is known as primary PM. Increasing the combustion temperatures and duration can lower PM but, of course, raise the NOx emitted. It should be noted here that there is no in-cylinder NOx-PM tradeoff under the laws of physics. Technologies that control NOx (such as retarding injection timing) result in higher PM emissions. Conversely, technologies that control PM often result in increased NOx emissions. However, reducing NOx emissions will yield reductions in ambient concentrations of secondary PM. For example, it is estimated that about 4 tonnes of nitrate particulate are formed per 100 tonnes of NOx emitted.

CO (Carbon Monoxide): This gas is a by-product of the combustion of fossil fuels. It is low in diesel engines relative to other prime movers. CO is considered a greenhouse gas (GHG) and its accumulation in the atmosphere contributes to global warming.

SOx (Oxides of Sulfur): These are the result of burning fuels containing sulfur. These emissions can be reduced by using a fuel having a lower sulfur content. Sulfur levels in diesel fuels are falling steadily in both Canada and the U.S.A.

O_3 (Ozone): This is a gas formed from the combination of NOx, HC and sunlight.

CO_2 (Carbon Dioxide): This gas is by far the largest by-product of combustion emitted from engines and is the principal greenhouse gas which, due to its accumulation in the atmosphere, is considered to be the principal contributor to global warming. CO_2 and water vapour are normal by-products of the combustion of fossil fuels. To reduce CO_2 emissions in transportation means using more fuel-efficient engines, using lower carbon-intensive fuels (such as natural gas), using a fuel such as biodiesel (the production of which is less CO_2 intensive), opting to use more fuel-efficient modes for the transport of passengers, goods and bulk commodities, or reducing mobility.

2) Technical areas where emissions reduction technologies can be applied:

Spurred by the promulgation of more stringent emissions standards, the OEMs, locomotive re-manufacturers and after-market suppliers are focusing on designing more effective controls for NOx, PM, HC and CO. One strategy is to better manage the process of fuel and air delivery to the cylinder, reducing emissions production. Another strategy is to use after-treatment (or post combustion) technologies to break down or capture emissions. Diesel engines of the future, particularly those in railway applications, will likely use a combination of strategies to reduce harmful emissions. The principal emissions control options include the following:

Fuel Delivery: Designing electronic controls and improving fuel injectors to deliver fuel at the best combination of injection pressure, injection timing, injection rate shaping, multiple injections and spray location. This allows the engine to efficiently burn the fuel without causing the temperature spikes that increase NOx emissions.

Intake Air Delivery: Redesigning turbochargers, aftercoolers and intake valving to provide optimum air manifold pressure, temperature and routing of the intake air. This is important for managing the physical and chemical processes needed to achieve good air-fuel combustion. Hybrid electric turbocharging promises to overcome air deliver lag.

Exhaust Gas Recirculation (EGR): Mixing some exhaust gas with the intake air. This is an established technique to manage emissions, but invariably lowers fuel efficiency.

Intake Air Composition: Controlling emissions emanating from the combustion chamber through the use of polymer membranes, for example, which effects a chemical reaction resulting in the separation of oxygen from the nitrogen. The oxygen is directed into the combustion chamber resulting in improved combustion characteristics. Similarly, techniques for adding hydrogen to the intake air can improve combustion.

Piston Design: Paying special attention to the design of the piston face and compression ratio to yield combustion characteristics tailored to reduce emissions. Reducing oil consumption by improved oil scraper ring design can also reduce PM emissions.

After-treatment Technologies: Using particulate traps or catalysts to convert or capture emissions between the cylinder exhaust valve and exhaust stack. Traps are used to filter out and then burn PM. Catalysts hold promise for reducing NOx and PM by conversion to less harmful compounds. One such process is **Selective Catalytic Reduction (SCR)** in which emissions flow through a special ceramic catalytic converter into which a diluted carbamide solution is injected. The carbamide is transformed into ammonia, which combines with the NOx and turns them into harmless nitrogen and water. Using catalysts is more complex for diesel engines than for automotive gasoline engines, and current designs would be quite bulky for most locomotive installations.

Diesel Fuel Parameters: Employing fuel additives and improving fuel properties, such as raising the cetane number, lowering the aromatics content and decreasing sulfur levels, to contribute to reduced NOx and PM emissions as well as unregulated pollutants.

Alternate Fuels: Less carbon-intensive alternative fuels, particularly natural gas and dimethyl ether (made from natural gas or coal feedstock) offer not only reduced emission of CO_2 but also NOx and PM benefits. However, lower specific energy efficiency could occur depending on how the fuel/air mixture is ignited in the combustion chamber. Bio-diesel production from oil seed and animal renderings results in lower CO_2 and PM.

Alternate Prime Movers: In North America, conventional railway engines are considered to be those medium-speed diesel engines as manufactured or re-manufactured to designs proprietary to the U.S. OEMs (GM EMD, GETS, Caterpillar or ALCO). Alternate prime movers include those diesel engines proprietary to other companies, whether in the U.S.A. (such as Cummins, Detroit Diesel, etc.) or elsewhere, higher-speed diesel engines, gas turbines, hybrid engine/storage-battery packages or fuel cells.

1.0 INTRODUCTION

The medium-speed diesel engine provides the predominant motive power for locomotives in operation on Canadian and American railways. It has found its niche as a result of its fuel-efficiency, ruggedness, reliability and installation flexibility. However, it also emits pollutants, the principal ones being oxides of nitrogen (NOx), particulate matter (PM), unburned hydrocarbons (HC), carbon monoxide (CO) and oxides of sulfur (SOx). These pollutants, either individually or in combination, cause many adverse health and welfare effects, including respiratory illness, environmental damage and visibility problems. For these reasons, in 1998 the U.S. Environmental Protection Agency (EPA) promulgated a rulemaking on emissions standards for locomotives and locomotive engines operating in the U.S.A. (1). These standards also have implications for the Canadian railway sector.

As contrasted to the use of locomotive-specific emissions legislation in the U.S.A, the Canadian approach has been to opt for voluntary limitation of the cumulative emissions from the railway sector. In 1995 the Railway Association of Canada (RAC) entered into a voluntary monitoring action with Environment Canada to strive to cap locomotive emissions at 1989 annual levels for 1990 through 2005 (2). This cap is 115,000 tonnes per year for NOx. Based on the total fuel consumed and emissions factors established for the locomotive types and mix in the Canadian fleet, the RAC reports annually to Environment Canada the calculated volume of NOx emitted and, for information purposes, other emissions such as HC, CO, PM, and SOx, as well as carbon dioxide (CO_2), which is a greenhouse gas (GHG).

In addition to the voluntary NOx cap, the Canadian railway sector must now adhere to the goals of the Kyoto Protocol on Climate Change that was ratified by the Canadian government in December 2002. This Protocol aims to reduce annual GHG emissions (which lead to global warming and climate change) by 6 percent of 1990 levels by the year 2012 (3). The volume of GHG emitted is directly proportional to the amount of fuel consumed. As its 2,000 locomotives consume about 2 billion L of diesel fuel per year, the Canadian railway sector is obviously implicated in achieving these goals (4). Most NOx reduction technologies currently available result in a fuel penalty that increases both railway operation costs and GHG emissions. Hence, the challenge is to develop technologies that, concomitantly, meet the EPA's locomotive-specific emissions limits, avoid the RAC's NOx cap being exceeded and do not incur a fuel penalty. The latter factor is a goal of obvious interest to Canadian railways as fuel is about 10 percent of their operating costs

This report identifies a wide range of diesel engine in-cylinder, after-treatment and related technologies and techniques being researched and offered in this regard.. It also contains a scenario for Canadian-side participation in the U.S. Department of Energy's initiative for the railway sector, entitled "Energy Efficient Technology within a Regulated Environment", being pursued in concert with the Association of American Railroads (AAR) and the locomotive Original Equipment Manufacturers (OEMs) (5).

2.0 PROMULGATION OF EPA EMISSIONS STANDARDS

Like all processes wherein combustion takes place (as in a diesel engine), the pollutants emitted are a negative reality that has to be taken into account. This reality is an ongoing concern of environmental and health regulators. However, in a technological sense, it was the impetus of the U.S. EPA rulemaking in 1998 that caused effort to be focused on the combustion process in the medium-speed diesel engine, which is ubiquitous in American and Canadian railway services. It was a major event in the history of North American railways. The EPA rulemaking legislated emissions standards for locomotives operating in the U.S.A. that, if not adhered to, would result in fines and penalties to both equipment suppliers and railway owners. As shown in Table 1, the EPA rulemaking that was promulgated contains three levels of locomotive-specific emissions limits corresponding to the date of a locomotive's original manufacture or re-manufacture, that is, Tier 0, Tier 1 and Tier 2. The units for emissions standards are grams per brake horsepower hour (g/bhp-hr).

Table 1: U.S. EPA Emissions Standards for Locomotives (g/bhp-hr)

Duty Cycle	HC*	CO	NOx	PM
Tier 0 (1973 - 2001)				
Line-haul	1.0	5.0	9.5	0.60
Switcher	2.1	8.0	14.0	0.72
Tier 1 (2002 - 2004)				
Line-haul	0.55	2.2	7.4	0.45
Switcher	1.2	2.5	11.0	0.54
Tier 2 (2005 and later)				
Line-haul	0.3	1.5	5.5	0.20
Switcher	0.6	2.4	8.1	0.24
Current Estimated Locomotive Emissions Rates (1997)				
Line-haul	0.5	1.5	13.5	0.34
Switcher	1.1	2.4	19.8	0.41
** HC standard is in the form of THC (total hydrocarbon) for diesel engines. For locomotives and locomotive engines fueled by alcohol or natural gas, equivalent THC standards apply.*				

In terms of the 1997 reference baseline, Table 2 shows the percent reductions in emissions rates to be achieved.

Table 2: Percentage Reductions from 1997 Emissions Baseline

Tier 0 (1973 - 2001 locomotives):	34% NO_x reduction, caps on other pollutants
Tier 1 (2002 - 2004 locomotives):	49% NO_x reduction, caps on other pollutants
Tier 2 (2005+ locomotives):	62% NO_x reduction, 50% PM and HC reductions

The EPA is also drafting more stringent Tier 3 and Tier 4 standards to be introduced later this decade. Similarly, 500 ppm sulfur content diesel fuel will be mandated by 2007 (6).

As seen in Tables 1 and 2, NOx, PM and HC are the principal emissions to be reduced in the EPA rulemaking. NOx is an invisible, toxic gas that can form fine aerosol particles that contribute to acidic precipitation (commonly known as acid rain or acid fog). NOx formation is a function of the maximum combustion temperature in the cylinder of a diesel engine. If the combustion temperature is decreased to reduce NOx, a corresponding increase in the amount of uncombusted fuel may be emitted as PM or gaseous HC. HC reacts with NOx and other pollutants to form ground-level ozone (smog). Ozone and PM are associated with many adverse health and welfare effects. The reduction of both NOx and PM simultaneously in medium-speed diesel engines presents a unique emissions control challenge: some techniques that are used to control one of these pollutants increase the production of the other. Also, and unfortunately, most emissions reduction technologies lead to an increase in fuel consumption, resulting in a significant impact on the economics of railway operations. The challenge is to develop emissions technology without fuel penalties – a goal of obvious interest to Canadian railways, technology developers and regulators.

3.0 STATUS OF LOCOMOTIVES MEETING EPA STANDARDS

The EPA rulemaking in 1998 triggered a surge of developmental activity by the two principal U.S. OEMs – namely General Motors Electro-Motive Division (GM EMD) and General Electric Transportation Systems (GETS) – and some re-manufacturers to meet the emissions limits, preferably without compromising fuel efficiency. There was initial concern in the railway sector about whether the standards could be achieved and the financial impact to the operating railways in complying with, in their view, a public policy issue that provided no commercial benefit to them. However, it was observed that a similar situation had existed for the heavy-duty trucking sector in the 1980s. The subsequent research actions did achieve the EPA reductions goals for heavy-duty diesel engines and have contributed to the scientific knowledge base of diesel combustion.

The current status in the industry is that during 2000 the two principal OEMs began offering EPA-certified technical solutions for selected locomotive models to meet Tier 0 emission standards. The GM EMD solution applicable to its model 710 two-cycle medium-speed diesel engines is to retard the fuel injection timing by 4 degrees of crankshaft angle. Retarding the timing lowers the peak combustion temperature, which results in lower NOx formed, thus meeting Tier 0 standards but increasing the fuel consumption by 2 to 4 percent. GETS was able to meet Tier 0 and then Tier 1 without a fuel penalty on its four-cycle GE 7FDL engine by incremental improvements to power assembly components (7). In January 2003 GETS announced that it had achieved Tier 2 on its 12-cylinder 4,500 hp GEVO™ engine model a full two years before the EPA 2005 deadline, and with a 3 percent improvement in fuel consumption. Some third-party re-manufacturers of locomotives and diesel engines are developing Tier 0 retrofit kits for the older GM EMD 645 engine models that power the popular GM EMD SD-40 locomotives. Two of these re-manufacturers, Hatch & Kirk Inc. (California) and the CSX Railroad (Florida), as well as GETS have obtained EPA certification for their Tier 0 retrofit kits for EMD 645 engines. A test program has been initiated by the Southwest

Research Institute, San Antonio, Texas, to evaluate the relative performance of locomotives having the alternate Tier 0 kits installed. Appendices A and B list the details of EPA Tier 0 emissions reduction kits certified for retrofitting into existing locomotives.

4.0 EPA STANDARDS AND THE CANADIAN RAILWAY SECTOR

As no legislated standards exist in Canada for locomotive emissions, the EPA standards have become the de-facto technical standard of reference for Canadian railways due to the fact that their equipment and operating context are highly integrated with those of their American counterparts via the interchange rules of the AAR (8). Despite the absence of emissions standards for railway operations in Canada, when considering the purchase of freshly manufactured or re-manufactured locomotives the Canadian railways now specify the EPA Tier level corresponding to the date when the purchase, or re-manufacturing, is to occur. As of 2003, new locomotives meeting Tier 0 and Tier 1 standards are now in operation on Canadian National Railway, Canadian Pacific Railway and VIA Rail Canada. The motivations for the railways to do this include, inter alia:

a) the reality that to vary from the basic EPA-compliant locomotive build specification configured for the U.S. marketplace would add to the purchase cost;
b) offsetting the increased emissions resulting from traffic increases so as to keep within the annual NOx cap of 115,000 tonnes that the RAC voluntarily strives to meet;
c) the availability of Canadian locomotives meeting EPA standards for incidental operations into the U.S.A. as a contingency that the EPA may overrule the current exemption permitting non-compliant Canadian locomotives to operate in the U.S.;
d) maintaining the value of the locomotive assets in case of resale into the U.S. market;
e) ensuring availability of Canadian locomotives that would meet emission standards that may possibly be put in place in Canada in the future;
f) ensuring that there is an up-to-date technical knowledge base and testing capability in Canada concerning emissions from locomotive medium-speed engines; and
g) reinforcing the image that as a transport mode the railways are less harmful on the environment and are contributing to Canada's commitment to the goals of the Kyoto Protocol on Climate Change.

5.0 EMISSIONS STATUS OF CANADIAN LOCOMOTIVES

Table 3 shows the profile of the Canadian locomotive fleet as of 2001. The emissions standard that pre-2001 Canadian locomotives should meet when re-manufactured is still being addressed by the railways. In the absence of guidelines, the principal railways are making their own decisions whether to install EPA-compliant Tier 0 retrofit kits from those available on the market (as listed in the Appendices). Of note in Table 3 is how much lower the NOx emissions factor is for the Tier 0 retrofitted GE Dash 9 locomotives. Table 4 shows that about 1,000 older GM EMD locomotives with the model 645 two-cycle engine will come up for re-manufacture over the next five to seven years (9).

Table 3: Emissions Factors for Canadian Mainline Locomotives (as of 2001)

Loco Model	Number in Fleet	Engine Model	Horsepower	Emissions Factors (grams / imperial gallon)			
				NOx	CO	HC	PM
SD-40	944	EMD 645	3,000	247.5	52.7	12.9	4.7
SD-50	64	EMD 645	3,600	247.5	52.7	12.9	4.7
SD-60	63	EMD 710	3,800	340.1	22.1	9.0	7.2
F59PH	52	EMD 710	3,000	324.1	22.4	8.7	7.4
SD-70	12	EMD 710	4,000	338.8	21.9	8.6	7.2
SD-75	179	EMD 710	4,300	339.5	22.2	9.1	7.3
SD-90	61	EMD 710	4,300	339.5	22.2	9.1	7.3
SD-90	4	EMD 265H	6,000	340.0	22.3	9.2	7.4
B39	30	GE FDL16	3,600	241.5	126.7	12.9	7.0
Dash 8	84	GE 7FDL	4,000	241.5	126.7	12.9	7.0
Dash 9	229	GE 7FDL	4,400	310.7	20.4	7.4	2.7
Dash 9	179	7FDL **Tier 0**	New & Rebuilt	204.6	20.4	7.4	2.7
Other	34	MLW & Caterpillar		247.5	52.7	12.9	4.7
Total:	**1,935**	**Factor: Freight Locomotives**		**269.2**	**53.8**	**10.8**	**5.6**

Table 4: Profile of Canadian Mainline Locomotive Fleet (1997 to 2001)

Locomotive Model	Engine Model	hp	Age	1997	1998	1999	2000	2001	Change since 1997
MLW	251	3,000	**pre-1990**	86	41	61	31	31	**- 55**
EMD SD-40	645	3,000	pre-1990	1,567	1,238	1,130	1,044	944	**- 623**
EMD SD-50	645	3,600	pre-1990	66	66	66	64	64	**- 2**
EMD SD-60	710	3,800	pre-1990	69	63	63	63	63	**- 6**
GE	7FDL	2,250	pre-1990	3	0	3	3	3	**0**
GE	7FDL	3,000	pre-1990	0	10	0	0	0	**0**
GE B-39	7FDL	3,200	pre-1990	0	0	15	15	15	**15**
GE B39-7	7FDL	3,600	pre-1990	16	5	6	12	12	**- 4**
Caterpillar	3516	3,100	pre-1990	1	0	0	0	0	**- 1**
EMD SD-70	710	4,000	**post-1990**	26	76	26	0	12	**- 14**
EMD F59PH	710	3,000	post-1990	50	45	45	52	52	**2**
EMD SD-75	710	4,300	post-1990	139	167	180	179	179	**40**
EMD SD-90	710	4,300	post-1990	0	0	61	61	61	**61**
EMD SD-90	265H	6,000	post-1990	0	0	4	4	4	**4**
GE Dash 8	7FDL	4,000	post-1990	109	61	87	84	84	**- 25**
GE Dash 9	7FDL	4,400	post-1990	291	317	302	352	408	**117**
Caterpillar	3608	2,075	post-1990	4	3	0	3	3	**- 1**
			Totals:	**2,427**	**2,092**	**2,049**	**1,967**	**1,935**	**- 492**

6.0 EMISSIONS REDUCTION / FUEL TRADE-OFF SCENARIOS

Projecting the volume of emissions produced by the Canadian railway sector over the next 20 to 30 years is fraught with uncertainty. As indicated in Table 3, the railway fleet is a mixture of locomotives having varying emissions factors. Also, the fleet profile is shrinking annually, as shown in Table 4. The principal railways are replacing their 1970-era 3,000 hp locomotives on a three-for-two or two-for-one basis with modern fuel-efficient 4,300 hp to 6,000 hp locomotives. Despite the fact that the new locomotives consume less fuel for the power produced, those acquired prior to the promulgation of the EPA emissions standards produce more emissions per unit of fuel consumed.

When projecting alternate scenarios, the question arises as to what the fleet profile will be and, in particular, what will happen to the older locomotives. For example, will they be rebuilt by the principal railways, or sold to leasing companies that will rebuild them for sale/leaseback to the railways that do not wish to rebuild their own units on their own tab? Another reality is that the OEMs supplying the new locomotives offer to take the older locomotives as trade-ins and then scrap them. One railway school of thought is that there is little benefit continuing to utilize older locomotives that are not fitted with advanced productivity-improving microprocessor-based electronic sensors and control systems. Another school of thought is that even though these locomotives may cascade to railyard switching and short-line operations, they should be retrofitted with up-to-date safety and emissions-reduction technology so as to maintain value of assets. However, notwithstanding uncertainties in traffic growth and operational strategies that influence both positively and negatively the total emissions produced, the following three options were examined and summarized in Table 5 as a basis for analyzing emissions reduction scenarios and trade-offs for the Canadian railway sector (10).

Option 1: Replace all SD-40 era locomotives through the purchase of new locomotives meeting EPA Tier 1 and then Tier 2 after 2005. Currently, about 50 new (freshly manufactured) locomotives are purchased by the Canadian railways per year. In 20 years, they could displace the approximately 1,000 SD-40 locomotives currently producing 51 percent of the 115,000 tonnes of NOx emissions (58,650 tonnes). If one quarter of these locomotives met EPA Tier 1 limits (in which NOx emissions are to be reduced 49 percent below baseline), and three quarters met EPA Tier 2 limits (in which NOx is reduced 62 percent), after 20 years they could contribute an annual reduction of NOx of 34,450 tonnes (based on the current freight locomotive fleet and fleet NOx cap of 115,000 tonnes). This is a 30 percent reduction in NOx by 2022.

Option 2: Retrofit all SD-40 era locomotives to meet Tier 0 limits when they are re-manufactured during the coming decade. Retrofitting all locomotives of this era to Tier 0 limits would yield a 34 percent reduction in NOx, according to EPA projections. Applying this value to the Canadian situation, in which there are 1,000 SD-40s producing 51 percent of the NOx of the current fleet, would yield a 20,000 tonne reduction in the annual 115,000 tonne NOx cap. This would contribute a 17 percent reduction by 2012, when the re-manufacturing process would be completed.

Option 3: Retrofit all non-SD-40 and non-Tier 0 locomotives in the current Canadian fleet (contributing 47 percent of NOx emissions) to meet Tier 0 limits when re-manufactured. This would yield 18,380 tonnes per year reduction in the 115,000 tonne cap. This is a 16 percent emissions reduction by 2012.

Table 5: Options and Projections for Reduced Emissions in Canada

Strategy	Action	Target NOx % reduction (as per EPA)	Portion of loco fleet	Number in fleet	NOx reduction (tonnes/yr)	Reduction (% below NOx cap)	Time Frame
Option 1:	Buy annually 50 new Tier 1 then Tier 2 *	49 } 62 }	50% in 20 yrs	1,000	34,450	30	by 2022
Option 2:	Retrofit all SD-40s to Tier 0	34	51% at present	1,006	20,000	17	by 2012
Option 3:	Tier 0 retrofit all non-Tier 0 locomotives	34	47% at present	698	18,380	16	by 2012

* presumes 50 SD-40 locomotives retired per year

Regarding Options 2 and 3, it is presumed that emissions reduction kits would be installed when the older locomotives are scheduled for re-manufacture, normally every five to seven years. Hence, the only emissions-related incremental cost would be the purchase of the actual Tier 0 retrofit kit. If a kit providing Tier 0 emission standards with no fuel penalty were to be opted for (as described in Appendix C for the 645 E3B engine model having a list price of $31,650), the cumulative cost to retrofit the fleet of 1,000 locomotives equipped with the 645 engine could total $31.65 million. As shown in Table 5, for Option 2 this would yield an annual NOx reduction of 20,000 tonnes, or 20 tonnes per locomotive. Each locomotive produces about 60 tonnes per year of NOx. Fitting each locomotive with a Tier 0 kit lowers this figure to 40 tonnes per year. When amortized over a seven-year average rebuild period, this equates to $31.65 million ÷ (20,000 tonnes/year x 7 years) = $226 for each tonne of NOx reduced per locomotive.

Alternately, lower-priced retrofit kits are available that permit EPA Tier 0 compliance but incur a 2 to 4 percent fuel penalty as the NOx reduction is primarily due to retarding the injection timing. As listed in Appendix C, these are available for about $20,000 each. In this case, Option 2 would result in a cost of $143 for each tonne of NOx reduced per locomotive when amortized over a seven-year rebuild period. However, the additional fuel cost must be added to this amortized cost for a true life-cycle cost comparison. Mainline railway operations consumed 1.82 billion L of diesel fuel during 2001 (11). Assuming that the locomotives with model 645 engines in mainline service consume approximately one half of the 1.82 billion L consumed per year, the fleet incremental consumption using these kits would be 18.2 million to 36.4 million L per year or, at $0.40 per litre, an incremental cost of $7.28 million to $14.56 million, equating to $7,280 to $14,560 per locomotive per year. For the 20 tonnes of NOx reduced per year per locomotive with the lower-priced kit, the fuel penalty ranges from $364 to $728 per tonne. Thus, combining the kit and fuel penalty cost, the cost per tonne of NOx reduced ranges from $507 to $871 per locomotive per year with the lower-priced Tier 0 kit.

From the above analysis, it is apparent that the $10,000 saved to purchase the lower-priced kit would be offset within two years by the $7,280 to $14,560 additional fuel consumption cost if the locomotive were used in mainline service. However, for light-duty switching or branch-line services having lower fuel consumption, it may be that the lower-priced Tier 0 retrofit could be justified.

7.0 EMISSIONS CONTROL TECHNIQUES

Despite continual design improvements, railway medium-speed diesel engines in general still contribute significant quantities of NOx, PM and, to a lesser extent, HC and CO emissions. These are the emissions targeted by the EPA to be successively reduced. As mentioned in Section 3.0, spurred by the promulgation of the ever more stringent EPA emissions standards, the OEMs and some re-manufacturers are focusing on the development of technology and controls to reduce NOx, PM and HC, and at the same time trying to avoid compromising fuel economy and mechanical durability. Various strategies are being pursued, either separately or in combination, such as:

a) better management of the process to deliver air and fuel to the power cylinder so as to create conditions that limit the production of harmful emissions from the resulting combustion;
b) the use of after-treatment (or post-combustion) technologies to break down or capture emissions;
c) opting for alternate prime movers provided by builders other than the traditional OEMs, such as higher-speed diesel engines that already exceed Tier 1 and Tier 2; and
d) the consideration to use alternate fuels, particularly for operations around urban areas.

To date, priority has been on strategy a) for both the pre-2001 locomotives (to comply with Tier 0) and the post-2000 new locomotives (to comply with Tier 1 and Tier 2 limits). Development work for strategy b) is still at the exploratory stage, the principal challenge being the limited space on board a locomotive to fit after-treatment technologies that have been scaled up from automotive applications. Strategies c) and d) are primarily decisions to be taken by individual railways. The challenge in this regard is to provide confidence to railways to try non-conventional engines and fuels in their operations (12)(13)(14). One way to gain such confidence is via a site-specific demonstration project in which the non-conventional technologies are first tested and operationally evaluated in a dedicated railway service. An additional benefit of using less carbon-intense alternate fuels would be the lower production of CO_2, a greenhouse gas, thus providing a railway sector contribution to the goals of the Kyoto Protocol on Climate Change.

7.1 Techniques to Meet EPA Tier 0 Limits

As listed in Appendices A and B, emissions reduction kits complying with EPA Tier 0 are now available from the OEMs and certain U.S. re-manufacturers, and can be retrofitted into candidate Canadian locomotives identified in Table 3. The underlying technical approach in the development of the kits was to permit pre-2001 locomotives to meet Tier 0 with minimal hardware changes so as to accommodate the railways' caveat that there be no impact on performance and reliability, and minimum negative impact on fuel efficiency and costs. Two categories of kits have received EPA certification. One category permits Tier 0 to be achieved, but with a resulting increase in fuel consumption. The other category permits Tier 0 to be achieved without a fuel penalty. The respective features of each category are reviewed in sections 7.1.1 and 7.1.2.

7.1.1 Meeting EPA Tier 0 With a Fuel Penalty

NOx and PM are the principal emissions targeted by the EPA. For Tier 0, NOx levels are to be reduced up to 34 percent below baseline. Within the constraints of existing designs of in-service locomotive engines, the most direct way to reduce NOx emissions so as to comply with Tier 0 is through late fuel injection, generally known as "retarding timing". This is a relatively straightforward software change on engines equipped with electronically controlled fuel injection systems as on some versions of the GM EMD model 710. On mechanically controlled systems, adjustment of the camshaft timing is required.

The principal way to keep the PM capped at the baseline level, as required by Tier 0, is to use fuel injectors of the "zero-sac" type, which have no after-drip and an improved fuel spray pattern to facilitate more complete combustion.

The technologies of the Tier 0 retrofit kits being offered for a particular engine model vary according to how the supplier was able attain compliance within a targeted price range and railway service. For example, some kits incorporate only late fuel injection, whereas others combine retarding timing with improved fuel injectors to attain Tier 0. Examples of such combinations of kits offered by GM EMD are shown in Appendix B.

7.1.2 Meeting EPA Tier 0 Without a Fuel Penalty

As exposed in Section 6, it is advantageous for both the operating railways and engine suppliers to offer retrofit kits that permit Tier 0 emissions limits, particularly NOx and PM, to be attained without a fuel penalty. Within the constraints of existing engine designs, this target requires technical changes additional to those in Section 7.1.1 and include, inter alia:

a) late fuel injection, generally known as "retarding timing";
b) reducing the temperature of the air entering the combustion cylinder by improving the effectiveness of intercoolers;

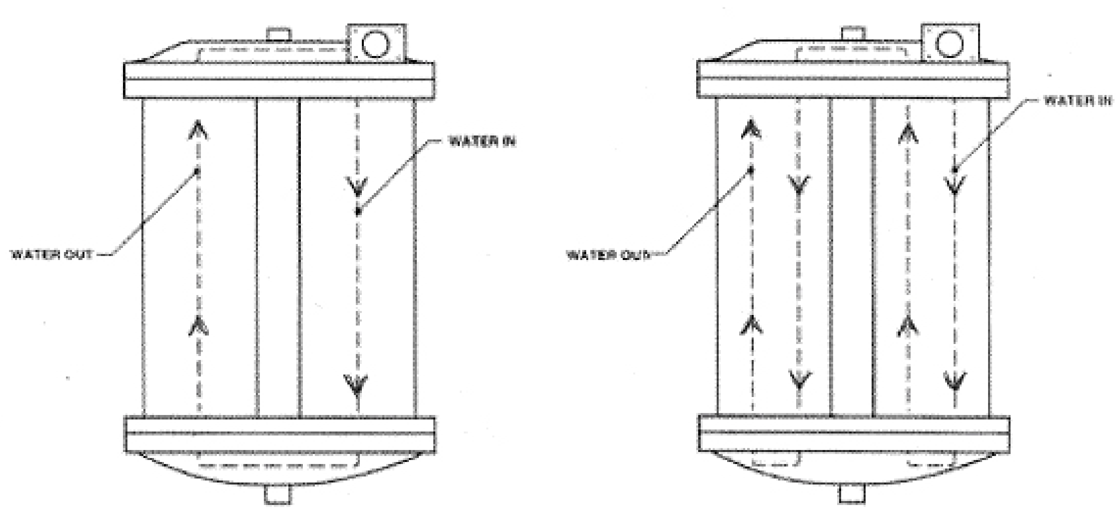
c) improved fuel injectors, such as the "zero-sac" type, which have no after-drip and an improved fuel spray pattern to facilitate more complete combustion; and
d) new power assembly components, such as pistons with crown shapes optimized for the improved fuel spray pattern with re-matching of turbochargers.

The additional technical changes are required to improve the physical and chemical processes needed to achieve better air-fuel combustion, with particular attention to reduce NOx formation. As mentioned earlier, NOx formation is an exponential function of the peak flame temperature in the combustion cylinder. The flame temperature is determined only by the properties of the fuel and the starting temperature of the air and its oxygen content. This means that the engine designer has only limited tools to reduce NOx formation in the cylinder. Also, a reality is that many of the measures that reduce NOx formation also tend to increase PM and soot.

Increasing the pressure ratio of the turbocharger permits more air to be available to effect the diesel combustion process and, hence, results in more power produced per unit of fuel consumed. Increasing the effectiveness of the intercooler, which cools the pressurized inlet air between the turbocharger and the cylinder intake air manifold, will result in a lower peak combustion temperature and, hence, less NOx formed. Generally, high horsepower medium-speed V-type engines incorporate two turbochargers and two intercoolers: one set for each bank of cylinders of the V-configuration. The intercooler is an air-to-water heat exchanger, the coolant water for which is supplied from the locomotive radiator. Its effectiveness is a function of the number of heat-exchange passes incorporated into its design. Figure 1 shows the design progression from a two-pass to an upgraded four-pass intercooler that is now available with most retrofit kits.

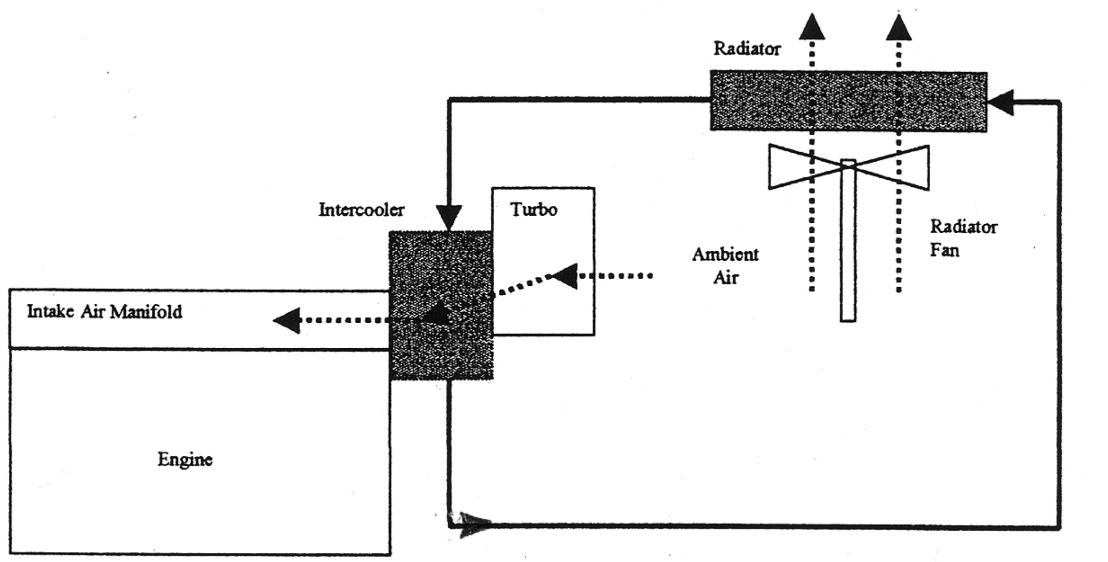
Figure 1: Increasing Effectiveness of Intercooler

Two-Pass Intercooler **Four-Pass Intercooler**



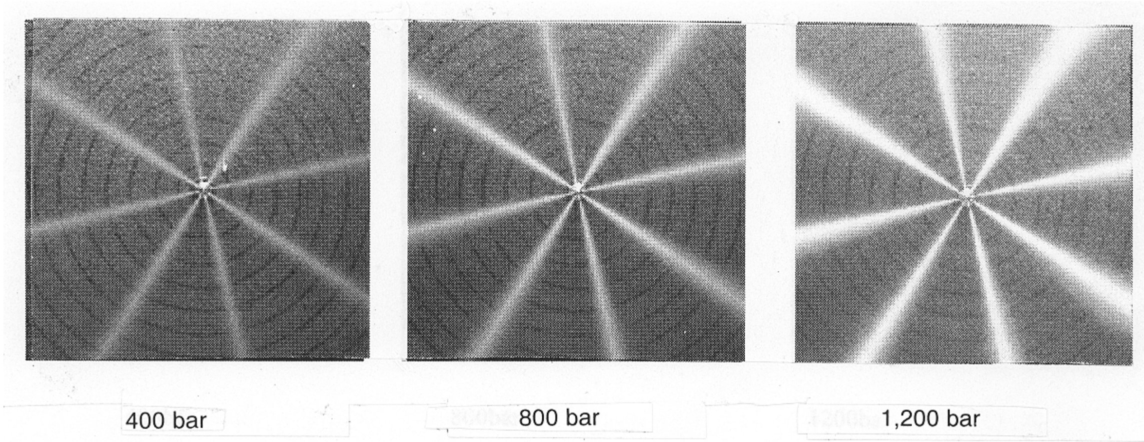
As can be observed from the descriptions listed in the Appendices, those retrofit kits indicating no fuel penalty all include an upgraded intercooler. As shown in Figure 2, the water that is circulated through the intercooler is cooled by the locomotive's roof or side-wall mounted radiator. Hence, the performance of the radiator system directly influences the capacity and effectiveness of the intercooler. A reality is that locomotives, being bi-directional, cannot benefit from ram-air cooling of their radiators, as can automotive vehicles. To ameliorate this within the constraints of the locomotive body, some designs have incorporated side extensions, or wings, to increase the capacity of the radiator.

Figure 2: Locomotive Intercooler / Radiator Cooling System to Reduce Cylinder Intake Air Temperature



The fuel injector (which sprays fuel into the combustion cylinder) is the core component of diesel technology. It exists in two versions: mechanically actuated and electronically actuated. Both versions have received significant R&D effort applied to them over the last decade. As electronic fuel injection (EFI) in medium-speed engines was only introduced in recent years, the great majority of locomotive engines candidate for retrofit to Tier 0 have mechanically actuated fuel injection (MFI). The principal features of the upgraded MFI fuel injectors include manufacture to closer tolerances using harder materials and redesigned nozzle tips. The latest versions have "zero sac" nozzle tips that eliminate after-drip of the sprayed fuel. After-drip compromises complete combustion, increases fuel consumption and leads to increased PM formation and smoke. Also, to improve fuel spray patterns, the newer nozzle designs have more holes and different spray angles, and operate at higher pressures. Figure 3 shows how increased injection pressure distributes the fuel more uniformly over the piston face. This uniformity results in a more complete combustion that yields a lower fuel consumption for the power generated, and conditions conducive to lower NOx and PM formation.

Figure 3: Effect of Injection Pressure on Fuel Spray Pattern

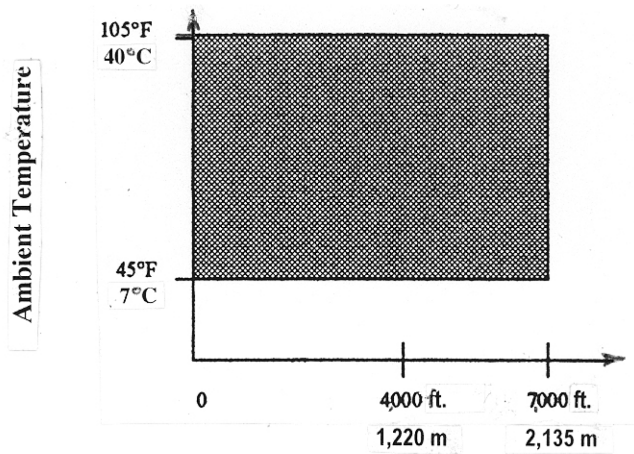


The piston design is the other principal variable affecting the diesel combustion process. There is a symbiotic relationship between the shape of the piston face and the injection spray pattern. In the combustion chamber, the fuel spray pattern must be compatible with the predominant mode of turbulence of the air being compressed so that the flame front along the sprays is as uniform as possible. The designer tries to avoid pockets of either too rich or too lean amounts of fuel within the cylinder as combustion takes place.

7.2 Techniques to Achieve EPA Tier 1, Tier 2 and Beyond

It goes without saying that diesel combustion research and development (R&D) is a complicated integration of a multitude of variables. It requires a cautious, incremental and mostly empirical process that is linked with careful and repetitive testing to understand and measure the range of variables affecting performance, fuel economy, emissions, reliability, durability, maintainability, safety and cost. Medium-speed engine development effort still lags behind that which is applied to high-speed diesel engines used in heavy duty trucks. One reason for this is that the latter are produced in the hundreds of thousands per year (hence justifying large R&D efforts), while only some 500 to 1,000 medium-speed engines are produced annually. It is common for totally new high-speed engine designs to be introduced regularly, whereas the principal medium-speed engine designs are basically incremental revisions to those that have been in existence for 50 to 75 years. Also, technology developed for high-speed automotive and industrial diesel engines is neither readily scalable nor easily transferable to locomotive-sized medium-speed diesel engines. Locomotives have a life expectancy averaging 40 years and, during that time, their engines could be rebuilt seven or eight times. The EPA requires the emissions reduction technology to perform consistently over the life of the locomotive at ambient air temperatures ranging from 7 to 40°C (45 to 105°F) and up to an altitude of 2,135 m (7,000 ft.), as illustrated in Figure 4.

Figure 4: EPA Compliance Rectangle



Altitude

The principal elements being investigated to control and reduce exhaust emissions from medium-speed engines to meet the more stringent EPA limits, yet at the same time minimize any negative impact on fuel consumption, include the following (15).

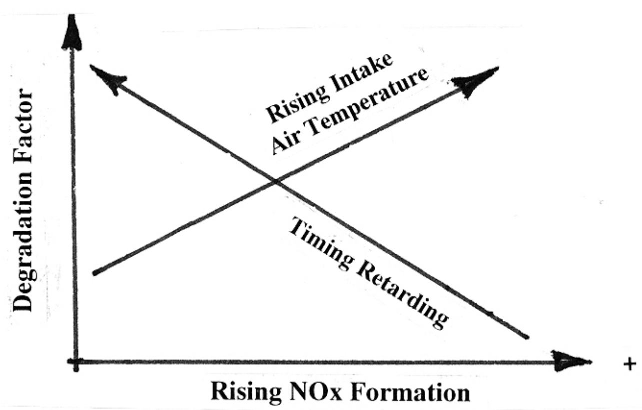
7.2.1 Air Control Techniques

a) **Intake Air Delivery:** Techniques to pre-condition the intake air and improve its delivery to the combustion cylinder include redesigning inlet filters, turbochargers, intercoolers, intake air manifold orifices and valving to provide smoother routing of the intake air and to optimize air manifold pressure and temperature. This is important for managing the physical and chemical processes needed to optimize the air-fuel combustion process. The effectiveness of future intercooler designs and their associated radiator cooling systems will still be a principal determinant to reducing peak flame temperature in the combustion cylinder and the concomitant NOx formation level. Future intercooler designs envisage six-pass configurations, superseding the current four-pass ones. A recent move to separate the intercooler heat exchange system from the engine radiator system is expected to become commonplace. Also, to upgrade the effectiveness of locomotive radiator systems, nanofluids having high heat transfer coefficients are being investigated as alternatives to the use of water, the traditional coolant fluid. Nanofluids are a category of the emerging nanotechnologies scientific field in which the structures of materials have been modified at the nanoscale to tailor and optimize their properties to specific applications. Traditionally, the railway sector has resisted using any fluid other than plain water in locomotive engine cooling systems because of the propensity for leaks and to avoid the costs associated with the additive. However, if research proves the merit of nanofluids, the railway sector could accept non-water coolants on future locomotive models if this technology facilitates EPA Tier 3 or Tier 4 limits to be met.

b) Hybrid Turbocharging: A conventional turbocharger is an exhaust-driven turbine to which an air compressor is directly coupled to provide supercharged air to the combustion cylinder. This results in improved diesel combustion efficiency. However, when a diesel engine is accelerated or experiences a transient load, there is a lag until the turbocharger can re-match its output to the new condition. During this lag, the combustion conditions are off-optimum, resulting in increased emissions and decreased fuel efficiency. This lag can be overcome with a hybrid turbocharger in which a high-speed permanent-magnet electric motor supplements the turbine during transients.

c) Adaptive Control Strategy: Without changes to component configurations, GETS has demonstrated the ability to achieve Tier 1 without a fuel penalty on its FDL engine certified originally to Tier 0. Its strategy to achieve Tier 1 was through an electronic adaptive control strategy that offsets the NOx increase by retarding fuel injection timing as the intake air temperature rises within the capacity limits of the radiator cooling/intercooler system, thus optimizing fuel consumption for any operating condition. Via the use of electronic sensors linked to the engine's adaptive control system, NOx increases are offset with timing retard, permitting the locomotive to operate at nearly constant NOx emissions with concomitant fuel consumption at all power levels. This strategy is illustrated in Figure 5.

Figure 5: Adaptive Control Strategy of Timing Retarding versus Intake Air Temperature



d) Exhaust Gas Recirculation (EGR): This is the mixing of a portion of the exhaust gas with the intake air. The mixing lowers the oxygen concentration, thereby lowering NOx formation during combustion. It is an established technique, particularly for on-road automotive applications, to manage NOx emissions by lowering peak combustion temperature, but it invariably worsens fuel efficiency and increases PM emissions. For medium-speed engines used in off-road applications (which includes railways), it is a technique yet to be resorted to by the OEMs for the EPA Tier 1 and Tier 2 compliant locomotives, or by those third parties supplying Tier 0 kits. However, it could very well be a technique to obtain compliance with the future, more stringent Tier 3 and Tier 4 emissions limits expected later this decade for new locomotives. Essential ingredients for the effective use of EGR include, inter alia:

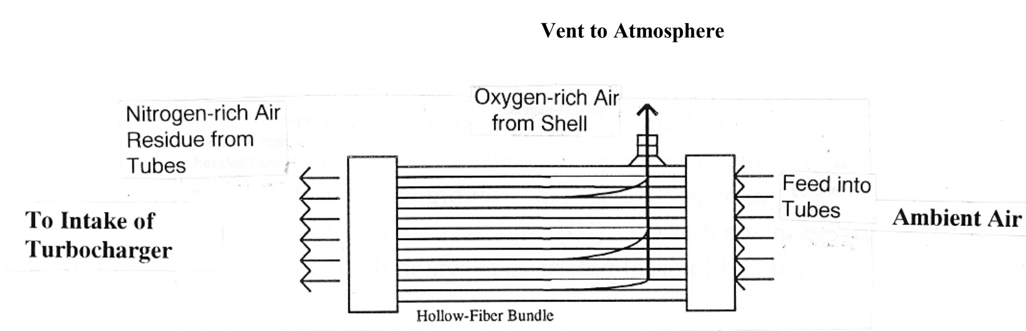
i) fuels that have a low sulfur content. For automotive diesel applications, the sulfur limit for effective EGR use is 0.015 percent (15 ppm), the level mandated by the EPA for on-road use in the U.S.A by 2007. For off-road (including railway) applications, the EPA intends to regulate sulfur levels at 0.5 percent (500 ppm) by 2007. However, this level would appear too high for EGR for medium-speed engines.

ii) electronic sensors and microprocessor-based control systems. Electronics-based control systems are essential to ensure that the ingress of the EGR is carefully matched with engine operating conditions. As electronic sensors and microprocessor-based systems are becoming an integral part of advanced locomotive designs, the introduction of EGR would be facilitated by their widespread usage.

EGR can be used directly or can be cooled before mixing with the intake air. Cooled EGR would overcome decreases in fuel efficiency and power density resulting when non-cooled EGR is used. However, cooled EGR would add a further burden to an already overtaxed locomotive cooling system. In addition, EGR may adversely affect engine durability due to certain products of the recirculated exhaust gases contaminating the metal parts and oil film in the combustion chamber.

e) Intake Air Composition: Varying the intake air composition, namely the oxygen-to-nitrogen ratio of the air that enters the combustion chamber, is a technique aimed at influencing emissions resulting from the diesel combustion process. For example, passing intake air through polymer membranes effects a chemical reaction that results in the separation of the oxygen from nitrogen. Experiments conducted at Argonne National Laboratory in Illinois have demonstrated the feasibility of this air separation technique (16). This technique could be an effective alternate to EGR because it promises to overcome the control and durability complications posed by, in particular, a cooled EGR system (which also lowers NOx formation by lowering the oxygen concentration during combustion). Via the use of a counterflow hollow-fibre polymer air separation membrane module, as shown in Figure 6, nitrogen-rich air is extracted and directed into the combustion chamber as a diluent, thus lowering the oxygen concentration, which in turn lowers the peak flame temperature and, hence, reduces NOx formation during combustion. The air separation membrane module would be installed in the air intake system of a locomotive upstream of the turbocharger.

Figure 6: Air Separation Membrane to Produce Nitrogen-Rich Intake Air



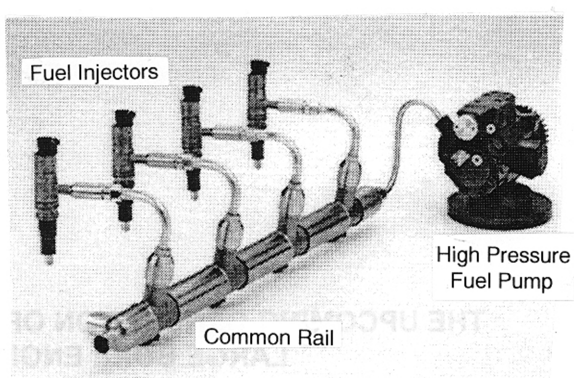
Similarly, techniques are under development for adding hydrogen to the intake air. They show promise to modify the combustion characteristics, particularly of older engine designs, so as to yield lower PM emissions without increasing NOx (17). The hydrogen gas is generated by on-board electrolysis of distilled water.

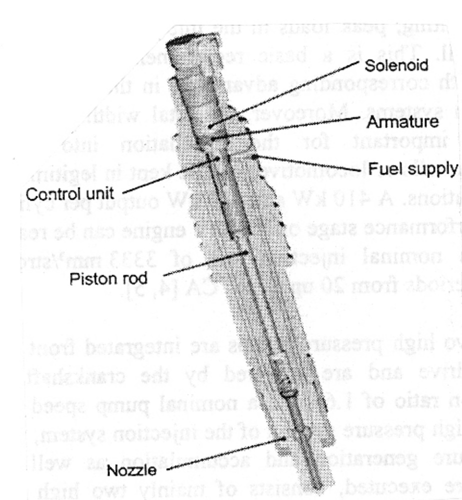
Another technique for modifying the intake air to lower NOx formation levels is to inject a water mist into the engine manifold. This is a practice used in large marine diesel engines. However, its acceptance for use in railway applications is problematic due to the limited space on board a locomotive for water storage, the complications of preventing freezing and the uncertainty regarding the effect on engine durability.

7.2.2 Fuel Delivery and In-cylinder Combustion

a) **Fuel Delivery/Injection Techniques:** Improvements to the fuel system are expected to contribute most to gains in the thermal efficiency of medium-speed engines. It is envisaged that improvements stemming from a focused R&D program could raise the thermal efficiency from 40 to 50 percent, which in turn would yield improvements in specific fuel consumption of 15 to 20 percent. The focus of these improvements is the designing of electronic controls and improved fuel pumps and injectors to deliver fuel to the combustion chamber at the best combination of injection pressure, injection timing, injection rate shaping and spray location. This helps the fuel to ignite and combust more uniformly in the power cylinder without causing the temperature spikes that increase NOx emissions or the fuel-rich pockets in which off-optimum combustion causes PM formation. The evolution of a common-rail fuel delivery system sized for a medium-speed diesel engine and combined with electronically controlled fuel injectors optimized for the railway 8-notch power settings appears to have potential to effect improvements to a number of interconnected combustion-related variables. Figure 7 shows a representative diesel common-rail injection system and the cross section of an electronically controlled, solenoid-actuated fuel injector.

Figure 7: Electronic Common-Rail Fuel Delivery and Injection System





Diesel combustion R&D is the art of combining science with empirical know-how due to the fact that in-cylinder transient interactions between the injected fuel jet and air flow pattern, and subsequent compression ignition and combustion, are complex and influenced by many factors. As the processes of diesel combustion and emissions formation become better understood in medium-speed engines, more effective fuel systems can be designed and developed. These processes are expected to follow incremental step-by-step understanding of, and improvements to, the following technological elements:

i) the use of common-rail delivery versus individual fuel pumps and lines for each cylinder. This not only reduces the number of components but also permits fuel of significantly higher pressure to be delivered to the injector. Common-rail systems provide a free choice of injection timing and a higher injection pressure that tends to reduce PM formation without a corresponding rise in NOx.

ii) the electronic control of injection timing, injection rate and fuel pressure that permits an instant and precise correlation with engine speed, load and ambient condition changes.

iii) the use of "smart" fuel injectors that incorporate variable orifice diameters, smaller orifice diameters, different spray angles, multiple orifice sizes, and pilot, split and multiple sprays, plus the ability to precisely shape the fuel injection rate, that is, the gradient of the nozzle opening and closing process. Electronically controlled, solenoid-actuated injector nozzle needles have the potential to be controlled to close precisely in microseconds to avoid after-dribbling (which is not possible with mechanically-actuated conventional systems). These features and, perhaps, the use of multiple injectors in each power cylinder are foreseen to overcome the design limitations of the current single injector having large orifice diameters. The large orifice diameters are required to supply sufficient fuel at high-load (Notch 8) conditions but result in off-optimum combustion at lower power settings.

iv) the materials that are used in the fuel delivery and injector components. It is envisaged that future injection equipment will adopt some of the advancements in new materials that exhibit properties to overcome the wear and durability limitations of conventional fuel components. The use of ceramics in injectors is expected to increase, as well as materials having a greater hardness and an ability to be machined to closer tolerances with lubricity-enhancing surface finish properties. The latter is to replace the lubricity that was provided by the high sulfur content of railway diesel fuel that will be phased out in favour of mandated low-sulfur fuels.

v) the electronics and software of the control systems so as to be able to control the parameters of the fuel injection process on a cycle-by-cycle basis or within a cycle, while correlating inputs from an array of sensors monitoring other engine, combustion and ambient conditions. Associated with this development would be extensive simulation requirements.

b) **Piston Design:** Special attention to the geometry of the piston crown and the compression ratio, plus such features as piston cooling designs, thermal barriers, ring spacing and materials properties or coatings can result in combustion characteris-tics tailored to reduce emissions. Also, reducing oil consumption through improved oil scraper ring design and related details can reduce PM emissions. The selection of piston crown geometry (generally bowl-shaped) tends to be a tedious process in engine development as changes or modifications elsewhere such as the fuel injection parameters can have significant positive or negative influences on differing piston designs. Traditionally, a piston crown geometry that enhanced turbulence of the air and fuel mixture in the combustion cylinder was considered desirable. However, it has subsequently been realized that the combination of precisely shaped fuel injection sprays into a more quiescent power cylinder would effect more complete combustion due to the avoidance of pockets of off-optimum air-fuel mixtures in the turbulence. Also, it is now realized that certain swirl-type turbulence flows induced by traditional piston crown designs actually increased the heat transfer to the combustion cylinder walls, resulting in a reduction in engine power produced. Similarly, turbulence could vary from one cylinder to another, resulting in uneven engine operation.

c) **Intake and Exhaust Port and Valve Design:** As for piston design, a similar attention to detail vis-a-vis the air-to-fuel mixture is required to ensure an optimum flow field is created by the air entering the combustion chamber through the intake port and valve and exiting via the exhaust valve and port. The principal parameters are a minimum pressure loss, minimum turbulence and stable conditions compatible with quiescent conditions preferred in the combustion cylinder to benefit from multi-spray, high-pressure electronic fuel injection. A possible evolution for medium-speed diesel engines is the development of electronically controlled, solenoid-actuated intake and exhaust valves, replacing current designs actuated by the camshaft. This would provide the freedom to vary the timing of the opening and closing of valves according to engine speed and power setting so as to approach optimum combustion conditions.

d) **Computational Fluid Dynamics Modeling:** In-cylinder combustion development concerns the understanding of the motion of the air entering the cylinder, the combustion of the air-fuel mixture in the cylinder, its subsequent energizing of the power piston and then the exiting of the products of combustion. The in-cylinder combustion process is still not fully understood and has been complicated to simulate mathematically or observe via photographic or remote means. However, a technique known as computational fluid dynamics (CFD) is now available that combines fluid mechanics theory, applied mathematics and powerful computers to simulate the motion of air around and within shapes. It has been used extensively in the aircraft sector and is now being applied to any design application for which air or fluid flows occur (18). The CFD process consists of selecting the equations that best describe the flow physics, i.e., the CFD code, using a powerful computer to solve the equations, interpreting the results and correlating them with actual test data. For diesel engine design, it is considered that advanced numerical models using CFD can facilitate the understanding of advanced combustion concepts and their relative merits.

7.2.3 After-treatment Technologies

After-treatment technologies are catalysts, particulate traps or techniques to convert or capture, between the power cylinder exhaust valve and exhaust stack, harmful emissions such as NOx and PM. They are in common use in automotive gasoline engines and will likely be utilized to permit diesel trucks to meet the more stringent EPA Tier 3 and Tier 4 emissions standards. Their use in diesel engines is more complex than for gasoline engines because of the "trilemma" between the generation of NOx, PM and fuel consumption (19). It is when automotive after-treatment equipment designs are scaled up to locomotive-sized applications that their use for the railway sector appears problematic. Some would require large storage tanks, scrubbers and storage of emissions products. It suggests the need for a tender for each locomotive, a consideration that would be resisted by railway operators as the tender would replace a revenue-generating railcar. Also, some of the after-treatment solutions require ultra-low sulfur fuel and no contamination from exhausted lubricating oil to be effective. However, as a contingency should the OEMs require after-treatment to accomplish EPA Tier 3 or Tier 4 emissions limits, three technologies are being examined for scale-up possibilities for locomotive applications:

a) **Selective Catalytic Reduction (SCR):** SCR reduces NOx in the engine exhaust to less harmful states as well as absorbing some PM. The principle behind SCR is that emissions flow through a special ceramic catalytic converter into which a diluted carbamide solution is injected. The carbamide is transformed into ammonia, which combines with NO and NOx and turns them into harmless N_2 and water. The components of the SCR system include a storage tank for the carbamide-water mixture, an electronic dosage control unit and the ceramic catalytic converter, which is built into the exhaust muffler. The ratio of carbamide to diesel fuel is about 6:100.

b) **Particulate Traps:** This after-treatment technique uses vortex separators and filters to remove PM from the exhaust stream. The PM residue is disposed of either on a continuous basis by in-situ burning or on an as-required basis via an automated scrubber or washing process. It appears to be an effective process but, over the longer term, the filters and traps may lose their effectiveness as a result of becoming clogged with ash from oil additives and other contaminants.

c) **Plasma Arc Treatment of Exhaust Gas:** When excited nitrogen (N*) atoms generated by an arc are introduced into a diesel engine's exhaust gas containing NOx, a resulting reaction occurs that reduces a portion of the NOx to straight nitrogen and oxygen. Experiments at Argonne National Laboratory with a pulsed plasma arc system being injected with pure nitrogen have confirmed the concept. The challenge for practical locomotive applications is the need for a continuous supply of high-purity nitrogen gas to feed the plasma. One possible solution is if the air separation membrane shown in Figure 6 were to be perfected.

7.2.4 Diesel Fuel Parameters

Currently, railway locomotive engines are designed to burn ASTM D975 Number 2 distillate fuel (also know as Diesel No.2). It is with this fuel that EPA certification of locomotive emissions standards is sought. Employing fuel additives and improving fuel properties such as raising the cetane number, lowering the aromatics content and decreasing sulfur levels can contribute to reduced NOx and PM emissions. The EPA has mandated that a sulfur limit of 0.5 percent (500 ppm) be in place by 2007 in the U.S.A. for off-road (including railway) applications. Environment Canada is expected to take a similar action to harmonize Canadian standards with those mandated in the U.S.A. Actually, the sulfur content of fuel in Canadian railway operations now averages 0.5 percent (500 ppm). One factor contributing to this is that 60 percent of the fuel comes from low-sulfur synthetic crude extracted from the Athabaska Tar Sands. This offsets the higher sulfur content fuel refined from off-shore supplies and delivered in Eastern Canada.

Several after-market suppliers offer fuel additives that purport to improve combustion and reduce certain emissions. Both the railway operators and OEMs are reticent to try such additives without first having proof of their performance under controlled test conditions. The AAR has a rigorous test protocol to screen additives that is costly to conduct. However, the Engine Systems Development Centre Inc. in Lachine, Quebec, has had accepted by the railway sector a simplified railway fuel additive evaluation test protocol using its single-cylinder medium-speed test engine (20).

7.2.5 Alternate Fuels

Less carbon-intensive alternate fuels, particularly natural gas and dimethyl ether (made from natural gas or coal feedstock) not only offer reduced emission of CO_2 but also NOx and PM benefits. However, lower specific energy efficiency could occur depending on how the air-fuel mixture is ignited in the combustion chamber. Blends of 20 percent biodiesel in petrodiesel appear to be transparent to a railway locomotive, with the only concern being its high cloud point temperature vis-a-vis use during a Canadian winter. Blended fuels offer a displacement of petroleum and some emissions benefits. Biodiesel production requires less energy than petrodiesel; hence less CO_2 is emitted, thus contributing to Canada's commitment to the Kyoto Protocol on Climate Change. Blends of ethanol with petrodiesel (known as e-Diesel) appear to offer performance improvements and lower PM emissions but have a lower flash point relative to petrodiesel, requiring more careful handling procedures. Water-petrodiesel emulsions are being investigated for their potential of reducing the peak flame temperature of diesel combustion and, hence, NOx formation levels. Most railway operators are reluctant to consider alternate fuels, in part due to market conditions vis-a-vis petrodiesel and uncertainty about their performance need for more complex storage and handling procedure. At present, fueling locomotives is the lowest skill trade in the railways.

A reality concerning the consideration to use alternate fuels in the new locomotives meeting EPA emissions standards is that they have been certified based on fuel that meets or exceeds ASTM D975 Number 2 Class A diesel fuel specification. As the engines of these locomotives have been optimized to run on fuel of this specification, the OEMs cannot provide a warranty for their engines operating on alternate fuels. For the OEMs to supply a locomotive that they would warrant for operation on an alternate fuel would require a thorough testing program to overcome any detrimental aspect about the alternate fuel, as well as repeating the EPA certification process. This is not expected unless such a requirement becomes a procurement condition from a major Class I railway. However, operation on alternate fuels appears transparent to the older-design locomotives built prior to 2000 and for which most warranty periods have expired. Hence, the decision regarding alternate fuels is focused on the circumstance of individual railway operators.

7.2.6 Alternate Prime Movers

In North America, conventional railway engines are considered to be those medium-speed diesel engines as manufactured or re-manufactured to designs proprietary to the U.S. railway sector OEMs. Alternate, or non-conventional prime movers include those diesel engines proprietary to other companies (whether in the U.S.A. or elsewhere), higher-speed diesel engines, gas turbines, hybrid engine/storage battery packages or fuel cells. Some higher-speed diesel engines exhibit emission standards meeting Tier 1, with development work underway to meet or exceed Tier 2. However, the challenge for the deployment of these engines in railway applications is to find a railway operator in Canada having sufficient confidence and motivation to commit to using non-conventional engines. One option being promoted by Alstom Transport Canada is to provide re-manufactured locomotives with the UK-built Ruston engine that now meets Tier 1. Another option being promoted by Cummins Diesel is to install two of its higher-speed 2,250 hp engines in place of a 3,600 to 4,000 hp medium-speed diesel engine. The tandem installation provides higher maximum power, increased fuel economy when using only one engine for cruising, and limp-home capability in case one engine shuts down.

Regarding future prime mover evolutions for locomotive applications, one possibility being researched is the Homogeneous Charge Compression Ignition (HCCI) engine. It is an alternate piston engine combustion process that exhibits high, diesel-like efficiencies while producing ultra-low NOx and PM. The HCCI combustion process uses a dilute, premixed homogeneous air-fuel charge that reacts and burns volumetrically throughout the cylinder as it is compressed by the piston. The combustion occurs simultaneously throughout the volume as contrasted to the flame front that occurs in diesel compression ignition and combustion. This attribute of HCCI allows combustion to occur at much lower temperatures with a concomitant significant reduction of NOx and PM. The principal technological challenge for the perfection of HCCI is control of the combustion over the whole of the engine operating range up to high loads, with other challenges being multi-cylinder fueling consistency, cold-start capability and relatively high emissions of HC and CO. Tactics to address these challenges include extensive use of sensors, variable compression ratio, variable valve timing and tailoring a fuel to better match the characteristics of HCCI.

8.0 LOCOMOTIVE EMISSIONS REDUCTION PROGRAM FOR THE CANADIAN RAILWAY SECTOR

The U.S. EPA emission standards are, in reality, technology enablers that are pushing the technological frontier of engine combustion, particularly the medium-speed diesel engine, which is ubiquitous in North America. While no legislated standards exist in Canada for locomotive emissions, the EPA standards do affect the Canadian railway sector, albeit not in a jurisdictional sense. As already mentioned, they are the defacto technical standards for Canadian railways considering purchase of new locomotives due to the fact that the equipment and operating context of Canadian railways are highly integrated with those of their American counterparts. The U.S.-based OEMs are embarking upon a major development program, the results of which will cascade to the Canadian railway sector.

Reflecting the fact that fuel is a significant part of railway operation expenses and that the railways would inherently be reluctant to buy into an emissions reduction regime that ends up causing an increase in fuel consumption, the U.S. Department of Energy (DOE) has defined a US$105 million initiative for the railway sector aimed at developing "Energy Efficient Technology within a Regulated Environment" (21). This will be initiated in concert with the AAR and OEMs and use the resources of several public, private and academic organizations. It would appear that organizations in the Canadian railway sector could contribute technological solutions and undertake testing and evaluation programs in collaboration with the U.S. program. The collaboration with the U.S. program would be a cost-effective way to lever Canada R&D resources and appears in line the document tabled 25 February 2003 in the House of Commons by the Minister of Transport entitled *Straight Ahead - A Vision for Transportation in Canada,* which includes on its page 8 the statement "Transport Canada will promote innovation in transportation by supporting the development and implementation of advanced technologies to support environmental sustainability" (22).

Benefits would accrue to the Canadian railways as well as those organizations that could become participants in the ensuing research, development, testing and evaluation activities. Based on the outlook described in this report, proposed herein is a five-year emissions reduction development program aimed at helping the Canadian railway sector satisfy a combination of the following factors:

a) more stringent locomotive and locomotive engine emission standards;
b) compliance with Canada's commitments to the Kyoto Protocol on Climate Change;
c) minimization of negative health effects for railway personnel and the general public;
d) inducing environmentally sensitive innovation across the railway sector; and
e) ensuring that energy conservation, economic viability and sustainability prevail.

It is envisaged that the program would be led by industry with related assistance and co-financing provided by governmental agencies. The constituents of the Canadian railway sector having an interest in such a program include, inter alia, mainline and regional railways, OEMs, re-manufacturers and overhaul facilities, after-service parts suppliers, testing establishments, fuel and lubricant suppliers, environmental agencies and regulators, innovation and research organizations, academic institutions, consulting groups, employee and industry associations, and public advocacy groups. Through the stimulus of the program's funding, the Canadian railway sector is expected to:

a) realize a net reduction in emissions per locomotive operating in Canada;
b) harmonize equipment capability and emissions compliance with U.S. standards;
c) maintain the value of locomotive assets marketable throughout North America;
d) develop a cadre of expertise for the creation of new knowledge, information and data related to emissions, particularly to establish cost-benefit rationales;
e) establish testing facilities and related capability to ensure sustainable compliance;
f) develop and commercialize new products and processes; and
g) accrue kudos from the public as an environmentally friendly mode of choice.

The OEMs appear to have marshaled their own resources to attain Tier 2. It is for the challenge of achieving Tier 3 and Tier 4 levels over the coming decade that the U.S. DOE has initiated planning for a Locomotive Emissions Reduction R&D Program to assist the U.S. railway sector. The initiative outlined herein presumes that a Canadian program will complement and dovetail with the U.S. DOE program and, at the same time, seed opportunities for Canadian organizations to participate in the DOE program. Preferably, the programs would be implemented jointly, following appropriate consultations.

8.1 Envisaged Scope of Program

The principal activities that the program could encompass include:

a) **Program Management / Interaction with U.S. DOE Program:** This activity would focus on ensuring the smooth implementation of the Canadian program, that its thrust would complement the U.S. DOE program and that the resources are applied, utilized and accounted for appropriately. It would be guided by a stakeholders' Advisory Council.

b) **Setting Targets for Emissions Reduction in Canadian Railway Sector:** This activity is envisaged to be a secretariat function that assembles the information and data to establish the emissions targets for compliance by the Canadian railway sector. These targets will be the goals motivating the technology development and innovation elements to be implemented within the framework of the program.

c) **Baseline Measurement Action:** This would involve building a database by measuring the emissions of locomotives representative of the Canadian fleet, their duty cycles, fuel quality and operational exigencies in the Canadian climate. This could include equipping test facilities to comply with new EPA norms.

d) **Survey and Assessment of Applicable Emissions Reduction Technology:** This would entail assembling a database on relevant technologies existing, or under development, worldwide and benchmarking them vis-a-vis the emissions goals for Canada.

e) **Reinforcing the Infrastructure to Test and Measure Emissions Compliance:** This thrust is to ensure that there are Canadian test facilities with support capability that are accredited to measure the full range of emissions variables.

f) **Research and Development of New Technology and Processes:** An expectation of the program is new technologies for emissions reduction / energy efficiency that would be proprietary to Canadian companies (such as dynamic braking waste heat recovery and conversion, enhanced intercooling, etc.). The program would interact with federal innovation funding agencies such as, inter alia, National Research Council Canada's Industrial Research Assistance Program, Technology Partnerships Canada, Natural Resources Canada's Program for Energy R&D and the Technology Early Action Measures component of its Climate Change Action Fund, and Transport Canada's Freight Sustainability Development Program.

g) **Operational Trials to Evaluate New Emissions Reduction Technology and Fuels:** This would involve evaluating (in both controlled test cell conditions and actual railway operations) new technologies and alternate fuels having the potential to reduce both emissions and energy consumption, and contribute to energy sustainability.

h) **Data Gathering, Monitoring and Reporting Actions:** This activity entails the gathering on a macro-scale of operational experience with new emissions reduction technologies.

i) **Development of Human Resources Knowledgeable on the Subject:** This activity would have interaction with university and technical institutes to ensure a supply of expertise to support the overall emissions development program and thrust.

j) **Transmission and Diffusion of Knowledge Generated:** An important function to ensure the effectiveness of the program and that it yields benefits is to have an activity dedicated to awareness generation, information distribution and advisory services provision among the sector constituents and the country as a whole.

k) **Enhancing Innovation by Identifying Sustainable Financing, Outputs and Markets:** This function covers a wide range of strategies, tactics and policy inputs aimed at facilitating and promoting investment by the program constituents and country as a whole in railway locomotive emissions reduction technology. This includes, inter alia, measures such as tax incentives, incentives to assimilate technology transfer, venture capital initiatives, emissions credits and trading,

8.2 Resource Requirements to Mount Program

It is recommended that co-funding by Canadian governmental agencies be of the order of $5 million for a total Canadian effort of $10 million over five to seven years. This is about one tenth of the planned U.S. DOE initiative of US$105 million (based on the usual 10:1 ratio of overall population and relative locomotive fleet and economy sizes). This core funding would be used primarily for financing specific projects implemented on a competitive basis within the framework of the program elements identified in Item 8.1 a) above. Administrative costs should be kept within 5 percent of the total, with key staff seconded from organizations that will cover their salaries and office space. In-kind contributions could be in lieu of funding.

8.3 Suggested Administrative Structure

Two possible administrative structures are envisaged depending on the degree to which the Canadian-side and American-side emissions reduction programs are integrated, or separated:

a) **Integrated Cross-border Program:** This structure would be modeled after the cross-border 10-year, US$10 million Track-Train Dynamics program coordinated from 1975 to 1985 by the AAR with sponsorship from the U.S. Department of Transportation's Federal Railroad Administration, the RAC and Transport Canada. Transport Canada's Transportation Development Centre provided the coordination secretariat and co-funding of Canadian-side projects. Projects were implemented with specific technology developers and operating railways on a cost-shared, case-by-case basis.

b) **Separate Programs with Regular Consultations:** This structure would be modeled after sectoral R&D coordination organizations that receive lump-sum funding for an extended period from the federal government and stakeholders and, in turn, allocate the funds on a competitive basis to organizations developing technologies. Examples of such organizations are PRECARN (Pre-Competitive Advanced Research Network) for advanced manufacturing R&D or CANARIE (Canadian Network for Applied Research for Industry and Education) for Information Highway technologies. Consultations occur with international counterparts but there is no joint funding of projects, the solving of Canadian problems being the focus.

9.0 CONCLUSIONS

a) Despite the absence of legislated locomotive emissions standards in Canada, the U.S. EPA standards are, in reality, the technology enablers that are yielding environmental benefits to Canada because they are pushing the technological frontier of medium-speed engines, which are ubiquitous as locomotive prime movers in North America. To date, these railway locomotive prime movers have not been subjected to anywhere near the R&D effort that has been applied to automotive diesel engines to reduce harmful emissions and improve fuel efficiency.

b) EPA-certified kits developed by the OEMs and certain re-manufacturers are now available for retrofitting into pre-2001 manufactured Canadian locomotives so as to meet Tier 0 emissions limits when next rebuilt (generally every five to seven years). There are two categories of kits available:
   i) those that achieve Tier 0 limits by retarding the timing of the fuel injection and, as a result, create a fuel penalty; and
   ii) those that achieve Tier 0 limits without fuel penalties through a combination of timing retarding, improving the effectiveness of intercoolers to reduce the intake air temperature, and upgrading the various in-cylinder components, particularly the fuel injectors and piston crown shape.

c) The OEMs have been successful in achieving Tier 1 emissions limits in post-2000 freshly manufactured locomotives, with GETS announcing that its GEVO™ 4,500 hp, 12-cylinder engine already meets the Tier 2 limits to come into effect 1 January 2005. GETS also announced that, in addition, this engine yielded a 3 percent improvement in fuel consumption.

d) The EPA is expected to promulgate more stringent Tier 3 and Tier 4 emissions standards later this decade. The principal technical challenge will be to meet the emissions standards without fuel penalties and, preferably, with a minimum of after-treatment add-ons for which there is limited space on board a locomotive.

e) The EPA emissions standards and related initiatives in the U.S. have had, and will continue to have, an impact on the Canadian railway sector. To underpin Canadian positioning to keep pace with such actions in the U.S. and the possibility of similar regulatory actions promulgated in Canada, there appears to be the need for a well-coordinated "Locomotive Emissions Reduction Program for the Canadian Railway Sector" as proposed in Section 8.0 of this report.

f) As fuel cost is of the order of 10 percent of their operating expenses, North American railways are reluctant to buy into an emissions reduction regime that ends up causing an increase in fuel consumption. Recognizing this, the U.S. Department of Energy has defined a US$105 million program aimed at developing "Energy Efficient Technology within a Regulated Environment" to be undertaken in concert with the AAR and OEMs and using resources of several public, private and academic organizations. The results of this initiative will cascade to the Canadian railway sector and benefit the country as a whole. It would appear that organizations in Canada could contribute technological solutions and undertake testing and evaluation programs in collaboration with U.S. activities. Such an initiative appears to be in line with the Canadian government's initiatives for a "safe and secure, efficient and environmentally responsible transportation system", as set out in the document tabled 25 February 2003 in the House of Commons by the Minister of Transport entitled *Straight Ahead - A Vision for Transportation in Canada,* which includes on its page 8 the statement "Transport Canada will promote innovation in transportation by supporting the development and implementation of advanced technologies to support environmental sustainability".

10.0 RECOMMENDATIONS

In view of the significant cross-border interaction between the Canadian and U.S. railway sectors and their regulatory governance, it is recommended that steps be taken for the Canadian railway sector to:

a) maintain active monitoring and information dissemination actions to ensure that the Canadian railway operating, supplier and technology sectors are informed about the developments and opportunities stemming from the U.S. Department of Energy's US$105 million program aimed at developing "Energy Efficient Technology within a Regulated Environment".

b) undertake consultations and convene a workshop regarding consensus on the merit of, and implementation strategy for, a "Locomotive Emissions Reduction Program for the Canadian Railway Sector" as proposed in Section 8.0 of this report. This could fit within the context of the vision for an energy-efficient, environmentally sustainable transportation system as set out in the Transport Canada document *Straight Ahead - A Vision for Transportation in Canada.*

c) implement activities and arrange resources for Canadian organizations to participate in the R&D tasks of the U.S. programs being initiated to advance the technology of locomotives and their medium-speed diesel engines so as to further improve the energy efficiency and reduction of emissions harmful to humans and the environment.

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Bibliographic Survey of Internet Literature on Diesel Emissions Reduction for Locomotives

Several hundreds of pages of information were scanned electronically. The pages are filed under the following generic and specific titles and may be referenced by contacting the library of the Transportation Development Centre.

Volume I:	Commercial and Technological Solutions
Volume II:	Technology Updates from DieselNet
Volume III:	California Air Resources Board
Volume IV:	California Air Resources Board - Moyer Program
Volume V:	Associations and Governments
Volume VI:	California Air Resources Board Risk Management for Stationary Engines - Appendices 1-5

INFORMATION WORKSHOPS ATTENDED

In the course of undertaking this study, four workshops were attended by the author wherein sessions focused on the EPA locomotive emissions standards and energy efficiency in railway locomotives and operations.

Date	Place	Event	Convened by
April 2000	San Antonio Texas	Internal Combustion Engine Conference	American Society of Mechanical Engineers
January 2001	Argonne Illinois	Locomotive Emissions and System Efficiency Workshop	U.S. Department of Energy
March 2002	Montreal Quebec	Workshop on Locomotive Emissions	Transportation Development Centre of Transport Canada
September 2002	New Orleans Louisiana	Internal Combustion Engine Conference	American Society of Mechanical Engineers

APPENDIX A

LISTING OF RETROFIT KITS

CERTIFIED TO EPA TIER 0

Remanufacturing Kits Certified to Tier 0 (as of October 23, 2002)						
Mfr	**Engine Family**	**Certificate**	**Loco. Models**	**Locomotive MY**	**Emissions Standards***	**Remanufacture System:**
GE	1GETK0668EFB	GET-LOC-01-02	9-44-CW, 9-40-CW, 9-44-BW, 9-40-BW, AC-44-CW, AC-40-CW	1993-2000	LH FEL NOx=9.0; PM=0.44 SL FEL NOx=11.9;PM=0.54	injection pump, fuel injector, turbocharger, ECM & software, intercooler, short power assembly, and piston assembly
GE	1GETK0668EFB	GET-LOC-01-02.1	9-44-CW, 9-40-CW, 9-44-BW, 9-40-BW, AC-44-CW, AC-40-CW	1993-2000	LH FEL NOx=9.0 SL FEL NOx=11.9	injection pump, fuel injector, turbocharger, ECM, intercooler, short power assembly, piston assembly, and ECU software
GE	1GETK0668EFB	GET-LOC-01-02.2	9-44-CW 9-40-CW 9-44-BW 9-40-BW AC-44-CW AC-40-CW 8-40-CW	1993-2000	LH FEL NOx=9.0 SL FEL NOx=11.9	injection pump, fuel injector, turbocharger, ECM & software, intercooler, short power assembly, and piston assembly
GE	1GETK0959EFB	GET-LOC-01-04	AC-60-CW	1994-2000	LH FEL NOx=8.8; SL FEL NOx=11.0	injection pump, fuel injector, turbocharger, ECM & software, intercooler, upper power assembly, piston assembly
GE	2GETK0668EFB	GET-LOC-02-02	9-44-CW 9-40-CW 9-44-BW 9-40-BW AC-44-CW AC-40-CW 8-40-CW	1993-2001	LH FEL NOx=9.0 SL FEL NOx=11.9	injection pump, fuel injector, turbocharger, ECM, EGU software, intercooler, short power assembly, and piston assembly
GE	2GETK0668MFA	GET-LOC-02-03	8-40-CW, 8-40-C, 8-40-BW, 8-40-B, 8-41-CW, 8-41-BW, 8-39-C, 8-39-B	1973-1994	Tier 0	injection pump, fuel injector, turbocharger, intercooler, short power assembly, piston assembly, and camshaft sections
GE	2GETK0645MFA	GET-LOC-02-04	SD40-2 645E3, SD40 645E3, GP40-2 645E3, GP40 645E3, SD40-2 645E3B, SD40 645E3B, GP40-2 645E3B, GP40 645E3B, SD40-2 645E3C, SD40 645E3C, GP40-2 645E3C, GP40 645E3C, GP50 645F3B, and SD50 645F3B	1973-1985	LH FEL NOx=13.5 SL FEL NOx=17.0	fuel injector, turbocharger, aftercooler, power assembly, governor, camshaft

Remanufacturing Kits Certified to Tier 0 (as of October 23, 2002)						
Mfr	**Engine Family**	**Certificate**	**Loco. Models**	**Locomotive MY**	**Emissions Standards***	**Remanufacture System:**
GE	2GETK0645MSA	GET-LOC-02-04	SD38, GP38, SD38-2, AND GP38-2 all with 645E	1973-1985	SL FEL NOx=18.0	fuel injector, power assembly, blower, blower drive gears, camshafts, governor
GE	2GETK0959EFB	GET-LOC-02-06	AD-60-CW	1994-2001	LH FEL NOx=8.8 SL FEL NOx=11.0	injection pump, fuel injector, turbocharger, ECM, ECU software, intercooler, upper power assembly, and piston assembly
Hatch &Kirk	2KBIK0645E3A	KBI-LOC-02-01	SD40, GP40, SD40-2, GP40-2, SD45, SD45-2 all with 645-E3	1972-1986	Tier 0	fuel injector, any turbocharger capable of 18 psi min, cylinder liner, piston, required valve timing setting, two 4-pass aftercoolers
GMC	YGMXK0710EJ0	GMX-LOC-00-03	SD70MAC (codes 92115 & 92111) SD75I (codes 92120 & 92128) SD70, SD70M, SD75M	1994-1997	Tier 0	emissions labels & ECM software
GMC	1GMXK0710ES1	GMX-LOC-01-02	SD70MAC	1994-1997	Tier 0	emission labels and ECM software
GMC	1GMXK0710ES2	GMX-LOC-01-04	SD90MAC/43 SD80MAC	1994-1997	Tier 0	emissions labels & ECM software
GMC	1GMXK0710EJ0	GMX-LOC-01-06	SD70MAC (codes 92115 & 92111) SD75I (codes 92120 & 92128) SD70, SD70M, SD75M	1994-1997	Tier 0	emissions labels & ECM software
GMC	1GMXK0710MJ0	GMX-LOC-01-08	SD70M, GP60, SD60M, SD70MAC	1994-1997	Tier 0	emission labels, Falcon or EM2000 computer software & sixteen injectors
GMC	2GMXK0710MJ0	GMX-LOC-02-02	SD70 & SD70MAC	1994 - 1997	LH FEL PM=0.31; SL FEL NOx=12.0;PM=0.29	Emission labels, locomotive controller software, fuel injectors, turbocharger, governor, aftercooler core, power assembly (mini-pack)

Remanufacturing Kits Certified to Tier 0 (as of October 23, 2002)						
Mfr	**Engine Family**	**Certificate**	**Loco. Models**	**Locomotive MY**	**Emissions Standards***	**Remanufacture System:**
GMC	2GMXK0710MJA	GMX-LOC-02-03	GP59, GP60, GP60B, GP60M, SD60, SD60I, SD60M w/ 12-710G3A & 16-710G3A	1985 - 1993	LH FEL NOx=8.7; SL FEL NOx=10.2; PM=0.40	Emission labels, fuel injectors, R.bank aftercooler pipes, timing plate, turbocharger, governor, aftercooler core, piston, piston ring set, cyl. liner, cyl. head assem.
GMC	2GMXK0710EJ0	GMX-LOC-02-04	SD70, SD70M, SD70MAC, SD75I, SD75M w/ 16-710G3B-EC & 16-710G3C-EC	1994 - 1997	SL FEL NOx=10.9	Emission labels, ECM software, ECM, fuel injectors, turbocharger, aftercooler assem., power assembly (mini-pack).
GMC	2GMXK0710ES1	GMX-LOC-02-05	SD70MAC, SD75IAC w/ 16-710G3B-ES & 16-710G3C-ES	1996 - 1999	SL FEL NOx=11.0	Emission labels, ECM software, ECM, fuel injectors, turbocharger, aftercooler core, power assembly (mini-pack).
GMC	2GMXK0710ES2	GMX-LOC-02-06	SD80MAC w/ 20-710G3B-ES and SD90MAC/43 w/ 16-710G3C-ES	1996 - 1999	SL FEL NOx=9.5; SL FEL PM=0.38	Emission labels, ECM software, ECM, fuel injectors, turbocharger, aftercooler core, power assembly (mini-pack).
GMC	2GMXK0645E3B	GMX-LOC-02-07	GP39-2 havingengine12B645E3B and GP40-2 and SD40-2 having engine model 16B645E3B	1973 -1985	SL FEL NOx=12.5	emission control labels, fuel injectors, four-pass aftercooler, pistons, inlet and outlet pipe replacements for the right-bank aftercooler, turbocharger, governor, governor translator module, cylinder liner, piston ring set, cylinder head assembly
GMC	2GMXK0645EBL	GMX-LOC-02-08	SW1000 and SW1001 having engine 8 B645E; SW1500, MP15, MP15DC, MP15AC, GP15-1, and GP15-2 having engine 12B645E; and, GP38-2 and SD38-2 having engine 16-645E	1973 -1985	Tier 0	emission control labels, fuel injectors, scavenging blower assembly, governor, pistons, cylinder liners, piston ring sets, cylinder head assembly
GMC	2GMXK0645ESW	GMX-LOC-02-09	SW1000 and SW1001 having engine 8 B645E; SW1500, MP15, MP15DC, MP15AC, GP15-1, and GP15-2 having engine 12B645E; and, GP38-2 and SD38-2 having engine 16-645E	1973 -1985	Tier 0	emission control labels, fuel injectors, scavenging blower assembly, governor, pistons, cylinder liners, piston ring sets, cylinder head assembly

Remanufacturing Kits Certified to Tier 0 (as of October 23, 2002)

Mfr	Engine Family	Certificate	Loco. Models	Locomotive MY	Emissions Standards*	Remanufacture System:
GMC	2GMXK0645EAL	GMX-LOC-02-10.1	SW1000 and SW1001 having engine 8 B645E; SW1500, MP15, MP15DC, MP15AC, GP15-1, and GP15-2 having engine 12B645E; and, GP38-2 and SD38-2 having engine 16-645E	1973 -1985	SL FEL NOx=9.5	Emission control labels, fuel injectors, oil separator element, scavenging blower assembly, governor, pistons, cylinder liners, piston ring sets, cylinder head assembly
GMC	2GMXK16.5ES2	GMX-LOC-02-11	SD90MAC having engine GM16V265H	1998 - 2000	SL FEL NOx=9.5; SL FEL PM=0.34 LH FEL PM = 0.34	Software, camshaft drive gear, pump and injector assemblies, emission control labels, turbocharger, ECM, aftercooler, pistons, piston rings, cylinder liners, cylinder head
GMC	2GMXK0645F3B	GMX-LOC-02-13	GP40X, GP49, GP50, SD40X, and SD50 having engines 645F3, 645F3A and 645F3B	1978 - 1985	SL FEL NOx=12.0	Fuel injectors, 4-pass aftercoolers, right-bank aftercooler water inlet & outlet pipes, emission control labels, turbocharger, governor, pistons, piston ring sets, cylinder liners and head assembly.
GMC	2GMXK0645E30	GMX-LOC-02-14	GP39-2, GP40-2, GP40P-2, SD40-2, SD40T-2, SD40F, SDP40F, SD45-2, and SD45T-2 having engines 12-645E3, 16-645E3 or 20-645E3	1973 - 1979	SL FEL NOx=12.0 LH FEL NOx=9.1	Fuel injectors, 4-pass aftercoolers, right-bank aftercooler water inlet & outlet pipes, emission control labels, turbocharger, governor, pistons, piston ring sets, cylinder liners & head assembly
CSX	2CSXK645E00A	CSX-LOC-02-01	EMD GP38-2 w/ 16-645E	1973 - 1980	Tier 0	Fuel injectors, Blower, Power assemblies, Governor, & Auxiliary Power Unit
CSX	2CSXK0645E3A	CSX-LOC-02-02	EMD GP40-2 & SD40-2 w/ 16-645E3	1973 - 1981	Tier 0	Injection timing of 4° ATDC, timing plate, Fuel injectors, Turbocharger, Power assemblies, Governor, Camshafts, Aftercooler, Auxiliary Power Unit
CSX	2CSXK0645E3B	CSX-LOC-02-03	EMD GP40-2 & SD40-2 w/ 16-645E3B	1973 - 1981	Tier 0	Injection timing of 4° ATDC, timing plate, Fuel injectors, Turbocharger, Power assemblies, Governor, Camshafts, Aftercooler, Auxiliary Power Unit
CSX	2CSXK0645E3C	CSX-LOC-02-04	EMD GP40-2 & SD40-2 w/ 16-645E3C	1973 - 1981	Tier 0	Injection timing of 4° ATDC, timing plate, Fuel injectors, Turbocharger, Power assemblies, Governor, Camshafts, Aftercooler, Auxiliary Power

Remanufacturing Kits Certified to Tier 0 (as of October 23, 2002)					
					Unit

Remanufacturing Kits Certified to Tier 0 (as of October 23, 2002)						
Mfr	**Engine Family**	**Certificate**	**Loco. Models**	**Locomotive MY**	**Emissions Standards***	**Remanufacture System:**
CSX	2CSXK0645E3M	CSX-LOC-02-05	EMD GP40-2 & SD40-2 w/ 16-645E3M	1973 - 1981	Tier 0	Injection timing of 4° ATDC, timing plate, Fuel injectors, Turbocharger, Power assemblies, Governor, Camshafts, Aftercooler, Auxiliary Power Unit
CSX	2CSXK0645F3B	CSX-LOC-02-06	EMD SD50 w/ 16-645F3B	1983 - 1985	Tier 0	Injection timing of 4°ATDC, timing plate, fuel injectors, turbocharger, power assemblies, governor, camshafts, aftercooler, auxiliary power unit
CSX	2CSXK0645E20	CSX-LOC-02-07.1	EMD GP38-2S & SD38-2S w/ 16-645E2	1973 - 1981	Tier 0	Injection timing of 3°ATDC, timing plate, Fuel injectors, Turbocharger, Power assemblies, Governor, Camshafts, Auxiliary Power Unit
CSX	2CSXK0645E00	CSX-LOC-02-08.1	EMD SW1001, SW1500, GP15-1, MP15, MP15AC, GP38-2, & SD38-2 w/engine 8->, 12->, or 16-645E	1973 - 1981 (various)	Tier 0	Injection timing of 4°BTDC, timing plate, fuel injectors, blower, power assemblies, governor (no APU)
CSX	2CSXK0645E21	CSX-LOC-02-09	EMD GP38-2S & SD38-2S w/ 16-645E2	1973 - 1981	Tier 0	Injection timing of 3°ATDC, timing plate, Fuel injectors, Turbocharger, Power assemblies, Governor, Camshafts, (no APU)
CSX	2CSXK0710GBM	CSX-LOC-02-10	EMD GP60 & SD60 w/ 16-710G3B	1989 - 1995	Tier 0	Auxiliary power unit, injection timing of 3°ATDC, timing plate, fuel injectors, turbocharger, power assemblies, governor, camshafts, aftercooler
CSX	2CSXK0710GB0	CSX-LOC-02-11	EMD models GP60 and SD60 having engine 16-710G3B	1989 - 1995	Tier 0	engine timing change and timing plate, injection timing of 4 degrees ATDC, fuel injectors, turbocharger, power assemblies, governor, camshafts, aftercooler
CSX	2CSXK0710EC1	CSX-LOC-02-12	EMD models SD70M having engine 16-710G3B-EC	1995 - 1997	Tier 0	engine injection timing adapter, timing plate, auxiliary power unit, fuel injectors, turbocharger, ECM, power assemblies, aftercooler, camshafts
CSX	2CSXK0710EC2	CSX-LOC-02-13	EMD SD70M having engine 16-710G3B-EC	1995 - 1997	Tier 0	engine injection timing adapter and timing plate, fuel injectors, turbocharger, ECM, power assemblies, aftercooler, camshafts

Remanufacturing Kits Certified to Tier 0 (as of October 23, 2002)						
Mfr	**Engine Family**	**Certificate**	**Loco. Models**	**Locomotive MY**	**Emissions Standards***	**Remanufacture System:**
CSX	2CSXK0710ES1	CSX-LOC-02-14	SD70MAC having 16-710G3B-ES	1997-2000 mfr=d before 1/1/00	Tier 0	fuel injection timing adapter, fuel injectors, turbocharger, EMDEC, power assemblies, aftercooler, camshafts
CSX	2CSXK0710ES2	CSX-LOC-02-15	SD70MAC having 16-710G3B-ES	1997-2000 mfr=d before 1/1/00	Tier 0	fuel injection timing adapter, auxiliary power unit, fuel injectors, turbocharger, EMDEC, power assemblies, aftercooler, camshafts
CSX	2CSXK0645EC1	CSX-LOC-02-16	EMD GP15T & MP15T w/ 8-645E3C	1982	Tier 0	Injection timing = 4✍ATDC, timing plate, auxiliary power unit, fuel injectors, turbocharger, power assemblies, governor, camshafts, aftercooler
CSX	2CSXK0645EC2	CSX-LOC-02-17.1	EMD GP15T & MP15T w/ 8-645E3C	1982	Tier 0	Injection timing = 3✍ATDC, timing plate, fuel injectors, turbocharger, power assemblies, governor, camshafts, aftercooler (no APU)

APPENDIX B

DESCRIPTION OF EMISSIONS KIT FOR GM EMD 645 E3B - 12 CYLINDER ENGINE MEETING EPA TIER 0 WITH NO NEGATIVE EFFECT ON FUEL EFFICIENCY

EMISSIONS KIT

Model: **645 E3B - 12 Cylinder**

ELECTRO-MOTIVE
General Motors

Part Number: **40101545**

Application: This kit is designed to be used on locomotives equipped with a 12 cylinder 645 E3B engine and used in freight line service applications.

Kit Content:

- 12 - Utex Emissions Injectors
- 12 - Emissions Pistons
- 1 - Locomotive Emissions Label
- 1 - Engine Emissions Label
- 1 - Installation Instruction ETI 1517
- 2 - 4 Pass Aftercoolers
- 2 - Counter Flow Pipes
- 1 - Hardware Kit
- 2 - Label Laminate Covers
- 1 - Kit Registration Card

Benefits: This emissions kit is an environmentally friendly retrofit which provides a 34% reduction in the amount of nitrous oxides emitted, 2.5% reduction in hydro carbon, and 37%in carbon emissions as well. The introduction of a new emissions piston for this kit results in no negative effects on fuel efficiency. With the application of this kit, the locomotive achieves full compliance with EPA Tier 0 regulation 40 CFR Part 92.

Availability: Please contact your EMD Customer Service Representative

List Price: $31,650.00

APPENDIX C

DESCRIPTION OF EMISSIONS KIT FOR

GM EMD 645 E3 - 8 CYLINDER ENGINE

MEETING EPA TIER 0 AND WITH A

2% GAIN IN FUEL EFFICIENCY

EMISSIONS KIT

ELECTRO-MOTIVE
General Motors

Model: **645 E - Switch 8 Cyl.**

Part Number: **40101537**

Application: This kit is designed to be used on locomotives equipped with a 8 cylinder 645 E engine and used in switcher service applications only.

Kit Content:

- 8 - Utex Emissions Injectors
- 1 - Locomotive Emissions Label
- 1 - Engine Emissions Label
- 2 - Label Laminate Covers
- 1 - Installation Instruction ETI 1514
- 1 - Kit Registration Card

Benefits: This emissions kit utilizes special emissions injectors to achieve compliance and generate 2% fuel savings. The reduction in nitrous oxides, particulate matter and smoke makes this kit an environmentally friendly retrofit. With the application of this kit, the locomotive achieves full compliance with EPA Tier 0 regulation 40 CFR Part 92.

Availability: Please contact your EMD Customer Service Representative

List Price: $18,750.00

APPENDIX D

DESCRIPTION OF EMISSIONS KITS FOR

GM EMD 645 E AND 710GB - 16 CYLINDER ENGINES

MEETING EPA TIER 0, BUT WITH A

FUEL CONSUMPTION PENALTY

ELECTRO-MOTIVE
General Motors

EMISSIONS KIT

Model: **645 E - 16 Cylinder**

Part Number: 40100278

Application: This kit is designed to be used on locomotives equipped with a 16 cylinder 645 E engine and used in freight line service applications.

Kit Content:

16 - Utex Emissions Injectors
1 - Enhanced Oil Separator Element
1 - Locomotive Emissions Label
1 - Engine Emissions Label
2 - Label Laminate Covers
1 - Installation Instruction ETI 1515
1 - Kit Registration Card

Benefits: This emissions kit is an environmentally friendly retrofit which provides a 24.5% reduction in the amount of Nitrous Oxides emitted and over 30% reductions in Hydro Carbon and Carbon emissions as well. With the application of this kit, the locomotive achieves full compliance with EPA Tier 0 regulation 40 CFR Part 92.

Availability: Please contact your EMD Customer Service Representative

List Price: $22,750.00

ELECTRO-MOTIVE
General Motors

EMISSIONS KIT

Model: 710GB MUI - 16 Cyl SD70MAC

Part Number: **40088688**

Application: **This kit is designed to be used on locomotives originally equipped with a 16 cylinder 710 GB mechanically injected engine delivered on SD70MAC locomotives and used in freight line service applications.**

Kit Content:

- **1 - EM2000 Software Upgrade**
- **1 - Locomotive Emissions Label**
- **1 - Installation Instruction ETI 1509**
- **2 - Label Laminate Covers**
- **2 - Engine Emissions Label**
- **1 - Kit Registration Card**

Benefits: **This emissions kit is an environmentally friendly retrofit which provides a reduction in the amount of nitrous oxides, hydro carbon, particulate matter, and carbons emitted.. With the application of this kit, the locomotive achieves full compliance with EPA Tier 0 regulation 40 CFR Part 92.**

Availability: **Please contact your EMD Customer Service Representative**

List Price: **$17,415.00**

EMISSIONS KIT

Model: **710GB EUI - 16 Cyl**
SD90MAC/43 (SLAC)

Part Number: **40088685**

Application: **This kit is designed to be used on locomotives delivered on UP orders #936449 and #956613. These locomotives were originally equipped with a 16 cylinder 710 GC electronically injected engine delivered on SD90MAC/43 locomotives having separate loop after cooling. These kits are used for freight line service applications only.**

Kit Content:

- **1 - EmdecSoftware Upgrade**
- **1 - Locomotive Emissions Label**
- **1 - Installation Instruction ETI 1512**
- **2 - Label Laminate Covers**
- **2 - Engine Emissions Label**
- **1 - Kit Registration Card**

Benefits: **This emissions kit is an environmentally friendly retrofit which provides a reduction in the amount of nitrous oxides, hydro carbon, particulate matter, and carbons emitted.. With the application of this kit, the locomotive achieves full compliance with EPA Tier 0 regulation 40 CFR Part 92.**

Availability: **Please contact your EMD Customer Service Representative**

List Price: **$20,100.00**

EMISSIONS KIT

Model: 710GB EUI - 16 Cyl
SD90MAC/43 (SLAC)

Part Number: 40088687

Application:

This kit is designed to be used on locomotives delivered on UP orders #966714 and #976800. These locomotives were originally equipped with a 16 cylinder 710 GC electronically injected engine delivered on SD90MAC/43 locomotives having separate loop after cooling. These kits are used for freight line service applications only.

Kit Content:

1 - EmdecSoftware Upgrade	2 - Label Laminate Covers
1 - Locomotive Emissions Label	2 - Engine Emissions Label
1 - Installation Instruction ETI 1512	1 - Kit Registration Card

Benefits:

This emissions kit is an environmentally friendly retrofit which provides a reduction in the amount of nitrous oxides, hydro carbon, particulate matter, and carbons emitted.. With the application of this kit, the locomotive achieves full compliance with EPA Tier 0 regulation 40 CFR Part 92.

Availability:

Please contact your EMD Customer Service Representative

List Price:

$20,100.00

APPENDIX E

LISTING OF FRESHLY MANUFACTURED LOCOMOTIVE ENGINES CERTIFIED TO EPA TIER 0

Summary Tables October 23, 2002

FRESH Locomotive Engines Certified to Tier 0						
Mfr	EPA Engine Family	Certificate	Locomotive MY	Locomotive	Engine	Emissions Standards*
GE	1GETG0668EFB	GET-LOC-01-01	2001			LH FEL NOx = 9.0; PM=0.44 SL FEL NOx=11.9; PM=0.54
GE	1GETG0668EFB	GET-LOC-01-01.1	2001			LH FEL NOx=9.0; SL FEL NOx=11.9
GE	1GETG0959EFB	GET-LOC-01-03	2001			LH FEL NOx=8.8; SL FEL NOx=11.0
GMC	1GMXG0710ES1	GMX-LOC-01-01	2001			B
GMC	1GMXG0710ES2	GMX-LOC-01-03	2001			B
GMC	1GMXG0710EJ0	GMX-LOC-01-05	2001			B
GMC	1GMXG0710MJ0	GMX-LOC-01-07	2001			B

* g/bhp-hr. LH = line haul. SL = switch locomotive

APPENDIX F

LISTING OF FRESHLY MANUFACTURED LOCOMOTIVE ENGINES CERTIFIED TO EPA TIER 1

Summary Tables October 23, 2002

FRESH Locomotive Engines Certified to Tier 1						
Mfr	EPA Engine Family	Certificate	Locomotive MY	Locomotive	Engine	Emissions Standards*
GE	2GETG0668EFB	GET-LOC-02-01	2002			Tier 1
GMC	1GMXG04.31EJ0	GMX-LOC-01-08	2001	GP15D, GP20D	Cat 3512B & 3516B	Tier 1
GMC	1GMXG04.31EJ0	GMX-LOC-01-09	2001	GP15D, GP20D	Cat 3512B & 3516B	LH FEL PM=0.16 SL FEL NOx=8.6; PM=0.23
GMC	2GMXG0710ES3	GMX-LOC-02-01	2002	SD70M, SD70MAC	710G3B-T1, 710G3C-T1	SL FEL NOx=8.8
GMC	2GMXG4.31EJ0	GMX-LOC-02-12	2002	GP15D, GP20D	Cat 3512B & 3516B	LH FEL PM=0.16 SL FEL NOx=8.6; PM=0.23

* g/bhp-hr. LH = line haul. SL = switch locomotive