Experience with High Performance AC Traction Diesel Locomotives on International Heavy Haul Railways

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Summary: High performance AC traction diesel locomotives from EMD have been in service in heavy haul railway operations in North America since 1993. More recently, EMD and two associates – EDI Rail in Australia and Indian Railways in India – have put high performance AC traction diesel locomotives into service at lower axle loads. In 1999, EMD began delivering AC traction locomotives designed for Indian Railways. These 3000 kW (4000 thp) locomotives are designed for 21-tonne (46,000 lb.) axle load and broad gauge track. In 2000, EDI Rail began delivering state-of-the-art AC traction locomotives to Queensland Rail in Australia. These 2250 kW (3000 thp) locomotives have an axle load of only 20 tonnes (44,000 lb.) and operate on narrow gauge track. These locomotives have demonstrated very high levels of wheel-rail adhesion, with dispatchable adhesion in the range of 32 to 39 percent and starting adhesion in the range of 43 to 50 per cent.

Index Terms: Diesel Locomotive, AC Traction, Wheel-Rail Adhesion

INTRODUCTION

After successfully introducing AC traction technology into heavy haul service in North America, Electro-Motive Division (EMD) of General Motors Corporation identified the advantages of this technology for international railways having lower axle loads. The basic advantages of AC traction technology included superior levels of wheel-rail adhesion along with improved traction motor reliability and durability associated with a simpler motor design. The challenge came in combining the power and performance of AC traction with the lighter axle loads required by the international railways. Successful application to this market has been achieved in the design, manufacture, and service of new GT46MAC locomotives for Indian Railways (IR) and new GT42CU/AC locomotives for Queensland Rail (QR) in Australia.

In 1999, a new generation of AC traction diesel locomotives designed for Indian Railways was put into service. By the end of 1999, IR had begun to assemble this new model in their own facilities using components supplied by EMD. The process of transferring technology to IR is continuing with the objective of manufacturing nearly all of the components locally in India. As described by Swenson [1], these high performance 3000kW (4000 thp – tractive horsepower) GT46MAC locomotives are designed for 21-tonne (46,000 lb.) axle load and broad gauge (1676 mm or 5 ft. 6 in.) track.

Thirteen GT46MAC locomotives, as pictured in Figure 1, were built in EMD's North American manufacturing facilities and were then put in service in India. Components and systems for an additional eight locomotives were supplied by EMD in the form of "Partial Knock Down" (PKD) kits. All of these kits have been assembled by IR into locomotives that are now in service. In addition, a technology transfer program is underway to enable IR to not only continue building these locomotives but to eventually manufacture or source nearly all the components locally in India and build the complete locomotive at Diesel Locomotive Works (DLW) in Varanasi, India.

In 2000, new, state-of-the-art GT42CU/AC locomotives were delivered to Queensland Rail in Australia by EDI Rail (formerly Clyde Engineering). As pictured in Figure 2 and described by Semple [2], these 2250 kW (3000 thp) locomotives develop tractive effort of 600 kN (135,000 lb.) but have an axle load of only 20 tonnes (44,000 lb.) and operate on narrow gauge (1067 mm or 3 ft. 6 in.) track.

Figure 1

EDI Rail, EMD's associate in Australia, received an order from QR in 1998 for thirty eight AC traction locomotives. In addition to AC traction, these locomotives use EMD's 12-cylinder, 710G3B engine. They also incorporate an ergonomically designed driver's cab and radial steering bogies. The locomotives were designed with a mechanically isolated driver's cab to provide very low interior noise levels under all operating conditions. The locomotives also incorporate special features for reduced fuel consumption including separate aftercooling of the diesel engine and multiple speed, electrically driven equipment ventilation blowers.

Both of these locomotive models in India and Australia use modern AC traction inverters and traction motors and have demonstrated very high levels of wheel-rail adhesion performance, with dispatchable adhesion in the range of 32 to 39 percent and starting adhesion in the range of 43 to 50 per cent.

MODERNIZATION OF INDIAN RAILWAYS

Indian Railways had signified its interest in investing in new diesel electric locomotive technology as early as the mid 1980s. At that time, its interest was in buying conventional DC technology to replace its aging fleet of diesel locomotives. While the initial discussions were focussed on DC traction technology, IR developed a strong interest in EMD's progress in developing AC traction technology and chose this technology to take advantage of its superior adhesion levels.

IR's confidence in the new technology was confirmed in 1996 with the signing of a 10-year technology transfer agreement to provide full manufacturing rights to EMD's GT46MAC locomotive and its passenger locomotive equivalent, the GT46PAC. Both powered by EMD's 16-cylinder, 3000 kW (4000 thp) 710G3B engine, these AC traction locomotives utilize high-efficiency turbochargers, simple but robust traction motor design, traction inverters derived from North American locomotives, and EM2000 locomotive computer systems complete with self diagnostics to provide greatly improved levels of operating reliability and serviceability. The 6-axle GT46MAC provides 540 kN (121,000 lb.) of tractive effort and 270 kN (61,000 lb.) of dynamic braking effort.

Figure 2

HEAVY HAUL ON NARROW GAUGE IN AUSTRALIA

The application of AC traction technology on Queensland Rail was unique because it was the first use of AC traction for a narrow gauge heavy haul railway. To maximize the performance of the locomotive, the traction motors were designed to make full use of the available space between the narrow gauge wheelsets. Siemens provided a special version of the model IBT2622 traction motors; EMD provided the roller bearing housings, traction gears and gearboxes. EDI Rail designed and manufactured the fabricated-frame radial steering bogie. Design reviews were held throughout the process to ensure the components being designed in three continents would fit together perfectly when they were finally assembled in Australia.

Another important aspect of the Australian locomotives is the high level of computer technology used on these locomotives. In addition to the traction inverters and EMD EM2000 locomotive computer system, the locomotives feature Integrated Cab Electronics (ICE), Integrated Distributed Power (IDP) from GE Harris, and Knorr CCBII electronic air brakes. To ensure that all of the electronic systems would function correctly in service, a complete integration test of the electronic systems was completed at EMD's Engineering facility prior to commissioning of the first locomotive in Australia.

The IDP system is used to remotely control locomotives in a train. This system is used extensively by QR for their coal operations. In several operations, the coal trains operate as "push-pull" trains with locomotives placed at either end of the train. A train can be driven into a coal mine and loaded, and then the crew can change to the locomotive at the opposite end of the train and drive to the port.

LOCOMOTIVE TEST PROGRAMS

The first Indian Railways GT46MAC underwent engineering tests at EMD and then underwent running tests at the Transportation Technology Center in Pueblo, Colorado. Its progress was followed closely by officials of IR who were a part of the design and planning process from the very beginning. Engineering personnel from Research Designs and Standards Organization (RDSO) and factory personnel from DLW became regular visitors at EMD facilities in LaGrange, Illinois, USA and London, Ontario, Canada.

For the tests in Pueblo, the GT46MAC locomotive was fitted with special wheelsets to enable this broad-gauge locomotive to be tested on standard-gauge track. The tests included vibration tests, bogie tests, load control tests, AC traction inverter tests, locomotive adhesion tests, control system tests, and air brake system tests.

An extensive test program was also conducted for the Queensland Rail GT42CU/AC locomotives. This included adhesion testing that was carried out in Australia to fine tune the traction control software. Exceptionally high adhesion levels were attained after only a short test period.

PERFORMANCE ON INDIAN RAILWAYS

When the first locomotives were shipped to India, additional tests were conducted on the broad-gage track of the Indian Railways to confirm the high performance of the GT46MAC design under actual operating conditions. Tests were conducted on the Hubli Division which has a challenging terrain with 1 in 100 gradients and curves of 350 m (1150 ft. or 5°) to 250 m (820 ft. or 7°).

Testing on dry rail demonstrated that the GT46MAC develops 43% adhesion for starting trains. Further testing during the monsoon season showed that the GT46MAC sustains 32% adhesion and pulls smoothly during very heavy rains. Understandably, some railway experts were initially skeptical that such a dramatic increase in useable adhesion was possible. However, it became clear that the heavy haul experience of North America regarding high adhesion levels could be translated to IR.

The biggest train on the IR system is based on siding length and on axle loads, i.e., 58 wagons with a total weight of 4750 tonnes (5240 tons). This size train is normally pulled by two 2300 kW (3100 thp) diesel locomotives. Now, this 58-wagon train is being pulled by one 3000 kW (4000 thp) GT46MAC locomotive.

At the same time, the railway rates its 4500 kW (6000 thp), 6-axle electric locomotive for 52 wagons or 4258 tonnes (4695 tons). The GT46MAC locomotive represents a dramatic increase in productivity and has validated the decision of the Indian Railway to invest in AC traction for the next generation of motive power.

Significant reduction in operating costs has also been demonstrated regarding diesel fuel consumption as 16 to 18% fuel savings has been realized. Indian Railways is expected to achieve long term savings due to the reduced maintenance requirements for the GT46MAC locomotives. The maintenance staff requirement per locomotive is currently estimated by the railway to be less than half that of current IR locomotives.

PERFORMANCE ON QUEENSLAND RAIL

Queensland Rail was interested in adopting the latest technology to improve the efficiency of its diesel haul coal operations as well as supplementing its electric locomotive fleet to handle peak demands. The Moura coal system utilizes diesel locomotives to haul 9.5 MTPA (million tonnes per annum). Unit trains of 4450 tonnes (4900 tons) are hauled by three EMD GL26-2 locomotives. The goal was to replace these unit coal trains with more productive and efficient ones within the crossing loop restraint. Using two new GT42CU/AC locomotives and a new wagon design, train tonnage of 6050 tonnes (6670 tons) has been achieved. This is a one for two replacement of locomotive power.

The Blackwater coal system is an electrified system carrying 31 MTPA. Four electric locomotives haul unit trains of 8080 tonnes (8900 tons). To supplement peak periods, three new GT42CU/AC locomotives are used to pull trains of 9150 tonnes (10,100 tons). This equates to a three for four replacement of the current electric locomotives. The new AC traction locomotives require much higher levels of adhesion for starting and to climb the ruling grade. In both operations, the GT42CU/AC locomotives are being dispatched at 37% all-weather adhesion every day.

The QR locomotives incorporate several features to minimize fuel consumption. The engines have electronic fuel injection and separate aftercooling. The auxiliary support systems incorporate multiple speed AC drive motors. The separate aftercooling system provides a cooling circuit for the turbocharger aftercooler system. This system permits lower combustion temperatures, which result in improved fuel economy and reduced exhaust emissions. For the QR locomotive, EMD developed a unique cooling system with double pass radiators to minimize the piping on the locomotive. Extensive testing was completed in Australia to optimize the performance of this system.

QR maintains accurate records of the fuel consumed and the coal hauled on each route that they operate. It is therefore possible to compare the ratio of coal moved and fuel consumed with the new locomotives and wagons and with the older locomotives and wagons. Preliminary data shows savings of at least 16 per cent with the new equipment.

Both EDI Rail and QR expect that wheel life will be extended for the new locomotives with radial steering bogies compared to the older locomotives with conventional bogies. A program for detailed monitoring of wheel wear is being implemented.

DC AND AC TRACTION DEVELOPMENT

While numerous railway experts have witnessed the very high adhesion levels presented in this paper, discussions of these high adhesion levels are still met with skepticism by railway people in some countries – including regions of the world where these levels of adhesion are achievable and could be effectively utilized. Why is this so? In some cases, the reason may be that the new technology is several generations ahead of existing technology, and the various incremental steps of progress have not been adequately understood. Therefore, it may be useful to briefly review this development history.

Figure 3 outlines the adhesion improvement story in terms of dispatchable adhesion associated with each new model developed for the North American heavy haul locomotive market. The EMD 40-2 Series locomotives built in the 1970s with 2250 kW (3000 thp), DC traction, and conventional wheel slip control, could be dispatched at 21% adhesion. The 50 Series locomotives, with 2650 kW (3500 thp) and DC traction, introduced wheel creep control and raised the dispatchable adhesion significantly to about 28% adhesion.

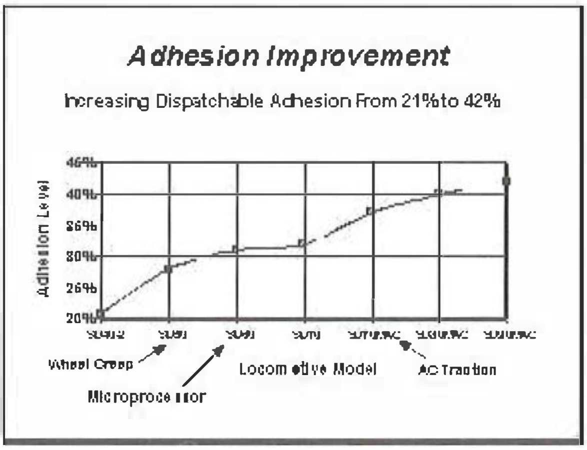

Figure 3

In 1985, EMD introduced the 60 Series locomotives with 2850 kW (3800 thp), DC traction, and microprocessor wheel creep control. This increased the dispatchable adhesion again, to about 31% adhesion. Then, in 1993, EMD introduced the 70 Series locomotives with 3000 kW (4000 thp), DC traction, and radial bogies, and the dispatchable adhesion was again increased.

Soon after that, EMD started production of the 70 Series locomotives with AC traction and then the 80 Series locomotives with AC traction, and the resulting field experience demonstrated dispatchable adhesion in the range of 35 to 40% adhesion. Finally, the 90 Series locomotives with 4500 kW (6000 thp), AC traction, radial bogies, and an advanced computer system, are targeted at 42% dispatchable adhesion so one of these locomotives can replace two 2250 kW (3000 thp) locomotives not only in power but also in tractive effort as well.

EMD first began research into AC traction in the late 1960s when several AC systems were designed and built for laboratory testing. The clear focus at that time was on applying new technology to the demanding needs of the heavy haul North American freight sector. In the mid-1980s, EMD and Siemens began to work closely together in the development of detailed requirements for such a system and to develop the accompanying software for the traction computers and locomotive control and diagnostic systems.

In 1992, the first EMD heavy haul freight demonstration units went into formal test and they immediately attracted industry-wide attention with their dramatic levels of pulling power, especially in difficult hauling environments.

DRAMATIC INCREASES IN ADHESION

As described earlier by Swenson [3,4,5,6,7], dispatchable adhesion levels of 35% were demonstrated in revenue train testing at high axle loads of about 30 tonnes (66,000 lb.) in 1992, and dispatchable adhesion levels of 35 to 38% have been employed on a wide scale in North America since 1994. In addition, starting adhesion levels up to 45% were shown to be possible on high axle loads. Later, starting adhesion levels up to nearly 50% were demonstrated on high axle loads in North America.

In this paper, we are addressing the more recent developments in which dispatchable adhesion levels of 32 to 39% have been demonstrated not only on high axle loads in North America but also at lower axle loads of 20 to 21 tonnes (44,000 – 46,000 lb.) in other areas of the world. In addition, extraordinarily high starting adhesion levels of up to 50% have been demonstrated on these lower axle loads.

These very high adhesion levels are not yet achievable under all extreme environmental conditions of the world's railways, for example, in some mountainous areas that receive an extraordinary amount of snowfall in a short period of time. In such cases, special efforts are required to clear the excessive snow off the top of the rail. However, even in this case, the new high adhesion systems deliver much higher performance than previously thought possible.

EVOLUTION OF AC INVERTER CONTROL

The AC traction equipment consists of two traction inverter cabinets, one of which is pictured in Figure 4, and six traction motors as pictured in Figure 5. Figure 6 shows the main circuit diagram for the GT46MAC traction system, and this is representative of the other AC traction models as well. This system was derived from the proven AC system of the North American freight locomotives, where more than 1500 of these AC systems are in revenue service and achieve outstanding performance and reliability.

Figure 4

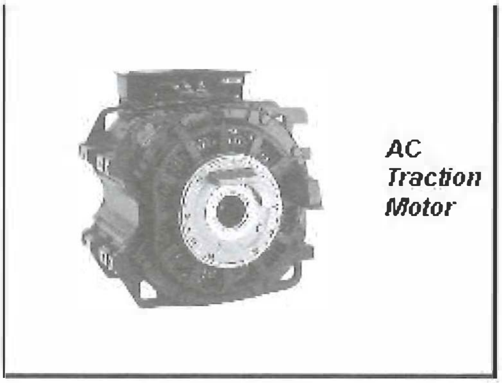

Figure 5

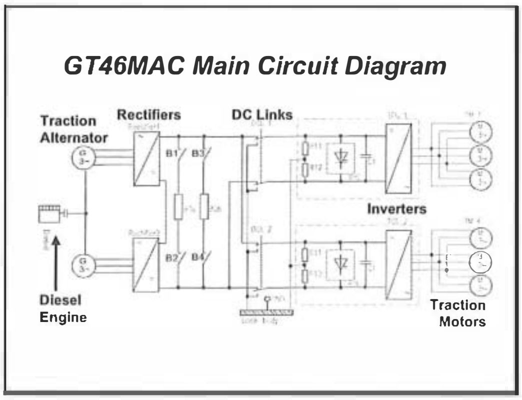

Figure 6

The concept of bogie control, i.e. each inverter supplies power to one bogie, has distinct advantages versus the so-called single axle control (with one smaller inverter per traction motor) because of a reduced number of components per locomotive. This concept offers the advantages of inherent reliability due to a smaller component count. The reliability level of this GTO inverter system has been established to now be four years MTBRF (mean time between road failures).

In 1987, EMD and Siemens tested the first AC traction locomotive in North America with six powered axles. This locomotive, the "268" test vehicle, was a conversion of an existing locomotive from DC traction to AC traction with one inverter per axle. In 1989, EMD built the first new locomotive design in North America with AC traction – the F59PHAC. The power level of inverters was increasing, and it was possible to use one inverter for two powered axles.

Just two years later, in 1991, EMD built the first heavy haul locomotives in North America with AC traction – the SD60MAC prototype. Now, it was possible to use one inverter for three powered axles. In 1993, EMD received the first order in North America for heavy haul AC traction locomotives – the SD70MAC – and put the one inverter per bogie configuration into series production.

HEAVY AXLE LOAD AC TRACTION

EMD's evolution of high power, high axle load, AC traction diesel locomotives is represented in Figure 7, which pictures the SD60MAC and SD70MAC locomotives at 3000 kW (4000 thp), the SD80MAC locomotive at 3750 kW (5000 thp), and the SD90MAC locomotive at 4500 kW (6000 thp). All of these locomotives have six powered axles and bogie control.

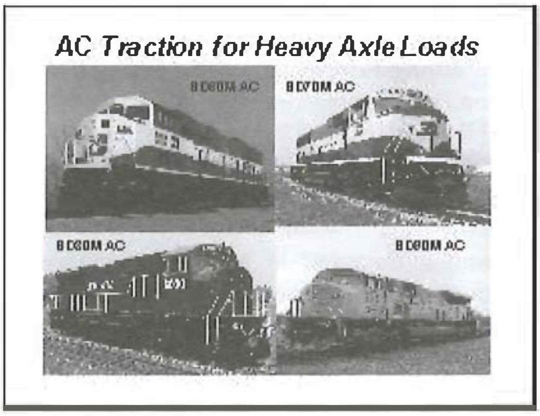

Figure 7

EMD's 3000 kW (4000 thp), AC traction, heavy axle load locomotives were originally targeted to provide 520 kN (117,000 lb.) of continuous tractive effort. Based on the exceptional adhesion characteristics of AC traction, this target was raised to 555 kN (125,000 lb.) during the development program. However, further tests in revenue service demonstrated that this new locomotive design could produce 610 kN (137,000 lb.) of continuous tractive effort (35% adhesion) and 780 kN (175,000 lb.) of starting tractive effort (45% adhesion). Even this continuous level of tractive effort was later established to be very conservative, and these locomotives can realistically be rated higher under most conditions.

These dramatic increases in tractive effort provide significant opportunities for improving locomotive productivity in heavy haul applications. The interest of the North American railroad industry was confirmed in 1993 when the Burlington Northern Railroad (now the Burlington Northern Santa Fe) placed an initial order for 350 model SD70MAC locomotives for coal service, signaling the start of production of AC traction heavy haul freight locomotives in North America. Since that time, AC traction technology has shown conclusively that heavy haul trains which previously required five 6-axle DC traction locomotives can be reliably pulled by only three SD70MAC locomotives. This unit reduction translates into substantial life cycle savings in operating costs for fuel and locomotive maintenance as well as facilities and manpower.

Today, there are close to 1000 SD70MAC locomotives in service. In coal service, heavy trains of 16,050 tonnes (17,700 tons) are routinely dispatched with three SD70MACs requiring 35% to 38% adhesion to get the train over the ruling grades.

SHIFT TO AC TRACTION AND HIGHER POWER

The success of the SD70MAC design led to strong interest by heavy haul railroads in higher diesel engine power levels for use with the high adhesion levels of the AC traction system. This led to the development of the SD90MAC locomotive with a new 4500 kW (6000 thp) diesel engine designed by EMD.

The SD90MAC locomotive, which has undergone extensive testing in revenue service and is now in series production, has demonstrated that it can deliver 900 kN (200,000 lb.) of tractive effort for starting heavy trains. This starting adhesion level of 48% sets new heavy haul standards for the world locomotive industry.

The transition from DC to AC traction for most North American coal trains has been rapid, and it has been a very successful shift in locomotive technology. Indian Railways and Queensland Rail are also now enjoying the benefit of this technology.

AC VS. DC TRACTION SYSTEMS

With the growing use of AC traction in freight locomotives, more railways are asking the question: "Is AC traction the best solution for our railway?" The answer to this question depends on the operation and other parameters.

AC traction is certainly the best solution for low speed, heavy haul applications where much higher adhesion produces significant improvements in productivity – especially where the number of locomotives can be reduced (like North America and India). Due to the higher power density (higher power per motor weight) of AC traction motors, this technology is also the preferred solution for very high power applications. The higher power density is also a key factor in pushing narrow gauge applications (like Queensland Rail) to higher power levels.

On the other hand, DC traction continues to be the preferred lower cost solution for moderate to higher train speeds where the adhesion demand is not so high. This is especially true for the passenger service and light tonnage freight service that is prevalent in many parts of the world. This is true also in North America where the demand for DC traction continues to be significant for non-heavy haul operations.

A notable example of this in the international marketplace was the decision of English, Welsh, and Scottish Rail to buy 280 "Class 66" and "Class 67" DC traction locomotives from EMD, with deliveries completed in 2000. In North America, Union Pacific Railroad ordered a quantity of 1000 SD70M locomotives, with delivery to be completed in 2002. These locomotives use DC traction but employ EMD's latest wheel slip control system that has been developed in parallel with the sophisticated AC traction wheel slip system.

While AC traction motors are simpler than DC motors, the high power electronics required for an AC system adds significant cost to the locomotive. However, as the cost of high power electronics is reduced, more railroads will find it attractive to move from DC to AC traction.

DESIGN FOR LIGHTER AXLE LOADS

The challenge for EMD to design the GT46MAC for Indian Railways was clearly built around the mass issue. The AC traction technology with its accompanying electrical cabinetry was fundamentally heavier than conventional DC based technology. The first essential requirement was to design and build a lighter and robust structure that would meet all of the IR's strict specifications and yet meet the lighter axle loads required for this order. In addition, savings in mass were also achieved by application of aluminum cast components in the traction motors. The GT46MAC was also powered by EMD's 16-cylinder 710 series engine which is common in the North American sector but not seen as often on the international scene where power requirements are seldom this high.

For Queensland Rail's 20-tonne axle load requirement, the challenge was even greater. The locomotive had to meet a very high buff load requirement of 4.5 MN (1 million lb.). The locomotive utilizes a narrow structural carbody. EDI Rail completed extensive finite element analysis (FEA) of the structure to meet the high load requirements while minimizing the mass.

MODERN BOGIE DESIGNS

In designing new AC locomotives for both freight and passenger service on Indian Railways, a decision was made to create a new bogie design common to both units. This was accomplished by creating the HTSC bogie - a high stability, non-steering design that is of very low mass and can also efficiently transfer the high tractive effort required in heavy haul freight service as well as provide stability at higher speeds.

For the narrow gauge locomotives in Australia, EDI Rail utilized a radial steering bogie. This bogie was first developed for narrow and standard gauge DC traction locomotives that EDI Rail provided to Westrail in Western Australia in 1997 and 1998. The steering mechanism of the bogie is similar to the EMD radial bogie. However, the EDI Rail bogie uses a fabricated frame. This permitted both narrow and standard gauge versions to be produced at minimum cost.

DIESEL ENGINE EMISSIONS

EMD began research on reduction of exhaust emissions from its engines in the early 1970s. For many years, EMD has been able to deliver locomotives conforming to the current UIC 12 g/kWh nitrogen oxides standard and to the previous 16 g/kWh standard. The development effort accelerated with the finalization in 1998 of the US EPA locomotive emissions rule, which included standards and verification procedures more stringent than those in any previous rule affecting locomotives. All of EMD's locomotive production for US railroads for the year 2000 conform to the Tier 0 standards of the rule, and retrofit kits are being made available for emissions reduction of 1994 and later locomotives with 710 engines. The first locomotives conforming to the more stringent Tier 1 standards, effective in 2002, will be tested in 2001. Development to meet the proposed UIC 2003 standards and the EPA 2005 Tier 2 standards is well under way.

IR's GT46MAC locomotives, while not being subject to exhaust emission regulation in India, are environmentally friendly with practically no visible smoke emissions, even at full throttle. This characteristic is shared with all EMD two-stroke-cycle diesel locomotives. The gear-driven turbocharger of the two-cycle engine provides an adequate supply of combustion air under all operating conditions, preventing the fuel-rich condition that can lead to smoke emissions in many other engines. This characteristic indicates low emissions of the exhaust particulates that are also regulated in a growing number of jurisdictions.

QR's GT42CU/AC locomotives also utilize both electronic unit injection and separate aftercooling to minimize fuel consumption and exhaust emissions.

LONG TERM PARTNERSHIPS

The decision for EMD to provide PKD kits enabled the Indian Railways to gain manufacturing experience in assembly and test of a modern AC traction locomotive design. This also started the process of updating and preparing IR's DLW factory in Varanasi for the new era of manufacturing these modern locomotives.

The objective of the transfer of technology program with IR is to transfer all technical information necessary to enable them to build, maintain, and service GT46MAC locomotives and 710 engines, and carry out system design modifications and improvements where desired. In order to fulfill this objective, the contract includes the transmittal of drawings, documents, and technical reports, providing technical assistance, and providing training of IR personnel regarding product design, manufacturing technology, and maintenance technology.

In addition, EMD is helping develop sources for locomotive components in India. An EMD office was set up in India in order to provide technical assistance and support to IR personnel on the mission to create locomotive manufacturing and maintenance facilities in India.

The Queensland Rail AC traction locomotive is a first for narrow gauge and a quantum leap in technology. Given the expected high reliability and the uniqueness of the equipment, QR decided to enter into a long-term partnership in the form of a ten-year spare parts support agreement. In this agreement EDI Rail holds and supplies the majority of spares for a fixed monthly sum. The spirit of the contract is collaborative in which it is envisioned both sides will have a long-term partnership in supporting the fleet to achieve high availability and reliability at a fixed cost.

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