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Anirudh Gautam · Ashok Pandey
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Locomotives and Rail Road Transportation

Technology, Challenges and Prospects

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Preface

Rail transport has played a very significant role in development of modern civilization over past 150 years. Due to its capability of bulk transportation of passengers and goods, it has proved to be more environmentally benign and energy efficient on a per capita basis, compared to any other mode of transportation such as road or air. Due to large system size and longer service life of involved systems, technological advancements in the field of combustion engine technology, alternative fuels, emission control technologies, system design and control, etc., are being implemented at a comparatively slower pace in railways across the globe. However, due to increased global awareness of global warming and air pollution, railways are committing themselves for setting up and meeting more stringent emission norms worldwide.

An international workshop, 3rd ISEES Workshop on “Sustainable Energy, Environment & Safety with Railway Centric Theme”, was held at Research Designs and Standards Organisation (RDSO), Lucknow, India during December 21–23, 2015 under the aegis of International Society for Energy, Environment and Sustainability (ISEES). This workshop provided a platform for discussions between eminent scientists and engineers from various countries including India, USA, South Korea, Thailand and Austria. In this workshop, eminent speakers presented their views related to different aspects of technology developments related to railroad transportation, use of numerical tools and modeling tools, and use of sophisticated experimental techniques, which enhanced our understanding of locomotive combustion technology. In addition, there is a great deal of interest in emissions control and use of advanced materials, production and utilization methods of various alternative fuels in conventional IC engine-based power trains, sophisticated and reliable control of big and complex energy systems in railroad transportation sector.

In recent past, lot of developmental activities related to reduction of emissions, using exhaust heat recovery system for electrical power generation, turbocharging, space-heating, increasing mechanical output and other feasible applications for increasing overall power train efficiency have been undertaken. For planning strategic implementation of these advancements in railways, an integrated and comprehensive plan needs to be developed. This research monograph is an effort in this direction and contains the main topics covered in the workshop and provides the latest developments in this domain. Main theme of this monograph is technological development of locomotive for overcoming current challenges related to energy saving, emission reduction and improving passenger comfort. Various chapters focus on effective utilization of fuels, production and utilization of other non-conventional fuels, emissions and noise reduction, effective power utilization and power production from waste heat, and fundamental study of combustion processes for increasing efficiency and reducing emissions.

The editors would like to express their sincere gratitude to the authors for submitting their work in a timely manner and revising it appropriately at a short notice. We would like express our special thanks to Dr. Dhiraj V. Patil (IIT Mandi), Dr. P. Anil Kishan (IIT Mandi), Dr. Srikrishna Sahu (IIT Madras), Dr. Krithika Narayanaswamy (IIT Madras), Sh. Sunil Patahk (IIP Deharadun), Prof. Tarun Gupta (IIT Kanpur), Dr. Rakesh Kumar Maurya (IIT Ropar), Dr. Dhananjay Kumar Srivastava (IIT Kharagpur) and Akhilendra Pratap Singh (IIT Kanpur), who reviewed various chapters of this monograph and provided their valuable suggestions to improve the manuscripts. We acknowledge the support received from various funding agencies and organizations for the successful conduct of the ISEES workshop, where these monographs germinated. These include Department of Science and Technology, Government of India (Special thanks to Dr. Sanjay Bajpai); RITES Ltd., India (Special thanks to Sh. Pradeep Gupta); Office of Naval Research Global, Singapore (Special thanks to Dr. Ramesh Kolar); TSI, India (Special thanks to Dr. Deepak Sharma); Caterpiller India; AVL India; Dynomerk Controls, India (Special thanks to Sh. Kishore Raut); CEI Softwares, India; ESi Group, Pune; BHEL India; and Bosch India.

We hope that researchers in various fields related to locomotive technologies such as emission control, efficiency improvement, alternative fuel production and utilization, noise and vibrations control will find this monograph helpful.

Kanpur, India	Avinash Kumar Agarwal
Kamand, India	Atul Dhar
Lucknow, India	Anirudh Gautam
Mohali, India	Ashok Pandey

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About the Editors

Prof. Avinash Kumar Agarwal joined IIT Kanpur in 2001. Professor Agarwal was at ERC, University of Wisconsin, Madison, USA as a Postdoctoral Fellow (1999–2001). His areas of interest are IC engines, combustion, alternative fuels, hydrogen, conventional fuels, lubricating oil tribology, optical diagnostics, laser ignition, HCCI, emissions and particulate control and large bore engines. Professor Agarwal has published more than 200 peer-reviewed international journal and conference papers. He is Associate Editor of ASME Journal of Energy Resources Technology and International Journal of Vehicle Systems Modelling and Testing. He has edited "Handbook of Combustion" (5 Volumes; 3168 pages), published by Wiley VCH, Germany. Professor Agarwal is a Fellow of SAE (2012), Fellow of ASME (2013) and a Fellow of INAE (2015). Professor Agarwal is the recipient of Prestigious Shanti Swarup Bhatnagar Prize-2016 in Engineering Sciences.

Dr. Atul Dhar is Assistant Professor at IIT Mandi since 2013. He received his M.Tech. and Ph.D. degrees from Department of Mechanical Engineering, IIT Kanpur in 2006 and 2013, respectively. Atul Dhar graduated from HBTI, Kanpur in 2004. He was awarded the Erasmus Mundus fellowship of European Union for pursuing postdoctoral research at Ecole Centrale de Nantes, France in 2013. He is recipient of young scientist award from ISEES in 2015. His areas of interest include reciprocating IC engines, emission control, alternative fuels and lubricating oil tribology. He has co-authored more than 30 international peer-reviewed journal papers.

Dr. Anirudh Gautam works with the Indian Railway Service of Mechanical Engineers. He holds degrees in Mechanical and Electrical engineering from SCRA scheme of Jamalpur, a Master's in Quality Management from BITS Pilani, and a Master's in Engineering in Engine Design from University of Wisconsin, Madison. He has served in various roles in the Indian Railways. He later worked at Diesel Locomotive Works including engine manufacturing, engine design and transfer of technology. He built India's first 4000 hp diesel locomotive indigenously under ToT with EMD, General Motors, USA, for which he was awarded a national award by the Railway Minister. He has successfully completed various R&D projects at Engine Development Directorate, RDSO. He completed his Ph.D. from IIT Kanpur in 2013. He has two patents, 10 technical papers and 50 technical reports to his credit. He is presently on deputation to RITES as Group General Manager Rolling Stock Design.

Prof. Ashok Pandey is Eminent Scientist at the Center of Innovative and Applied Bioprocessing, Mohali. His major research interests are in the areas of microbial, enzyme and is Eminent Scientist at the Center of Innovative and Applied Bioprocessing, Mohali. His major research interests are in the areas of microbial, enzyme and bioprocess technology. He has to his credit over 1150 publications/communications, including 16 patents, 50+ books, 140 book chapters, 423 original and review papers, an *h* index of 78 and ~25,000 Goggle Scholar citations. Professor Pandey is the recipient of several fellowships such as the Fellowships of Royal Society of Biology (UK), Academician of European Academy of Sciences and Arts, Germany; ISEES; National Academy of Science (India); BRSI; and awards such as Thomson Scientific India Citation Laureate Award, USA; UNESCO Professor; Raman Research Fellowship Award, CSIR; and GBF, Germany. Professor Pandey is Editor-in-chief of *Bioresource Technology*, Honorary Executive Advisor of *Journal of Water Sustainability* and *Journal of Energy and Environmental Sustainability*, Subject editor of *Proceedings of National Academy of Sciences (India)* and serves on the editorial board of several other journals.

Part I
General

Introduction to the Locomotives and Rail Road Transportation

Avinash Kumar Agarwal, Atul Dhar, Anirudh Gautam and Ashok Pandey

Abstract Development of locomotive and advancement of rail road transportation is important for reducing emissions and becoming less dependent on conventional fossil fuels. Utilization of available alternative fuels such as methanol, DME and biodiesel can resolve energy crises in the foreseeable future. Effective use of exhaust heat recovery can be helpful in increasing overall efficiency and power generation. After-treatment devices are now a necessity to meet the upcoming emission norms for the rail road sector. For meeting the challenges of energy and environment, there is a need for advanced technological development in locomotive and rail road transportation sector.

Keywords EHR system · Exhaust gas after-treatment · Greenhouse gas (GHG) emissions · Noise and vibrations · Biofuels · DME

In terms of per capita goods transport and passenger travel, railways are certainly most energy efficient, fast and environment friendly transportation mode. However in the developing countries, technological advancement in rail road sector is lagging behind the technological advancement in road transport sector. Absence of emission norms for railway locomotives in most countries of the world is a typical fact highlighting this lack of technological advancement in the rail road transport sector.

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Railways are also geared towards reducing their carbon footprint. For example Indian Railway (IR) has already started implementation of strategies to minimize environmental impact by developing carbon neutral infrastructure in new stations, which will reduce the carbon foot print for railways in long run [1]. IR is also working for improvement of energy efficiency, especially in the traction system, in order to reduce emissions.

Locomotives are large compression ignition engines using diesel. Large size of engine, long operating hours and older engine technologies lead to huge emissions of gases and particulate. The locomotive engines still use technology, which was used 30–40 years ago in automotive sector. Advancement in engine technology in diesel locomotives will be certainly helpful in reducing these emissions. Moreover absence of emission norms in rail road sector in many countries including India does not compel railways to use low emission technologies. In United States, vast reduction in CO_2 and NO_x emissions was achieved after implementing locomotive regulations [2]. There is 70% reduction in NO_x and particulate emission in locomotives meeting tier 4 standards, in comparison to locomotives meeting tier 3 standards and for this, mostly in-cylinder emission control approaches were used. Exhaust gas recirculation (EGR) is the most commonly used in-cylinder NO_x emission reduction technique. Implementation of properly designed EGR scheme can be helpful in simultaneous particulate and fuel consumption reduction or maintaining them in acceptable limits while reducing NO_x emissions significantly [2]. Particulate emissions in exhaust are solid particles consisting of condensed volatile matter around carbon core. They can also be reduced by improving in-cylinder fuel-air mixing and exhaust gas after-treatment. Detailed study of combustion processes reveals that evolution of soot consists of formation of nuclei, inception or nucleation and conglomeration, surface growth and oxidation of particles. Soot emissions can be reduced by efficient utilisation of fuel and homogeneous distribution of fuel in the combustion chamber. Study of soot formation with flame characteristics is a new area of research, which will have huge impact on soot reduction, especially in the context of large size locomotive engines. Different after-treatment devices are used for reduction of emission such as (i) diesel oxidation catalytic convertors (DOC), which reduces CO, HC and soluble organic fraction (SOF); (ii) diesel particulate filter (DPF), which traps soot from the engine emissions and (iii) selective catalytic reduction devices, which reduce NO_x emissions into N_2. All these have great potential for locomotive engines.

Environmental and public health aspects compel researcher to reduce noise levels from the locomotive engines. Main parameters responsible for locomotive noise are locomotive engine technology, use of noise suppression devices, track condition, track roughness, number of bridges and other track crossings, weight of coach, imperfect contact between coaches, length of the train, speed, vibrations and site area for propagation of noise waves. In various countries, different models are being used for numerical analysis of noise from locomotives. Passenger comfort and quality perception of the travellers is highly dependent on noise, vibrations, and harshness (NVH) characteristics of trains and locomotive is one of the main sources for these. Various devices and equipment are developed for finding solution to this problem. There is room for improvement in the NVH characteristics of locomotives and trains in rail road sector.

Significant amount of heat is wasted in locomotives via cooling system and exhaust gas. Part of this waste heat can be recovered. Energy recovery is important because this energy production involves use of conventional petroleum fuels. Diesel production from crude petroleum involves fuel extraction, fuel processing, and fuel delivery. In the locomotive, combustion of diesel converts chemical energy of fuel into thermal energy and finally it is converted into mechanical power which is then converted to loco motion. A sizeable amount of heat energy remains unused in this conversion process and is rejected into the atmosphere via exhaust system and cooling system. This wasted heat energy can be partially recovered with the help of thermoelectric generator (TEG) and organic Rankine cycle (ORC), which can be used for meeting auxiliary power requirements of the train and/or for increasing the mechanical power output i.e. traction capacity of the locomotive. A typical locomotive at heavy-haul loses 2 MW energy via the radiator. With 2% conversion efficiency of TEG, 50 kW energy can be recovered by the application of TEG in the radiator. TEG can recover up to 100 kW energy from the locomotive exhaust gas (at temperature 350 °C). Efficiency of ORC based turbine is much higher than TEG however they have installation and operational challenges [3].

Total dependence on conventional fuel (diesel) comes with threat of interruption in supply in future for rail road transportation sector. Therefore efforts are needed for migration towards alternative fuels, which have nearly identical combustion characteristics as that of diesel but with relatively lower emissions. These alternative fuels can be produced from locally available renewable resources. Biodiesel, alcohols (methanol and ethanol) and Di-methyl ether (DME) are some examples of available alternative fuels. Among various prevailing alternative fuel options for diesel engines, combustion related properties of biodiesel are closer to mineral diesel. Due to similar properties, it is accepted as a locomotive fuel based on the availability. Availability of methanol in bulk quantities and its clean burning characteristics due to absence of carbon-to-carbon bonds, makes it a suitable alternative fuel for locomotives. Methanol produces lower particulate and sulphur oxides and it has higher cetane rating than mineral diesel. However it has blending issues with mineral diesel and is poisonous in nature. Di-methyl ether (DME) is a clean burning alternative fuel, which has nearly same physical properties as that of liquefied petroleum gas (LPG). DME has unique auto ignition characteristics and very high cetane number. If the problems related to pressurised fuel injection system, fuel supply system, inferior lubricating properties and low calorific value can be resolved, DME can emerge as an excellent alternative fuel for locomotives with soot-less emission spectra.

Various issues, opportunities and challenges related to development of locomotive engine are covered in this monograph. Specific topics of this monograph include:

- Introduction to the Locomotives and Rail Road Transportation
- Diesel Locomotives of Indian Railways: A Technical History

- Exhaust Heat Recovery Options for Diesel Locomotives
- Diesel Locomotive Noise: Sources, Reduction Strategies, Methods and Standards
- Biodiesel as an Alternate Fuel for Diesel Traction on Indian Railways
- Fuel Properties and Emission Characteristics of Dimethyl Ether in a Diesel Engine
- Potential of DME and Methanol for Locomotive Traction in India: Opportunities, Technology Options and Challenges
- Exhaust After-treatment System for Diesel Locomotive Engines—A Review
- Catalytic Control Options for Diesel Particulate Emissions Including that from Locomotive Engines
- Soot Formation in Turbulent Diffusion Flames: Effect of Differential Diffusion
- Development of a Mobile Emission Test Car for Indian Railways

The above topics have been categorised into four groups: (i) General, (ii) Efficiency improvement and noise reduction, (iii) Alternate fuels for locomotive traction, (iv) Locomotive emission reduction and measurement.

The first section deals with technical history and general description of Indian railways. Indian railway is the second largest railways network in world, which is now planning for major technology improvements for improving the operational efficiency of railway infrastructure and improving the service quality. IR consumes approximately 2.6 billion liters of diesel per year [4]. ALCO-DLW diesel-electric engine, Electro-Motive diesel (EMD) engine, diesel multiple unit engines are main types of locomotives used in India. ALCO-DLW diesel-electric engine contains 6, 12 and 16 cylinder and each cylinder produces 200–225 hp. These cylinders are water cooled, turbocharged and after-cooled. However these engines do not meet any international emission standard. EMD engines have 16 cylinders and each cylinder produces 280 hp. These cylinders are water cooled, turbocharged and after-cooled. EMD engines also do not meet any international emission standard as of now. Diesel multiple units are equipped with Cummins KTL 50L engines, which meets the US EPA tier 0 standards [4].

The second section deals with efficiency improvement and noise reduction by continuous improvements in design and structure of locomotives. Description of NVH characteristics identifies various components of locomotive for reduction of noise and vibrations, describes measurement methods and suggests measures for reducing them in locomotives. Exhaust heat recovery is a promising method for improving the overall efficiency of locomotives. Larger size of diesel locomotives compared to the space available makes the installation of exhaust heat recovery systems in diesel locomotives more practical. In this chapter, feasibility and suitability of various exhaust heat recovery options for diesel locomotives has been discussed.

Third section on alternate fuels for diesel locomotive traction deals with use biodiesel, methanol and DME. Indian railways have already allowed 5% or higher biodiesel blends in diesel locomotive, depending on availability. Technical feasibility, opportunities, challenges and potential of DME and Methanol as locomotive fuels in India is also discussed. These fuels are ultra-low-emission fuels, which have been overlooked in both energy policy and industry discussions, despite many attributes, which make them attractive for locomotives. DME is especially suitable in diesel locomotives due to its fuel characteristics. Motivation to use DME as a fuel candidate in locomotives comes from its soot-free emission due to absence of C–C bonds. It can be blended with mineral diesel to overcome limitations of using 100% DME namely low viscosity and density. Similarly Methanol can be blended with mineral diesel for use in locomotives however it has blend stability issues. Methanol has a high latent heat of vaporization; highest oxygen content amongst fuels, is sulfur free and has higher burning speed. When burned at high temperature, it can reduce smoke and NO_x emissions from CI engines.

Fourth section deals with locomotive emission measurement and reduction strategies for making them environment friendly. One chapter presents detailed review of after-treatment emission control options, which are relevant to locomotives. This chapter also covers fundamental investigations on soot-formation mechanism. Another chapter describes design, development and use of mobile emission measurement test car for locomotives for gaining necessary data for developing emission norms.

Technical aspects presented in this monograph include after-treatment options, energy recovery options, noise reduction options and approaches, alternative fuels for reducing carbon foot print, and combustion improvement for improving overall performance of locomotives for rail road transport sector. The information here is aimed to provide knowledge for development of various technologies, challenges and opportunities related to locomotives in terms of emission reduction and energy savings. The content is expected to give useful information to the end user, researchers and development engineers working in the field of rail road transport sector.

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Diesel Locomotives of Indian Railways: A Technical History

Joydeep Dutta and Avinash Kumar Agarwal

Abstract In this article, we would like to trace the history of the growth of diesel traction of Indian railways without completely sacrificing technical details. It starts from the very early times and discusses at length the coming of the ALCO locomotives on the Indian Railways (IR) and the reappearance of EMD locos on IR. We have tried to mix the historical facts with technical facts therefore calling the study presented in this paper as technical history.

1 The Early Diesels

Since this is a technical article on the diesel locomotives of the Indian Railways (IR), we urge the reader to first have a look at the appendix, where the locomotive codes are explained and then it would be easier to go through this article.

Diesel locomotives on IR have a long history. However the early history of diesel locomotion on IR is not very clear. It is usually assumed that the WDS1 broad-gauge diesel shunters worked in the Bandra area of Bombay (now Mumbai) in the 1930s. However Terry Martin [1] in his wonderful study on the Darjeeling Himalayan Railways, mentioned that one of the first successful dieselization in India occurred on Gaekwad's 2 ft 6 in. narrow-gauge Baroda State Railway in 1932, when Armstrong-Witworth sold four 80 hp diesel railcars. The same company supplied 90 hp diesel electric railcars to the Kalka-Shimla railway in 1933. In fact Terry Martin [1] wrote about an attempt to use diesel traction on the Darjeeling Himalayan Railways (DHR) when their directors put an order for a diesel locomotive fitted with a 165 hp General Motors (GM) diesel engine with Walford

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Transport Limited, which had its main office in Calcutta (now Kolkata). The unit cost was 23,950 rupees. However this locomotive was not successful on the DHR. Terry Martin [1] also claimed that this was one of the first diesel locomotives to be built in India. This had a mechanical drive with a five speed gear box.

Though IR now appears to be a broad gauge railway, the first mainline dieselization on IR began with the introduction of YDM1 locomotives in 1955 on the meter-gauge and they were first homed in Gandhidham on the Western Railways. There were 20 such locomotives with hydraulic transmission. One of the first beneficiaries of dieselization in India was the Northeast Frontier Railway. Its important rail junction Siliguri was the first home to YDM3 class diesel-electric locomotives built by the Electromotive Division of the GM. These locomotives were transferred later on to the Abu Road diesel shed of the Western Railways. The GM was the ruling king among diesel locomotive manufacturers. IR had however decided that though they need to move from steam to diesel, they did not want to remain captive to the big international manufacturers. They wanted to get a technology blueprint of a simpler locomotive and manufacture it in India. Though they approached GM for a technology transfer, GM was reluctant. However they did supply India with the superb 2400 hp WDM4 class, Co-Co diesel-electric locomotives, which were an export version of SD-24 class locomotives used on the railroads in the USA. These were supplied in 1962 and homed in Mughalsarai with a specific shed built for them. These locomotives were praised by most railwaymen associated with diesel traction in India. Only 72 of them were bought. Meanwhile IR experimented with hundred WDM1 class diesel-electric locomotives manufactured by American Locomotive Company (ALCO) in 1958. Dubbed as the “World Locomotive” by ALCO, these locomotives were mainly used in the Eastern and South Eastern Railways. Fitted with an ALCO class 244, V-12 diesel engine producing 1800 hp, it was used mainly for coal trains, but was also used for dieselization of some important trains like the Howrah-Madras Mail. It might be interesting to speculate why ALCO christened the WDM1 as ‘World Locomotive’. These locomotives were provided with swing bolster, double suspension “World” Co-Co bogies. The term “World” refers to the fact that WDM1, which was called DL-500-C could work across various railways of the world. This locomotive had a 16 tonne axle load thus it could work in places where high-axle loads were not possible but had demand for faster trains. Apart from the IR, DL-500-C had worked in many other railways, for example RENFE in Spain. Once inside the locomotive cab, one would be surprised that it still used a steam-era whistle chord. In fact it has one control stand and boasted a dead-man’s paddle, which the driver had to keep his foot on while driving. The drivers however were clever enough to just put a brick on the dead-man’s paddle to save them from the irritation to keeping one of their feet on the paddle throughout. The WDM1 had a good visibility and was of the carbody design where all the equipment including the cab were hosed under a single casing.

IR at that period of time operated all trains with vacuum brakes, a legacy of the British Raj though air-brakes were more efficient. If one walks down from the cab of the WDM1 through the equipment section, one would first come across the electrical compartment, which consists of the main DC generator and an auxiliary generator and then the prime-mover, the V-12 ALCO 244 four-stroke diesel engine and then the compressor-exhauster unit. This exhauster was a special fitment for the IR, since the exhauster is used to create the vacuum in the train brake pipe. With a gear-pinion ratio of 92:19, this locomotive was capable of reaching upto 122 km/h though as per IR practice, it was restricted to 105 km/h. It had a fuel tank with a capacity of 3000 l diesel. At a speed of around 22 km/h, the maximum continuous tractive effort was achieved by the WDM1 which was about 19,280 kg. Continuous tractive effort is the tractive effort that can be maintained by the locomotive for a great length of time without damaging the traction motors. For more details on tractive effort, see the Wikipedia article (https://en.wikipedia.org/wiki/Tractive_force). Note that one should not confuse it with maximum tractive effort, which is achieved at much lower speeds but cannot be maintained for a long-time. The WDM1 locomotive did not have a dynamic brake, which was indeed a disadvantage for heavy freight operation and a more powerful and well equipped diesel locomotive was sought by the IR. The first ALCO shed was built in Gaya on the then Eastern Railway to home the WDM1 class locomotives. It was later dismantled, when the route was electrified.

Since higher horsepower locomotives were required by the IR, they originally approached the GM for a technology transfer, which as we mentioned, did not work out. However ALCO agreed to transfer the technology of DL560C class 2400 hp locomotive with a V16 engine, dubbed as ALCO 251B. In fact the ALCO 251-B prime mover was delivering 2600 hp under ideal test conditions, which translated to 2400 hp braking horsepower, that too under ideal test conditions, as prescribed by the Association of American Railroads (AAR). It was rechristened as the WDM2 and was capable of operating at a maximum speed of 120 km/h on IR and it became the most reliable broad gauge (5 ft 6 in. gauge) locomotive in the history of IR (Fig. 1). Though it was bought in as an intermediate step before electric traction takes over, however to the dismay of many electrical engineers on IR, the WDM2 had a complete sway over the IR operations. It was a locomotive adapted to operate in our dusty conditions and was very versatile in operating freights and cross-country mail/express trains. The testimony of the operating capability of DL 560C was borne out by the fact that it operated with an amazing reliability on the Andes mountain route to Cuzco from Lima, which was in 1960s, the highest altitude railroad in the world. The WDM2 was a Co-Co locomotive fitted with ALCO-trimount bogies of asymmetrical design with traction motors fitted in an asymmetrical fashion too. This bogie caused track damage on IR initially but then IR tweaked the design in a way that the tracks are not harmed. In fact this Co-Co trimount bogie did a lot of track damage on the US railroads, which finally led to ALCO going out of favour with important railroad companies and then closing down altogether in 1969. In fact, ALCO had licensed the technology to companies in developed countries like England, Spain, France, Australia and Canada. India was the only developing country included in this list by ALCO.

Compared to the WDM4, the machinery of the WDM2 was very simple and thus was easy to maintain by engaging a workforce, which had just moved into diesel from steam. The only new thing was the electrical components as the WDM2 was a diesel electric locomotive, for which the staff was required to be trained. The WDM4

Fig. 1 A WDM2 class locomotive built by DLW, homed at Pune Shed of Central Railway

needed specially trained staff. In fact ALCO completely transferred the technology of WDM2 to IR and helped it build its first indigenous diesel locomotive manufacturing facility in Varanasi, which was named as the Diesel Locomotive Works (DLW). It first began by assembling the knocked down kits sent from ALCO. This first such assembled kit was the WDM2 numbered 18233, which was dedicated to the service of the nation by the then Prime Minister Shri Lal Bahadur Shastri. ALCO meanwhile supplied around 121 fully assembled WDM2 to IR. DLW later on built WDM2's on its own and carried out several design modifications. More than 50 years of its coming to IR, the higher horsepower variants of the WDM2 family still continue to serve the IR and the nation. For more details on the WDM2, and various ALCO locomotives of IR, we would request the reader to consult the only book written about Indian ALCOs, which is titled "*The Story of Indian ALCOs: Legend of the WDM2*" by S. M. Sharma and J. Dutta [2].

It will indeed be a good idea to take a closer look at the WDM2 locomotive. The WDM2 is a road-switcher design, if we use the terminology of the US Railroads. It has a short-hood and a long-hood housing, the machinery with a cab in between the long and short-hoods with an inspection walkaway. We would take a walk from the short-hood peep into the cab and then walk along the inspection walkways and look at various machines in the WDM2. The short-hood houses the dynamic brake grids and the blower motor to cool the grids. It also houses the braking system. In fact, the early WDM2 were equipped only with vacuum brakes and used a Westinghouse braking system called 28LV1. When DLW started making WDM2's capable of both, air-brake and vacuum-brake operation, the braking system was called 28-LAV-1. The battery knife-edge switch, which is a prime requirement before starting a dead locomotive, is also housed in the short-hood. Now once inside the cab, one would find WDM2 to be quite ergonomic by the standards of the 1960s. There are two control stands. One for the short-hood operations and the other one for the long-hood operations. In both cases, the driver sits on the right, while the assistant sits on the left. The visibility of the WDM2 in both operations was pretty good and the drivers were very happy with these sturdy machines. Originally backrests were provided in the driver's seat however they were removed later on. We say that the layout was ergonomic in the sense that the control stand was clearly divided into two parts. The pneumatic part consisted of the gauges for the braking system like brake cylinder and brake pipe pressure, auxiliary reservoir and main reservoir pressure and a vacuum level measuring gauge along with the train brake handle (A9) and independent locomotive brake handle (SA9). Among electrical parts, we have the throttle, which can be operated over a range of eight notches. It has a reverser handle and also has a dynamic braking handle, an ampere meter, an electrical speedometer (on the long-hood control stand), warning lights, head lights and classification light switches, multiple-unit shut down switch and so on. If we sit in the short-hood control stand facing the short-hood, the wall separating the cab and the long-hood houses the electrical contactor, which are used to supply the current to the DC traction motors on the axles. It also houses the engine control switch and the traction motor cut-out switch. Then as we leave the cab and move down the walk way, we first find the electrical cabinet having the main generator and the auxiliary generator. Just on the inspection door is the front-truck traction motor blower. As we open the inspection door, we see huge ALCO 251-C prime mover and its Woodward governor. Further down, we have the compressor-exhauster cabinet followed by the radiator room with a huge radiator fan and a water tank attached to the roof, from where the water is supplied across the main engine to keep it cool. Inside the radiator compartment, apart from the huge radiator fan, one can see the encasing of lube-oil filters. The WDM2 has a big fuel tank (5000 litres capacity) and two main air reservoirs hung on two different sides. The one on the right side is for braking and the other one on the left side is for other pneumatic activities such as sander, windshield wiper, etc. For more details, please refer to ref [2]. With a gear-pinion ratio of 65:18, ALCO DL 560-C gave the maximum speed of 129 km/h with 17 MT axle load. On IR, WDM2 had 18.8 MT axle load and with the same gear-pinion ratio, its maximum speed was restricted to 120 km/h.

The WDM2 locomotive came in several series of road numbers. They were in 18 series, 17 series and 16 series and built in that order. The first WDM2 i.e. the class leader was 18040, which is now on display in the National rail Museum in Delhi. However the first WDM2 to reach the Indian shores was 18046. In fact from 18,000 to 18039, IR had numbered the WDM4 s the great rivals for WDM2. The WDM2's made by ALCO achieved under test conditions a continuous tractive effort of 28580 kg at a speed of 18 km/h.

The WDM2's have a life of 36 years. In fact one of the most important features of the approach to dieselization on IR was the standardization of WDM2 as the main broad gauge locomotive. Hence all over India, it was the same locomotive and a particular locomotive could be attended to, even if it was hundreds of kilometres away from its home shed. This had not been the characteristic of development of electric traction in India, which experimented with various classes of locomotives, making the maintenance of an electric locomotive very difficult and challenging, if it was far from the home shed or home railways. This simple standardization of diesel locomotives turned the WDM2 into the most reliable locomotive in the entire history of the IR. We must also take a careful note that all future developments of diesel locomotives done by the Indian railways were based on ALCO technology on WDM2 platform.

Looking at the success of the WDM2, IR also went in for an ALCO locomotive for the meter-gauge sections. This locomotive classified DL 535 by ALCO was rechristened as YDM4 in India (Fig. 2). Several locomotives of this class were built by the Montreal Locomotive Works (MLW), Canada, which was an ALCO subsidiary. Unlike the broad-gauge designs, the YDM4 was fitted with an ALCO 6-cylinder in-line 251-D engine, which gave 1350 hp and a brake horsepower in the range of 1100–1200 hp. Without any competition from electrics, this locomotive

Fig. 2 A DLW manufactured YDM4 meter-gauge diesel of the ALCO design

continued to hold its dominance over the vast meter-gauge network in India. These locomotives were capable of going to a maximum speed of 96–100 km/h and thus allowed introduction of many crack-trains on some important meter-gauge routes. The DLW started building this locomotive from 1968 till early 90s before the project-unigauge slowly took many YDM4's out of service. Many of them still work in Malaysia. In fact, the locomotives built in MLW were rechristened YDM4A and were used for hauling crack meter-gauge expresses like the Delhi-Jaipur Pink City Express and the Madurai-Chennai Egmore Vaigai express. These trains had very tight schedules, which would be envied even by the broad-gauge Shatabdi express trains. The YDM4 was a road-switcher like the WDM2 but had only one control stand. So if the loco ran with the short-hood face, then the driver sat on the right and while operating in the long-hood mode the driver sat on the left. In fact the Engine control switch (ECS) is in the control stand unlike the WDM2, which was in the electrical cabinet. The YDM4 had fuel tank quite similar in looks to that of WDM1 and had a capacity of 3000 l. With a gear-pinion ratio of 92:19, the locomotive ran at a maximum speed of 96 km/h, which was tweaked to 100 km/h on the YDM4A's, which led IR to introduce many meter gauge crack trains.

A very interesting experiment was carried out on the south central railways around 1970s, where they bought around eight diesel-hydraulic locomotives, which operated at a speed of 120 km/h. Two of them were fitted with Mercedes-Benz engines, while others were using a transmission designed by an Indian engineer M. M. Suri. All the eight locomotives were built by Henschel, Germany. Though they were very sophisticated locomotives (Christened as WDM3) and were efficient, their maintenance cost increased since they could not operate in dusty environment, typical to India. The only resource for WDM3 seems to be the website of the Indian Railways Fan Club (http://www.irfca.org/faq/faq-loco2d.html).

On the narrow gauge however, the diesel-hydraulic locomotives became the mainstay with ZDM3 and ZDM4 still operating Kalka-Shimla railway and NDM6 on the Darjeeling Himalayan Railway. These locomotives were in fact built at the Chittaranjan Locomotive Works (CLW), Kolkata, which is mainly an electric traction building unit but has developed facilities to build diesel hydraulic locomotives. They built famous shunters of WDS4 class, which were seen in major terminus stations and later replaced by DLW built WDS6 class 1350 hp diesel-electric shunters, having a YDM4 power-pack under a broad-gauge hood.

2 Improving WDM2

It was realized during 1980s that in order to keep up with the growing demand of railroad transportation in India, a higher-horsepower version of WDM2 locomotive was essential. The Engine Development Directorate of the Research Design and Standards Organizations (RDSO), Lucknow has been making efforts for quite some time since 1980s to improve the horsepower of ALCO 251-B prime mover. They could successfully uprate it to produce 3100 hp over a period of time. This could be done by design and development of double helix fuel injection pump, use of steel cap pistons and optimised turbochargers, in addition to few other changes. In fact at the Charbagh diesel shed, Lucknow, a WDM2 locomotive (18589) was fitted with this higher horsepower engine, which is now called 251-C. Instead of the standard DC/DC transmission, they put in an AC/DC transmission bought from General Electric (GE), Canada. They also fitted it with a higher capacity fuel tank. Under test conditions, the locomotive produced 2800 hp, which was a significant jump over the original WDM2. Thus was born the WDM2C which was later rechristened as WDM3A (Fig. 3) (do not confuse with WDM3, which was diesel hydraulic locomotive). This locomotive thus became the benchmark for development of higher horsepower diesels in India. Further it was realised that time has come to give-up ALCO Co-Co trimount trucks and develop separate locomotives for freight and passenger services. The WDG2C, which was finally called WDG3A with the 251-C, 3100 hp prime mover and high-adhesion bogies, became an instant success in freight operations (Fig. 6). IR wanted to move forward and have higher horsepower locomotives. The latest in that line was WDM3D, which was to have a 3400 hp power-pack however in actual operating conditions, it produced only 3300 hp. The WDM-3D was a micro-processor controlled locomotive, which performed in a reliable manner. There was also a model called WDP3A, which had a potential to operate up to 160 km/h and was of a very unique car body design, in sharp contrast to the traditional hood design of IR. This locomotive worked on crack express trains in the northern part of the country well into the mid-2000s and then was shifted to

Fig. 3 A WDM2 rebuilt as 3100 hp WDM3A by DMW patiala

ordinary passenger services. This class of locomotives still haul the Rajdhani Express from Hazrat Nizamuddin to Trivandrum Central in the Baroda-Trivandrum segment of the journey. An earlier experience in building the passenger locomotive was gained by using an upgraded version of ALCO-244 V-12 engine, which is now rated at 2300 hp. These locomotives with Bo-Bo bogies and classified as WDP1 were thought to be good for fast intercity services however they didn't perform well in practice.

The Diesel Modernization Work (DMW) at Patiala, formerly known at the Diesel Component Works (DCW) regularly carries out mid-life rehabilitation of WDM2 class locomotives and rebuilds them as WDM3A class locomotives. See [2] for more details Fig. 4.

IR had very recently (2013) developed a very unique diesel locomotive, where the diesel engine was replaced by three 800 hp diesel generator sets. This is a very energy efficient locomotive and looks almost like the ones found on US railroads. One can use all three, only two or just one generator set as per the duty assigned to the locomotive. It has been named WDM2G, and is made for light passenger trains. In fact, the current developed by the generator sets is fed to the traction motors and has a capacity of running at 120 km/h. Only two have been built until now and homed in Itarasi.

Before we end this section, it would be interesting to mention the role which IIT Kanpur has played in the development of the first Electronic Fuel Injection (EFI) system for the ALCO 251-C, 3100 hp diesel prime mover. This was achieved by a collaboration of Engine Research Laboratory (ERL, www.iitk.ac.in/erl), IIT Kanpur under the stewardship of Prof. Avinash Kumar Agarwal and Engine Development Directorate (EDD), RDSO under the stewardship of Dr. Anirudh Gautam.

Fig. 4 WDG3A class locomotives with high-adhesion bogies for heavy freight operations