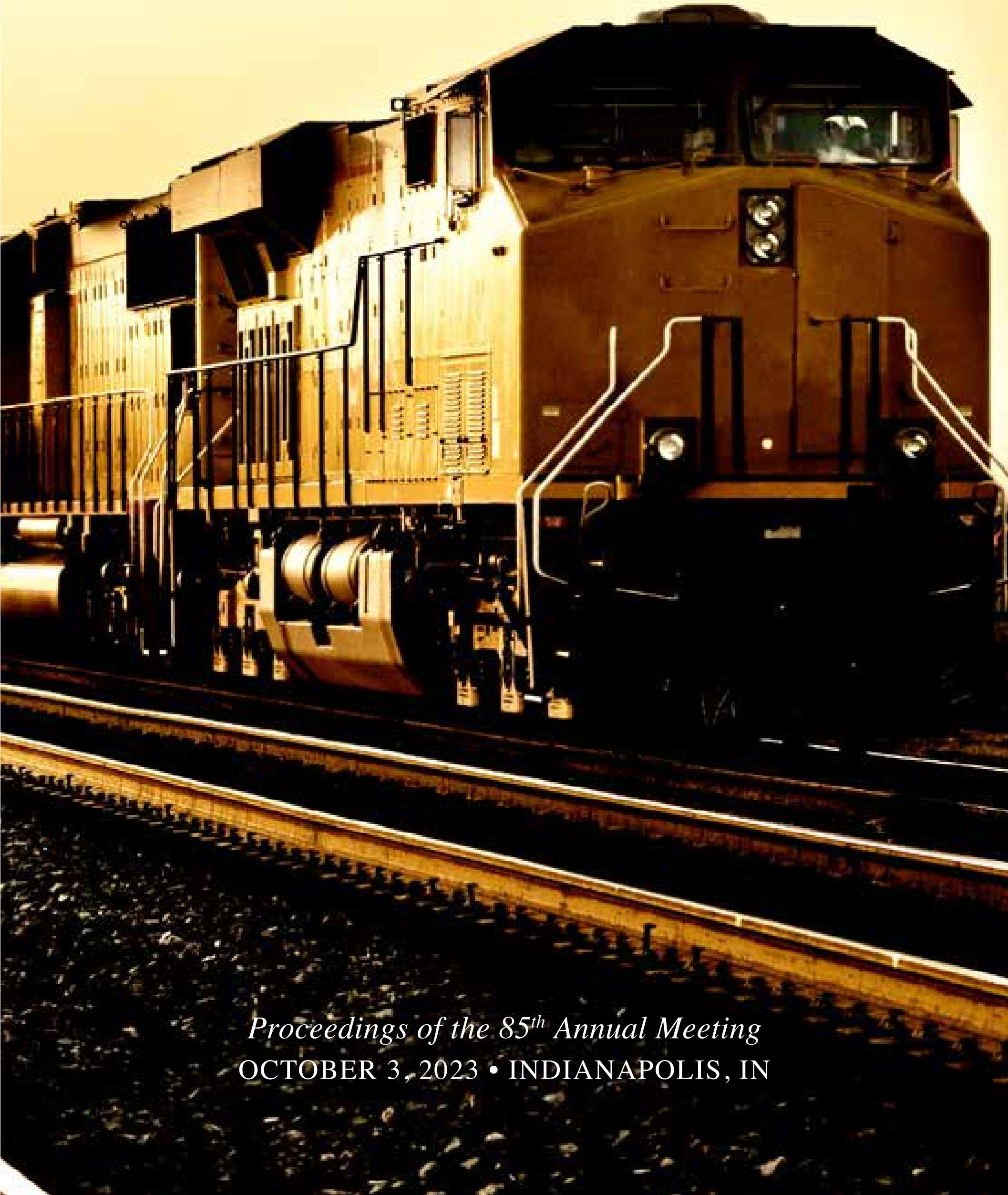
LMOA

Locomotive Maintenance Officers Association



Proceedings of the 85th Annual Meeting

OCTOBER 3, 2023 • INDIANAPOLIS, IN

2023 Advertisers Index

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2023 TOC and Index

2022 LMOA MVP RECIPIENTS

The Executive Board of LMOA wishes to congratulate the following individuals who were selected as the Most Valuable Person of their respective committees for 2022

NAME	COMMITTEE	COMPANY
Rusty Pochatko	Mechanical Maintenance	Alaska Railroad
Steve Fritz	Fuel, Lubricants & Environmental	Southwest Research Institute
Brent Brown	Electrical Maintenance	Transportation Products Sales
Tim Bernat	Facilities, Material and Support	LinkUp International

This honor is bestowed on an annual basis to those individuals who perform meritorious service and make significant contributions to their respective committee. The honoree receives a plaque that is presented to them by their supervisor.

LMOA EXECUTIVE COMMITTEE

LMOA JOINT TECHNICAL COMMITTEE MEETING – MONTREAL, QUEBEC – MAY 8-9, 2023

The LMOA annual Joint Technical Committee was recently held in Montreal, Quebec Canada.

The Executive Committee of LMOA would like to express their sincere appreciation to Ekyrail Enterprises for hosting the event. They provided financial and logistical support along with:

Canada Allied Diesel
Mikael Levy/Barton James Taban

DLL
Annie LaBlanc/ Lynne LeBlanc/ Eric Fortin

Ekyrail
David Caron/Yan Taillon/Emmanuel Taillon/ Gilles Barbeau/Emilie Gervais

Wabtec-Canada
Chad Thompson

Genesee & Wyoming-Canada
Rick McLellan

Thanks to all these companies and especially to those companies who provided tours of their facilities.

Special thanks to David Caron of Ekyrail whose tireless efforts in arranging all of the details made our annual joint technical committee meeting a success.

Tim Standish
President, LMOA

PAST PRESIDENTS

1939 & 1949	F.B. DOWLEY (Deceased) Shop Supt., C. & O. Ry.
1941	J.C. MILLER (Deceased) MM, N.Y.C. & St. L.R.R.
1942-1946, Inc.	J.E. GOODWINN (Deceased) Exec. Vice President, C. & N.W. Ry.
1947	S.O. RENTSCHILLER (Deceased) Chief Mechanical Officer, Bessemer and Lake Erie R.R.
1948	C.D. ALLEN (Deceased) Asst. C.M.O. - Locomotive, C. & O. Ry. & B. & O. R.R.
1949	J. W. HAWTHORNE (Deceased) Vice-Pres.- Equipment, Seabord Coast Line R.R.
1950	G.E. BENNET (Deceased) Vice-Pres.- Gen, Purchasing Agent, C. & E. I. Ry.
1951	P.H. VERD (Deceased) Vice-Pres.- Personnel, E. J. & E. Ry.
1952	H.H. MAGILL (Deceased) Master Mechanic, C. & N. W. Ry.
1953	S.M. HOUSTON (Deceased) Gen. Supt. Mech. Dept. Southern Pacific Co.
1954 & 1955	F.D. SINEATH, Retired Chief of Motive Power, Seabord Coast Line R.R.
1956	T.T. BLICKLE (Deceased) General Manager-Mechanical, A.T. & S.F. Ry.
1957	J.T. DAILEY (Deceased) Asst. to Pres.-Mech., Alton & Southern R.R.
1958	F.E. MOLLOR (Deceased) Supt. Motive Power, Southen Pacific Co.
1958	F.R. DENNY (Deceased) Mechanical Supt., New Orleans Union Passenger Terminal
1959	E.V. MYERS (Deceased) Supt. Mechanical Dept., St. Louis-Southwestern Ry.
1960	W.E. LEHR (Deceased) Chief Mechanical Officer, Pennsylvania R.R.
1961	O.L. HOPE (Deceased) Asst. Chief Mechanical Officer, Missouri Pacific R.R.
1962	R.E. HARRISON (Deceased) Manager-Maintenance Planning & Control, Southern Pacific Co.
1963	C.A. LOVE (Deceased) Chief Mechanical Officer, Louisville & Nashville R.R.
1964	H.N. CHASTAIN (Deceased) General Manager-Mechanical, A.T. & S.F. Ry.
1965	J.J. EKIN, JR. (Deceased) Supt. Marine & Pier Maintenance, B. & O. R.R.
1966	F.A. UPTON II (Deceased) Asst. Vice-President-Mechanical, C.M. St. P. & P. R.R.
1967	G.M. Beischer, Retired Chief Mechanical Officer, National Railroad Passenger Corp. Washington, D.C. 20024
1968	G.F. BACHMAN (Deceased) Chief Mechanical Officer, Elgin Joliet & Eastern Ry.
1968	T.W. BELLHOUSE (Deceased) Supt. Mechanical Dept., S. P. Co., - St. L. S.W. Ry.
1970	G.R. WEAVER (Deceased) Director Equipment Engineering, Penn Central Co.
1971	G.W. NEIMEYER (Deceased) Mechanical Superintendent, Texas & Pacific Railway
1972	K.Y. PRUCHNICKI (Deceased) General Supervisor Locomotive Maintenance, Southern Pacific Transportation Company
1973	W.F. DADD (Deceased) Chief Mechanical Officer, Chessie System
1974	C.P. STENDAHL, Retired General Manager, M.P.-Electrical, Burlinton Northern Railroad
1975	L.H. BOOTH (Deceased) Retired Assistant C.M.O.-Locomotive, Chessie System
1976	J.D. SCHROEDER, Retired Assistant C.M.O.-Locomotive, Burlinton Northern Railroad, 244 Carrie Drive, Grass Valley, CA 95942
1977	T.A. TENNYSON (Deceased) Asst, Manager Engineering-Technical, Southern Pacific Transportation Co.
1978	E.E. DENT (Deceased) Superintendent Motive Power, Missouri Pacific Railroad
1979	E.T. HARLEY, (Deceased) Senior Vice President Equipment, Trailer Train Company, 289 Belmont Road, King of Prussia, PA 19406
1980	J.H.LONG (Deceased) Manager-Locomotive Department, Chessie Systems
1981	R.G.CLEVENGER, Retired, General Electrical Foreman, Atchison, Topeka & Santa Fe Rwy
1982	N.A. BUSKEY (Deceased), Asst. General manager-Locomotive, Chessie Systems

1983	F.D. BRUNER (Deceased), Asst. Chief Mechanical Officer, R&D, Union Pacific RR
1984	R.R.HOLMES (Deceased), Director Chemical Labs & Environment, 600 Brookestone Meadows Place, Omaha, NE 68022
1985	D.M.WALKER, Retired, Asst. Shop Manager, Norfolk Southern Corp, 793 Windsor St, Atlanta, GA 30315
1986	D.H.PROPP, Retired, Burlington Northern RR, 10501 W. 153rd St, Overland Park, KS 66221
1987	D.L.WARD (Deceased), Coordinated-Quality Safety & Tech Trng, Burlington Northern RR
1988	D.G. GOEHRING (Deceased), Supt. Locomotive Maintenance, National RR Passenger Corp, 1408 Monroe, Lewisburg, PA 17837
1989	W.A.BROWN, Retired, I&M Rail Link, 9047 NE 109th St. Kansas City, MO 64157
1990	P.F.HOERATH (Deceased) Sr. Mech. Engr. Shop, Conrail 1534 Frankstown Rd, Hollidaysburg, PA 16648
1991	D.D.HUDGENS, Retired, Sr Mgr R&D, Union Pacific, 16711 Pine St., Omaha, NE 68130
1992	K.A.KELLER (Deceased), Supt. Locomotive Maint, Reading RR, 241 E. Chestnut, Cleona, PA 17042
1993	W.R.DOYLE, Retired Commuter Rail Transportation Superintendent, Sound Transit, Seattle, WA 98104
1994	M.A.COLES, Retired, Sr. Mgr-Loco. Engineering & Quality, Union Pacific RR, Omaha, NE 68179
1995	C.A.MILLER, Retired Mgr-Loco. Engineering & Quality, Union Pacific RR, 17745 Doras Circle, Omaha, NE 68130
1996	G.J.BRUNO, Retired, Supt.-Mechanical, Amtrak 14142 S.E. 154th Pl, Renton, WA
1997	D.M.WETMORE, Retired-Genl Supt.-Fuel Opns, NJT Rail Opns, 2005 Acadia Greens Drive, Sun City Center, FL 33573
1998	H.H.PENNELL, Retired-Ellcon National, 1016 Williamsburg, Lanne, Keller, TX 76248
1999	JAKE VASQUEZ, Retired, Asst. Supt.-Terminal Services, Amtrak, 25531 NE 138th St., Salt Springs, FL 32134
2000	RON LODOWSKI, Retired Production Mgr, CSX Transportation, Selkirk, NY 12158
2001	LOU CALA, Retired, Duncansville, PA 16635
2002	BOB RUNYON, Engineering Consultant, Roanoke, VA 24019
2003	BRIAN HATHAWAY, Consultant, Port Orange, FL 32129
2004	BILL LECHNER, Retired, Sr Genl Foreman-Insourcing-Air Brakes, Governors & Injectors, Norfolk Southern Corp, Altoona, PA 16601
2005	TAD VOLKMANN, Chief Consultant, Tadco Railroad Consultants, Omaha, NE 68179
2006	BRUCE KEHE, Retired, CMO, CSS&SB, Michigan City, IN 46360
2007	LES WHITE, Retired Applications Specialist, Bach-Simpson, London, Ontario N6A 4L6
2008	MIKE SCARINGE (Deceased), Director-Locomotives, Amtrak, Beech Grove, IN 46109
2009	DENNIS NOTT, (Deceased), Sole Member, Northwestern Consulting, Boise, ID 83703
2010	BOB REYNOLDS, Retired Sales Manager, Amglo Kemlite Laboratories, Calgary, Alberta T24 2V8
2011	JACK KUHNS, Retired, Director-Sales, Graham White, Salem, VA 24153
2012	RON BARTELS, Sr. Manager - Equipment Reliability and Electrical Engineering, Via Rail-Canada, Montreal, Quebec
2013	R. BRAD QUEEN, Manager of Locomotive Utilization - RCO, BNSF Railway, Fort Worth, TX
2014	DAVE RUTKOWSKI, President, JAB Rail Services, LLC, Green Cove Springs, FL
2015	BOB HARVILLA, VP-Sales, PowerRail, Inc., Duryea, PA
2016	STUART OLSON, Retired, Sales Director-Infrastructure, Wabtec Corporation, Alpharetta, GA
2017	JEFF CUTRIGHT, Contractor-L&J Services, Retired Norfolk Southern, Roanoke VA
2018	DWIGHT BEEBE, Temple Engineering, Liberty, MO
2019	IAN BRADBURY, President & CEO, Peaker Services, Inc., Brighton, MI
2020-21	TOM KENNEDY, President, Kennedy Rail Consulting, Omaha, NE
2022	TOM GALLAGHER, OEM Technical Liaison, Chevron Oronite, Allendale, MI

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Progress Rail-A Caterpillar Company,
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Higher Power Industries
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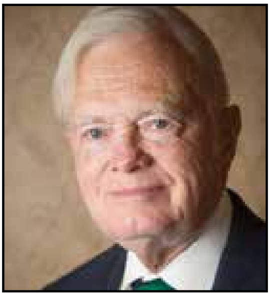
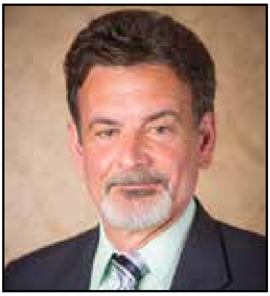
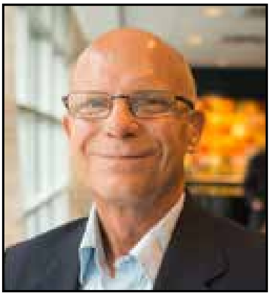
Kennedy Rail Consulting
Omaha, NE



ROBERT RUNYON
Norfolk Southern Corporation
RETIRED
Engineering Consultant
Roanoke, VA



DAVE RUTKOWSKI
President
JAB Rail Services
Green Cove Springs, FL

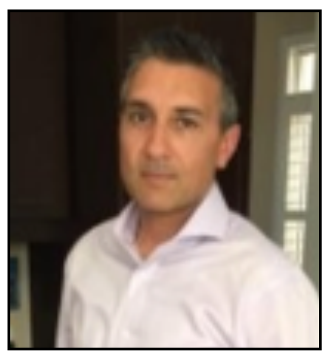


TAD VOLKMANN
Union Pacific Railroad
RETIRED
Chief Consultant
Tadco RR Consultants, Omaha, NE

Our Regional Executives

BOB HARVILLA
LMOA Past President
Vice President of Sales
PowerRail, Inc.
Duryea, PA

JERAINNE HEYWOOD
Senior Fuels and Lubricants Engineeer
Wabtec Corporation
Fort Worth, TX



AMARJIT SOORA
Senior Product Manager
ZTR
London, Ontario

2022 State of the Union Address

Tom Gallagher

October 12, 2022

Fort Worth, Texas

Ladies, Gentlemen, Colleagues, and Friends. It is a pleasure to be addressing you this afternoon in person following the long journey we have endured (professionally and personally) during the past three years. Referencing back to my Acceptance Speech one year ago, I will endeavor to employ the sage words shared by Ron Pondel on numerous occasions, "Less is More". My speech will be succinct and with a little luck, impactful.

The ongoing work of our LMOA Vice Presidents and Ron Pondel (our stalwart Secretary-Treasurer) and Executive Board may not have been visible to all as we have strived to progress forward with our CMA and RSI colleagues to re-establish this collaborative forum. The Regional Executives, Committee Chairpersons and individual members have continued the long-standing tradition identifying items of importance for enhancing the knowledge and effectiveness of the railroad industry. Their individual and collective efforts are commendable. LMOA's mission to effectively address environmental, technical, and operational challenges remains steadfast. Please give yourself a round of applause.

Looking forward, the opportunities to meet emerging regulations, lowering carbon intensity, improvement in operating efficiencies, and consumption of alternative fuels, will be adeptly addressed by one of our four respective LMOA technical committees and active participation by railroad supplier and industry members. It has been my honor and pleasure to serve as President of LMOA during the past year.

Editor's Note: Prior to Tom's State of the Union Speech, he asked those in attendance to have a moment of silence for LMOA members who passed away during the last year to include Tom Nudds, Ron Sulewski and Allen Keller

He also thanked Dan Myers and Edwin Bohr Electronics for hosting the annual LMOA joint technical committee meeting in Chattanooga, TN in May 2022

2022 Acceptance speech

Tim Standish

October 13, 2022

Fort Worth, Texas

Good morning to the LMOA executive committee, fellow members and RSI expo attendees. I am very proud to accept the position of President of the LMOA for the 2022-23 year. I was actually going to be 1st VP this year but Mike Hartung changed jobs and had to leave the 1st VP spot prior to becoming President and we wish him well for all his contributions to the LMOA. With that I thought I would have at least a year to work on my acceptance speech but had to wing it with a mere month's notice. I want to thank Tom Gallagher for his leadership over the last year as President of the LMOA and the executive committee for input and initiatives to improve the LMOA. Let's give a round of applause. We really had a lot of challenges this past year with continued Covid concerns, reorganization of the committees and working with the RSI for this year's Expo and Conference. I would also like to give a special thanks to our executive secretary Ron Pondel for his continued coordination of all activities within the LMOA, not sure how we would do this without him. Let's give him a round of applause. It's been a great conference this year with lots of great papers with two more presentations to go.

I want to thank all the committee chairs for their continued leadership along with their members for these presentations. I know the time it takes to organize these papers with everyone's normal day to day responsibilities along with submission deadlines that come all too fast. The information presented is what the LMOA is all about, helping the rail industry make day to day decisions with the latest information available to them.

I would also like to recognize the supplier community. A special thanks this year to Edwin Bohr in Chattanooga, TN for supporting our joint meeting and for all those who support either through hosting meetings or advertising in our proceedings book.

I've been part of the LMOA for over 15 years and recall my first meeting with the mechanical committee. Professionals from all areas of the rail business, welcoming me and of course eager to see when I can get my first paper written. But I do remember my first committee meeting. It wasn't the meeting itself but dinner the night before. I recall calling my wife after dinner telling her how wonderful the group was but had a couple of issues. One, I need to learn some new jokes; my dad jokes just won't cut it here. And two, I need to appreciate good beer. Well I've come a long way on one of those items. I was trying to come up with a fitting locomotive joke but I kept getting side tracked. But that aside, truly as you all know, the relationships that we make over the years is one aspect of the LMOA that makes it a successful organization. I have learned so much from committee members through their different perspectives, backgrounds and experience. The other aspect is what our members bring to the rail industry through collaboration and sharing of knowledge to help railroads improve their locomotive fleets and help plan for the future.

As President this year I want to share a couple of items that I want to focus on. One is to continue with the successful coordination we have with the AAR, EPA and CARB to bring more insight to industry trends and issues impacting railroads. There are many challenges for the rail industry, but we have a great group of members to help guide the way. If we learned anything over the last couple of years is that the only certain thing is uncertainty whether it's PSR, COVID, supply chain constraints or global issues.

Another area of focus, just like other businesses, is that the rail industry is not immune to the challenges of hiring, retaining, and bringing new employees up to speed quickly and the LMOA can help assist with information published in the past, along with future papers. We need to make sure that the industry knows that the LMOA is here to help with our knowledge along with moving forward on how we can connect virtually and have more of a social presence to share information between presentations.

So I look forward to another successful year for the LMOA and it's members, and thanks for making me your President and thanks in advance for your support.

Thanks

Past President Dwight Beebe, Temple Engineering, presents Past President's pin to outgoing President, Tom Gallagher, Chevron

Outgoing President, Tom Gallagher, Chevron gives gavel to newly elected President, Tim Standish, Progress Rail

Newly elected President, Tim Standish, Progress Rail, places LMOA blazer on newly elected 3rd Vice President, Mark Duve

Past President, Ian Bradbury, Peaker Services, presents LMOA watch to outgoing President Tom Gallagher, Chevron

Past President Ian Bradbury, Peaker Services, places LMOA blazer on newly elected 2nd Vice President, Cory Ruch, BNSF Railway

Front Row – Newly Elected President Tim Standish, outgoing President Tom Gallagher, Regional Executive, Jerainne Heywood
Back Row – Newly elected 1st VP Keith Mellin, Past President Dwight Beebe, Chair of Mechanical Committee John Hedrick, newly elected 2nd VP Cory Ruch, Past President Ian Bradbury, and newly elected 3rd VP Mark Duve

Pix of Executive Board meeting immediately following 2022 Rail Expo and Technical Conference, Fort Worth, Texas

Report on the Committee on Facilities, Material & Support

TUESDAY, OCTOBER 3, 2023

9:15 AM

Chair

Brandon Teal

Product Mgr-Railway Machine Systems

NSH USA Corporation, Albany, NY

Vice *Chair*

Tim Bernat

Account Manager

Linkup International, Roanoke, TX

Commitee Members

Derek Barber	Railroad Services Director	Nabholz Corporation	North Little Rock,AR
Dustin Berndt	VP of Motive Power	Reading and Blue Mountain Railroad	Port Clinton, PA
Josh Figurski	Purchasing Manager	Wheeling & Lake Erie RR	Brewster, OH
Bob Harvilla	Vice President of Sales	PowerRail, Incorporated	Exeter, PA *Reg Exec & Past President*
Dustin Hinkle	Technician	Railquip	Lawrenceville, GA
Robert Hodge	RR Division Manager	Industrial Maintenance & Engineering	Nashville, TN
Steve Hulshizer	Manager System Locomotives	BNSF Railway	Fort Worth, TX
Rhiannon Knezevich		Clark Industrial Power	Gilman, IL
Denise Louder	Transit Sales Manager	BBM Railway	Mt. Airy, MD
Craig Opacic	Sales & Business Development	R&W Machine	Bedford Park, IL
Tad Volkmann	Chief Consultant	TADCO Railroad Consultants, LLC	Omaha, NE *Past President*
Andrew Waltz	Asst Director of Material	Mid America Car	Kansas City, MO
Michael Zerafa	VP Business Process Development	PowerRail, Incorporated	Exeter, PA

PERSONAL HISTORY

Brandon Teal

Product Mgr-Railway Machine Systems

NSH USA Corporation

Albany, NY

Brandon Teal is the Product Manager, Railway Machine Systems at NSH USA Corporation in Albany, New York. Brandon started at NSH USA in 2006 as a Field Service Technician, installing and commissioning underfloor wheel lathes and other Hegenscheidt and Simmons products around the world. This hands-on knowledge proved valuable when he transitioned to Machine Sales Associate and later Sales Engineer. In his current role as a Product Manager, Brandon continues to lead sales efforts for the Simmons and Hegenscheidt wheel set maintenance product lines. He is involved with coordinating product specifications with Engineering, Sales, and Marketing, as well as developing strategies for next generation machines and continuous improvement of current systems.

Brandon is a native resident of Upstate New York. Brandon has been married for 11 years to wife Farrah. Brandon enjoys travelling, German Sports Cars, motorcycles, physical fitness and home renovations.

THE FACILITIES, MATERIAL AND SUPPORT COMMITTEE WOULD LIKE TO EXPRESS THEIR SINCERE APPRECIATION TO INDUSTRIAL, MAINTENANCE AND ENGINEERING FOR HOSTING OUR MEETING AND PROVIDING A TOUR AT THEIR NASHVILLE, TN PLANT ON MARCH 28, 2023. SPECIAL GRATITUDE TO ONE OF OUR COMMITTEE MEMBERS (ROB HODGE) WHO ORGANIZED THE ENTIRE EVENT.

THE COMMITTEE WAS ALSO ABLE TO TOUR THE CSX FACILITY IN THE NASHVILLE AREA AND WOULD LIKE TO THANK THEM FOR GIVING US THIS OPPORTUNITY

Storeroom Innovations

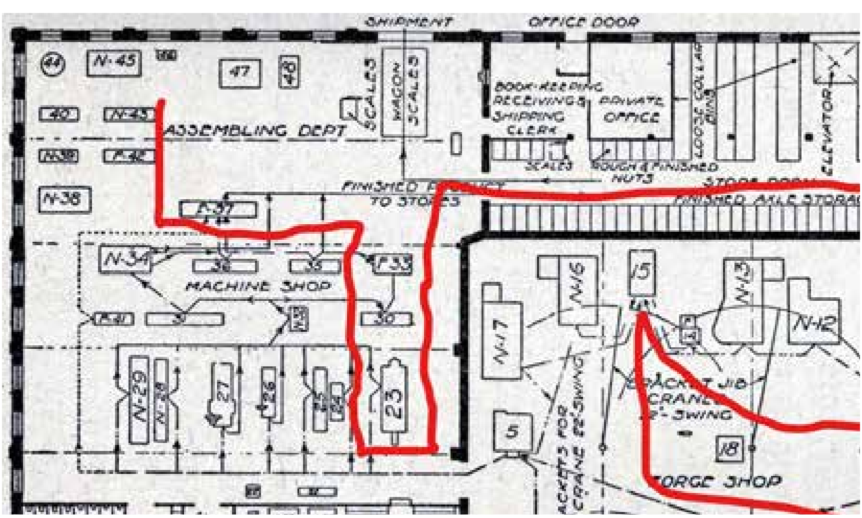
Prepared by:
Robert Hodge, Industrial Maintenance and Engineering

Storeroom innovations refer to the development of new and more efficient ways of managing and organizing storage spaces. The goal of storeroom innovations is to optimize the use of available space, improve accessibility and visibility, and enhance the overall functionality of storage areas. With the increasing demand for effective storage solutions across various industries, storeroom innovations have become an essential aspect of modern storage management.

Genesis of the Paper:

Around 2017, Norfolk Southern built three new locomotive shops, and material availability to workstations was a high priority. Having material on hand in inventory, where it was needed in the shop, and when it was needed, increased the shop's productivity.

Shop technicians in the past, would go to the stockroom for needed materials and tools. As the technician would travel from his/her workstation, or from a locomotive, stops would be made along the way to visit with co-workers.



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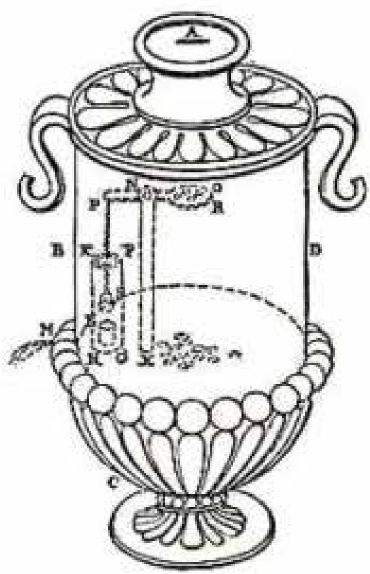
And, of course, once the technician gets to the store house, he/she would stop and chat with the store house attendant to discuss last night's game or to tell a few stories or jokes. So, a simple trip to the store house could take 30 to 45 minutes or an hour. The fully loaded cost of a technician can reach $80 to $100 per hour of compensation. That cost multiplied by dozens or hundreds of trips per day across a railroad's network of shops can end up being a huge expenditure of lost time and productivity.

How we got here:

Vending machines are automated machines that allow distribution of merchandise by accepting coins or by other forms of access (cards or PIN numbers). The earliest known reference to a vending machine is in the work of Hero of Alexandria, a Greek engineer and mathematician in first-century Roman Egypt, who invented a device that dispensed holy water in Egyptian temples.



Other early examples of coin-operated machines that dispensed tobacco were found in taverns in England around 1615. The first vending machines that sold postcards, envelopes, notepapers, and chewing gum were introduced in England in 1880 and in the United States in 1887. Vending machines have evolved and progressed over time to offer a variety of items and cater to a greater customer base.

Where we are going:

Today, industrial vending machines provide a straightforward way to store, dispense, and monitor frequently used MRO (maintenance, repair, and operations) and safety supplies. Employees input a personal code to retrieve commonly used maintenance items such as towels, gloves, degreasers, lubricants, and personal protective equipment (PPE). The system tracks the inventory and reports to the vendor all the items being used, and then invoices the customer for the materials. The vendor then restocks the vending machines on a regular basis, so the materials are always available.

The benefits of the use of vending machines are that usually only one Purchase Order is placed with the vendor each month instead of 15 to 20 orders being created to replenish inventory. Often the inventory is on consignment and is only paid for after it has been removed from inventory and used by the technician. The cost of the inventory can also be assigned to a particular job or project that the technician is completing so that all costs associated with the tasks can be accounted for in the overhead.

Fastenal vending dispensers, Wheeling Lake Erie Railway

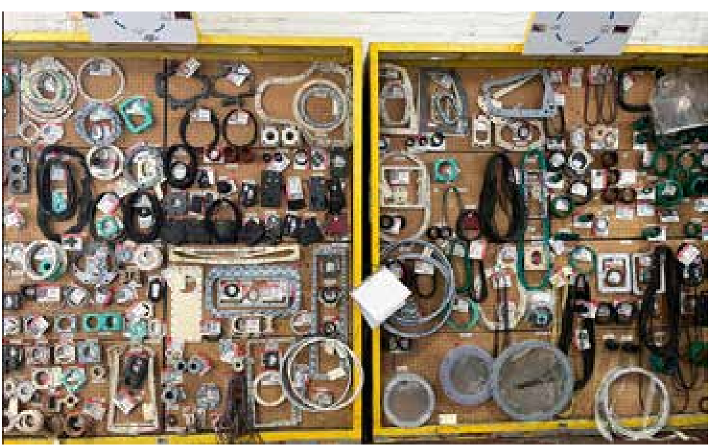
One of the most significant storeroom innovations is the use of automated storage systems. These systems use advanced technology to retrieve and store items in a highly efficient manner, thereby reducing the time and effort required for manual handling. Automated storage systems also provide better accuracy and reliability, ensuring that items are stored and correctly retrieved every time.

Another storeroom innovation is the implementation of vertical storage solutions. This involves maximizing the use of vertical space in storage areas by using tall shelving units or racks. Vertical storage solutions are ideal for small spaces or areas where floor space is limited. They allow for the storage of many items while taking up minimal floor space.

Material Carousels, CSX Huntington, WV

Large Material Carousels, CSX Nashville, TN

Storeroom innovations also include the use of modular storage solutions. These systems involve the use of interchangeable and customizable components that can be easily assembled or disassembled to meet the changing needs of a storage area. Modular storage solutions are highly flexible and can be configured to store a wide variety of items, making them ideal for businesses that require a high level of versatility in their storage operations.



Locomotive Gasket Inventory Storage, CSX Nashville, TN

Until recently, warehouse automation was equipped with automated guided vehicles (AGVs), which rely on predefined paths and human operators to complete tasks such as materials delivery. IT/OT convergence is an emerging approach which combines Information Technology and Operational Technology. Manufacturing provides data that IT uses to program robotic technology, allowing for the most efficient method of utilizing available storage automation. A significant advantage of this step is the ability to make real time adjustments to the tasks for which the automation is programmed. Weighing the cost of the technology against traditional labor utilization methods is critical. Does the cost of the advantages automation offer in efficiency, productivity, and reduced manpower offset the cost of the investment?

Another significant innovation in storeroom management is the use of robotic systems. Robotic systems can be programmed to perform a wide range of tasks, from retrieving and storing items to conducting inventory checks and performing maintenance tasks. Robotic systems are highly efficient and can help to reduce the time and effort required for manual tasks while improving overall productivity.

RFID (Radio Frequency Identification) technology is also a significant storeroom innovation. RFID systems use radio waves to identify and track items in a storage facility. This technology helps to reduce the time and effort required for manual inventory checks and provides accurate real-time inventory data.

Another innovation in storeroom management is the use of cloud-based inventory management systems. These systems use the power of the internet to provide real-time access to inventory data from anywhere in the world. Cloud-based inventory management systems are highly scalable, allowing businesses to expand their storage operations without having to invest in additional hardware or software.

Finally, the use of sustainable storage solutions is another significant innovation in storeroom management. Sustainable storage solutions involve the use of eco-friendly materials and practices to minimize the environmental impact of storage operations. This includes the use of recyclable materials, energy-efficient lighting, and green cleaning products.

In conclusion, storeroom innovations play a crucial role in modern storage management. With the increasing demand for efficient and effective storage solutions, businesses must continue to adopt new and innovative approaches to storage management to stay competitive in today's market. From automated storage systems and vertical storage solutions to cloud-based inventory management systems and sustainable storage solutions, there is a wide range of innovative storage solutions available to businesses today.

Overcoming the Supply Chain Issues

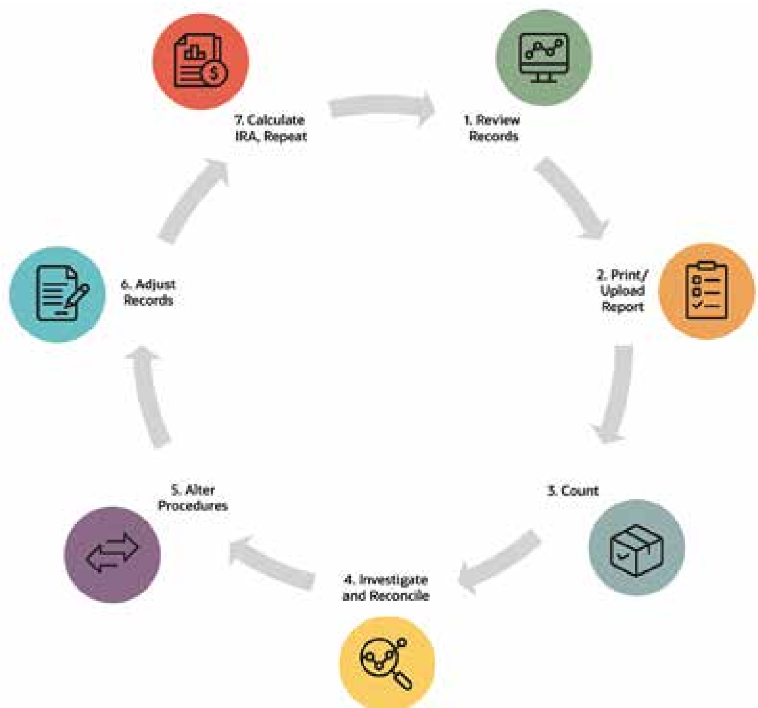
Prepared by:
Joshua Figurski
Wheeling and Lake Erie Railway
Supply Chain Practices

The procurement of materials to sustain basic operations continues to be a major economic challenge for the railroad industry. Current supply chain issues such as supply chain disruption, freight cost fluctuation, lack of data analysis systems and corporate culture can challenge the procurement process. With the challenges of current environment, all companies need to periodically reevaluate and adjust practices and policies to thrive and grow. The procurement team needs to create a collaborative team culture, one in which all departments within the company work towards a common goal of increasing revenues and eliminating delays and inefficiencies caused by the external environment.

Current Supply Chain Issues

Supply chain disruption continues to be a major issue faced by many procurement teams. Lead times for the purchase of required parts and materials are now measured in months instead of days or hours. One such example of this is with locomotive filters. These filters have now been on back order for nine months with the vendor not knowing when the requested filters will be delivered. As we all know, locomotives earn revenue. If these locomotives are not serviced properly, this causes unnecessary wear and tear. More wear and tear leads to loss of locomotive service time and greater repair expenditures in the long run and loss of revenue and potentially customers for the railroad.

One solution to this problem is to move away from a just in time inventory system, to a cycle count inventory system. With a cycle count inventory system, a company can utilize a perpetual audit procedure, to follow a regular repeated check on inventory subsets. This contrasts with traditional inventory models, in that traditional models cause a plant shut down for a period of time while the audits take place. Cycle counts are seen to be less disruptive to operations, provide an accurate view of inventory, and can be adjusted to focus on higher importance items, higher usage, or that are critical to operations (Schwarz, 2021). To transition to a cycle count will only help a company order mass amounts of product per quarter to help relieve these longer lead times.



(Abby, 2020)

Fluctuation in freight costs is another issue faced by procurement teams. With fuel cost rising across the country, freight companies are forced to raise prices to continue to generate revenue. The Wheeling and Lake Erie procurement team has seen a lot of freight bills that are in the thousands of dollars. The freight increases not only impact incoming shipments, but the costs to ship out locomotive parts that require external repair to keep the company running. All of these shipments that used to cost $500 to $600, now range from $1000 to $1500.

Our solution for increased freight cost was to transition to brokerage services. These are companies wanting to get their name out in the market to generate more business. These brokerage service solicits bids from multiple freight companies, and direct Wheeling and Lake Erie to the best price possible. With this approach, freight charges are down 33% in a time when fuel and surcharges continue to increase.

(n.a. & villa, Deanvilla Blog, 2023)

The lack of a data analysis system is another factor that impacts supply chain management. To rely on physical counts of materials, or to have employees alert the procurement team when inventories are low negatively impacts a company's ability to meet project needs. One such example where a data analysis tool could help is to track high volume locomotive parts that are essential for operations. One such area is to track periodic routine locomotive scheduled maintenance and what parts and supplies are required as part of this process. If the data is available, then these material needs can be forecasted to meet shop needs per quarterly scheduled maintenance.

Wheeling and Lake Erie Railway is currently in the process of looking into a data analysis system that will track inventory levels and utilize bar code scanning technology to track and forecast routine and complete locomotive overhauls. This data system will eliminate supply chain delays and keep locomotives moving, customer freight moving, and generate more revenue.

Corporate culture is the organization's value, vision, work and environment behaviors. It's what makes each company have a form of uniqueness. This varies in a different aspect from how the public views the organization, to employee retention on the purpose of this industry. The corporate culture of Wheeling and Lake Erie has an old style system. To where the employee gets use to the status quo and has no reason to evolve in a changing supply chain environment. These examples include the use of vendors that have been with the company since the beginning. Getting use to just ordering the materials instead of utilizing a bidding process. In many of these instances the vendors that are being utilized for locomotive needs do not have the infrastructure to maintain adequate inventory levels.

If multiple bids are sought, then the requirement should be made to identify timeframes for delivery. The bidding process and timeframe requirement can determine which vendor will be selected. This could possibly be an existing vendor, but at least alternatives can be sought. The company needs to change their corporate culture for vendor selection to survive the current supply chain environment. Companies that continue to only utilize long term relationship vendors may continue to experience supply chain disruption or delays in receiving required locomotive parts and supplies. Doing research and soliciting multiple vendor bids on a periodic basis can only help reduce supply chain disruption risk.

(n.a., Characteristics of Organizational Culture, 2023)

Price discrepancy is the variance between the advertised price and the point of sale price. These can result in shipping cost or unexpected price increases. The Wheeling and Lake Erie Company continues to struggle with having to adjust prices per month due to price discrepancy. Companies keep continuing to markup material cost due to multiple reasons which include inflation and supply chain issues. Examples include venders not having the workforce, cost to maintain facility's needs, surcharges for fuel price increase, and so on.

In conclusion, organizations need to seek out opportunities when looking to optimize issues within the supply chain. By taking the extra steps within research and development, the organization will continue to see effective change within the procurement of materials.

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Report on the Committee on Mechanical Maintenance

TUESDAY, OCTOBER 3, 2023
10:45 AM

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John Hedrick
Principal Scientist
Southwest Research Institute, San Antonio, TX

Vice Chair
Eric Dillen
Advanced Engineering Leader
Wabtec Corporation, Erie, PA

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G. Wilson	Superintendent of Cars	Iowa Interstate RR	Cedar Rapids, IA

PERSONAL HISTORY

John Hedrick

Principal Scientist
Southwest Research Institute
San Antonio, TX

John Hedrick has spent over 30 years at Southwest Research Institute (SwRI) conducting research, development and testing on medium speed and high horsepower engines. The focus has been on the effect of lube oil on fuel economy and emissions, facility engineering for a high horsepower large engines, assist in the development of a high-pressure, late cycle, natural-gas injected engine, and worked as a consultant to large-bore/medium-speed engine users in the industrial, marine, rail, and nuclear power plant settings to reduce emissions and determine causes of various engine failures.

Most recent focus has been targeted on performance and emissions related to medium speed engines used in locomotives, stationary power generators, and marine applications. He has also become a Test Inspector for European certification of railroad engines by the International Union of Railroads (UIC 623 & UIC 624 tests). Also awarded eleven US Patents that focus on engines and their supporting systems.

Married to his "Better ¾", Peggy and they have two grown sons. Graduated from Texas A&M University in 1989 with a Bachelor's Degree in Engineering Technology with a focus on Thermal and Fluid Systems.

THE MECHANICAL MAINTENANCE COMMITTEE WOULD LIKE TO EXPRESS THEIR SINCERE APPRECIATION TO SOUTHWEST RESEARCH INSTITUTE FOR HOSTING OUR MEETING IN SAN ANTONIO, TX ON MARCH 1, 2023.

THE COMMITTEE WOULD ALSO LIKE TO THANK PEAKER SERVICES IN BRIGHTON, MICHIGAN FOR HOSTING THEIR MEETING IN JULY 2023. SPECIAL THANKS TO ONE OF OUR COMMITTEE MEMBERS, IAN BRADBURY, FOR HIS GRACIOUS INVITATION AND COORDINATING A FOLLOW UP MEETING WITH THE EPA IN ANN ARBOR, MICHIGAN. IAN IS A PAST PRESIDENT OF LMOA

Thermoplastic Polymer Bushings in Locomotive Brake Applications: Benefits, Challenges, and Solutions

Prepared by:
Tom Casper (PowerRail) and Murray MacBeth (GWRR)

Introduction

The purpose of this paper is to highlight the importance of considering the use of thermoplastic bushings in locomotive brake applications. Thermoplastic bushings can offer several benefits when applied to locomotive brake rigging and truck assemblies. These benefits include, but are not limited to; 1) elimination of "frozen" or seized brake heads, 2) improved wear properties resulting in longer life of mating parts and reduced maintenance costs, 3) extended life between overhauls, 4) deferred maintenance justification due to longer life and potential elimination of overriding brake shoes resulting in an FRA Defect.

Issues Related to Steel-on-Steel Friction in Locomotive Brake Rigging

When the brake head assembly ferrule seizes to the brake head bushing in standard steel assembly applications, there are several issues resulting from the seized mating parts. The ferrule will either seize to the bushing and the brake head will lock or seize in place, resulting in a "frozen" brake head (Figure 1). Or, the ferrule will seize to the brake head bushing and pull the steel bushing out of the casting, resulting in a binding or floppy brake head. Both situations can result in FRA defects and will exaggerate overriding brake shoe issues (Figure 3), damage to the brake shoes, brake heads, and locomotive wheels. The illustrations below are not the only issues the locomotive mechanic encounters relative to steel-on-steel friction issues. The below examples are simply the most common and problematic issues.

Figures 1-3; GP Single Shoe live-lever brake head locations *(converted from Clasp Brakes). Issues resulting from steel-on-steel friction, live-lever defects due to excessive wear, and seizures of mating parts. The right-side bushing has seized to the steel ferrule causing "frozen" brake head (Figure 1); Entire Truck with two defects (Figure 2); Overriding brake shoe (Figure 3).*

Figure 1

Figure 2

Figure 3

In addition to seized or "frozen" brake heads, there are other examples of steel-on-steel friction issues relative to locomotive brake rigging. In some cases, when the steel ferrule seizes to the brake head bushing, normal lateral forces and brake pressure applied to the brake head will allow the bushing to remain seized to the ferrule, and the ferrule will "pull" the brake head bushing partially or completely out of the brake head casting. The result is a loose or floppy brake head that will not allow consistent or proper brake shoe application to the wheel. The brake head assembly will not be aligned to the wheel, and binding can occur causing other damage to the rigging and or locomotive wheel.

When out-of-line (overriding) brake shoes are discovered, the FRA inspector should try to determine the root cause of the defect (i.e., bushings, hangers, pins, etc.). Also, the wheel should be examined for thermal stress at the edge of the wheel, as evidenced by small thermal cracks, metal flow, or discoloration. The defect of overriding brake shoes can be caused by worn pins, bushings, hangers, frozen and seized brake heads, and brake heads where the bushing has failed to remain in the brake head casting.

Another example of a problematic steel-on-steel application are the bushings applied to the swing hanger assembly on two-axle Blomberg trucks, as shown in Figure 4. These particular bushings experience significant wear and tear, heavy loads, and lateral-horizontal-vertical movement. Depending on the operation, new steel swing hanger bushings can fail inside of a few months. The hardened swing hanger bushings also cause significant wear to the swing hanger forging, and will eventually wallow out the bushing holes causing the swing hanger to be condemned prematurely.

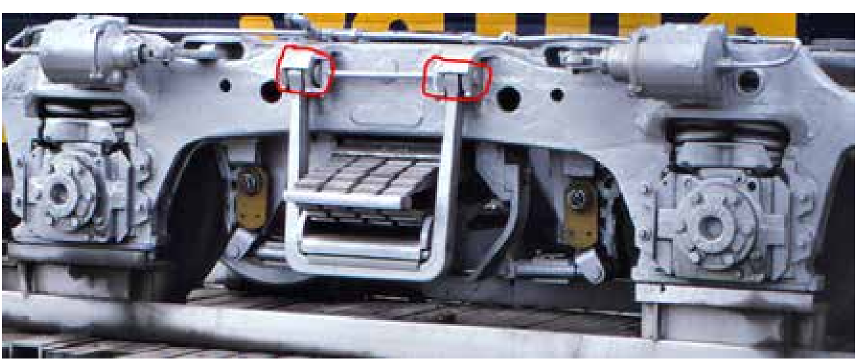

Figure 4 – Location of bushings on the swing hanger assembly on two-axle Blomberg trucks

Solutions to Friction Issues in Locomotive Brake Rigging: Thermoplastic Bushing Application and Material Details (Fitting and Function)

When fitting thermoplastic bushings, it is important to ensure all housing and pin dimensions are within the tolerance band stated on the relevant drawing. Additionally, the housing should be free of grease, corrosion deposits, burrs, paint, debris, etc. The correct bushing should be selected from the identification item number on the relevant drawing, and excessive force or lubricant should not be used when pressing the bushing into the housing. It is also crucial to check that the bushing cannot be moved by hand and there is sufficient clearance to enable free rotation. If there are binding or tight spots, examine the housing for damage or irregularity, and re-fit. The interference fit is sufficient such that no further retention methods (keeper plates, adhesives) are required.

The operating temperature limitations for these thermoplastic brake bushings are -212°F to 392°F (-100° C to +200° C). Moisture absorption and any small dimensional change as a result, are considered in the running clearances as determined by the manufacturer prior to production. There are no detrimental effects on thermoplastic bushings as a direct result of pin corrosion or contamination by brake dust.

The thermoplastic bushings researched in this paper are interchangeable with OEM hardened steel bushings, provided the housing condition is still within the originally supplied tolerance range. If the housing is worn, oversized thermoplastic bushings can be supplied and colored differently for ease of identification.

The thermoplastic bushings researched in this paper replace and improve upon the performance levels offered by materials such as bronze, brass, hardened steel, laminates, and incorrectly specified low-performance plastics. They have been proven to increase component life, extend the life of mating parts, increase service intervals, and be cost-effective. They do not require special fitting tools and are lightweight and easy to handle.

Seized Brake Head Solution: "Dead-Lever," Brake Head Assembly Locations

Through testing and usage, some locomotive owners have experienced brake-head-thermoplastic bushing "walk" due to normal lateral movement of the brake head while the locomotive is in operation. In three separate and distinct situations, the non-captive thermoplastic bushings at dead-lever brake head locations have "walked" out of the brake head casting. In every dead-lever brake head location for GP 2-axle trucks, and SD Flexicoil and HTC trucks, there is a ferrule applied and inserted into the brake head bushing as part of the brake head lever assembly arrangement, as shown in Figures 5 through 8.

The solution provided to eliminate bushing walk, is to use a steel bushing at the dead-lever brake head locations, with thermoplastic ferrules inserted into the bushings. In this scenario, the mating thermoplastic ferrules eliminate the steel-on-steel friction issues and the possibility of the ferrule seizing to the brake head bushing. Therefore, eliminating the possibility of brake head seizures and bushing failure. Improved wear properties of the mating parts will also allow for longer intervals between required maintenance, overhaul, and eliminate the FRA defect of overriding brake shoes.

Best Practice Figures 5-8; Dead-Lever Brake Head Mating Parts (Ferrules with Steel Brake Head Bushings)

Figure 5 - GP Clasp; Outside Dead-Lever Brake Head Assembly Application

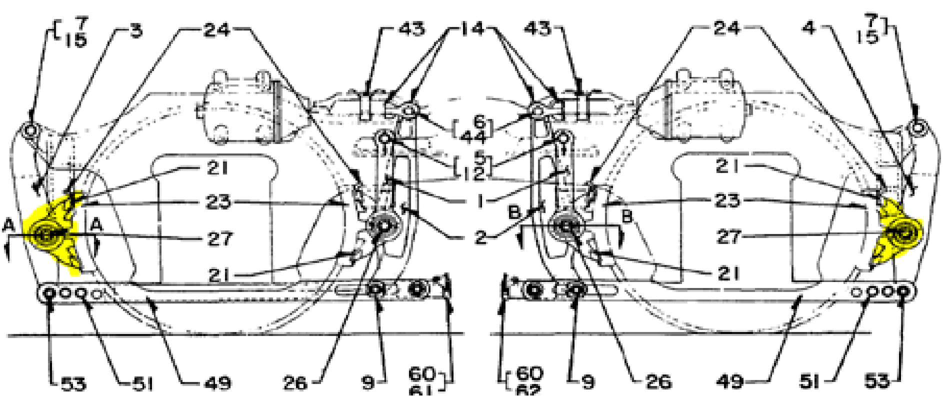

Figure 6 - GP Clasp Truck Assembly, Dead-Lever Brake Head locations (steel bushing mates with thermoplastic ferrule)

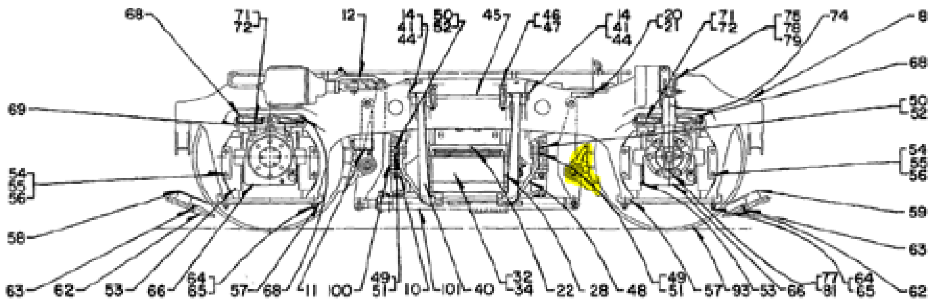

Figure 7 - GP, Single Brake Shoe Dead-Lever Brake Head location (steel bushing mates with thermoplastic ferrule)

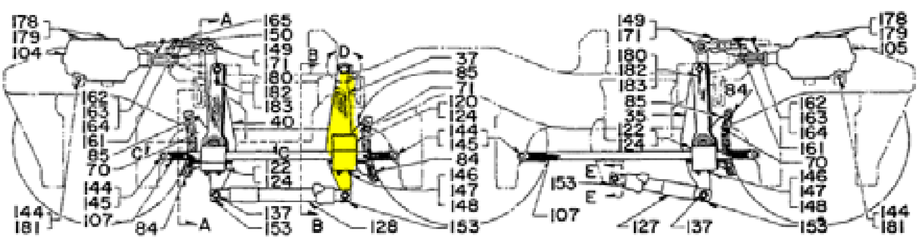

Figure 8 - SD40, HTC and/or Flexicoil 3-axle truck assembly; Dead-Lever Brake Head location (steel bushing mates with thermoplastic ferrule)

Seized Brake Head Solution; "Live-Lever" Brake Head Assembly Locations

Through testing and monitoring, the solution providing the best wear properties at the live-lever brake head locations resulted in using the OEM steel brake hanger hex style ferrules inserted into a thermoplastic bushing applied to the brake heads. There is no risk of the thermoplastic brake head bushings walking out due to normal lateral movement. The bushings in live lever brake head locations are captive within the assembly by the brake hangers and steel hex ferrules. There have been no reported mechanical issues at live-lever brake head locations where thermoplastic bushings have been applied to the brake heads, resulting in complete elimination of brake head seizures relative to the entire population of locomotives outfitted with thermoplastic bushings.

Best Practice Figures 9 - 12; Live-Lever Brake Head Mating Parts

Figure 9 - GP and/or SD, inside, Live-Lever Brake Head Assembly Applications (steel ferrule with thermoplastic bushing)

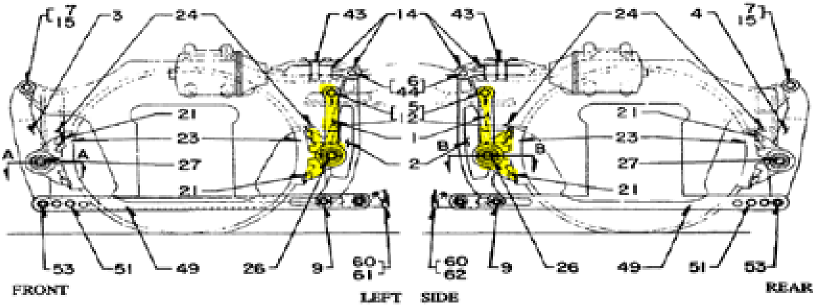

Figure 10 - GP Clasp, inside, Live-Lever Brake Head Assembly locations (steel brake hanger ferrule with thermoplastic bushing)

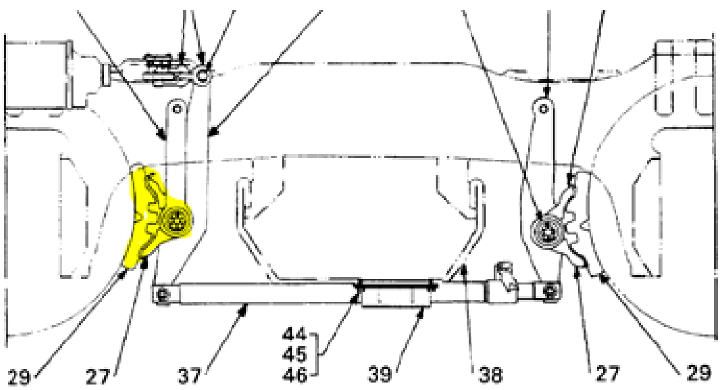

Figure 11 - GP OEM Single Shoe, Live-Lever Brake Head Assembly location (steel ferrule with thermoplastic bushing)

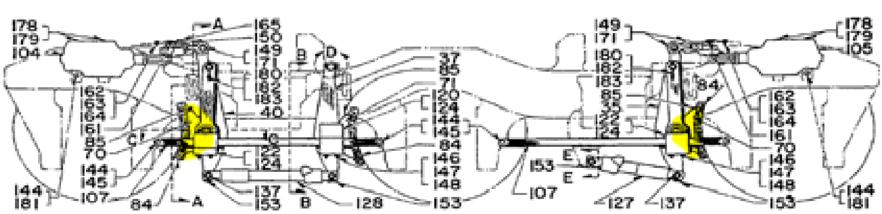

Figure 12 - SD Flexicoil and/or HTC Single Shoe, Live Lever Brake Head Assembly locations (steel ferrule with thermoplastic bushing):

Additional Benefits of Thermoplastic Bushing Applications

Other benefits experienced when using thermoplastic bushings in lieu of hardened steel bushings include easier application of the bushing. When applying thermoplastic bushings to steel brake rigging and truck frame cluster bracket assemblies, a press is not needed, as shown in Figures 13 - 15. The researched thermoplastic bushings in this paper can be applied to the rigging and truck frame with a rubber mallet or a block of wood, saving production and labor time. Additionally, changing a bushing in the field or at overhaul becomes a simple task.

Best Practice Figures 13-15; Installation of a thermoplastic bushing to a steel brake head

Figure 13

Figure 14

Figure 15

Longer Life of Mating Parts

A historic joint venture test with the locomotive OEM and the thermoplastic bushing OEM, resulted in some amazing results. After 1 million miles of operation over a ten-year period, brake hanger and brake head pins applied to the assemblies with thermoplastic bushings installed were able to be re-applied after tear down and inspection of the mating parts. Minimal wear of the bushings was detected with a micrometer, and all the pins were re-applied to the truck assemblies.

Figures 16-17; Examples of brake hanger and brake head pins after 1 million miles and 10 years of operation

Figure 16

Figure 17

Swing Hangers with Thermoplastic Bushings Applied

The swing hanger bushing location represents the first application of thermoplastic bushings by GWRR. The issue was repeated failures of hardened steel bushings in the swing hangers (location of these bushings are shown in Figure 4), and related damage to the swing hanger forgings. Once thermoplastic bushings were applied (as shown in Figure 18), the failures were eliminated, and the issue was resolved. After this initial test, GWRR Mechanical personnel applied this solution to dozens of locomotive truck assemblies within their fleet, and the application of thermoplastic bushings at the time of truck overhaul continues today.

Figure 18 - Application of thermoplastic bushings in swing hanger

Conclusion

In summary, the locomotive inspection and mechanical evaluations performed by GWRR personnel since 2018 indicate at least 20 labor-hours are saved at every inspection when comparing thermoplastic-bushed truck frame assemblies to steel-bushed truck frame assemblies. Technicians and inspectors have experienced significantly reduced maintenance issues when working on thermoplastic bushed locomotive trucks, resulting in a reduction in repair costs and associated labor costs. Regarding the GWRR locomotive population of thermoplastic bushed truck assemblies, no seized brake heads with thermoplastic bushings or ferrules applied have been reported from the field. Additionally, there have been no reports or evidence of overriding brake shoes, or “floppy” brake heads where the ferrule has seized to the brake head bushing and pulled it from the casting. Based on this multiyear investigation, the use of thermoplastic bushings in locomotive brake and truck assembly applications offers several benefits. Primarily, the thermoplastic bushings evaluated in this paper are proven to be cost-effective, extend the life of mating parts, reduce maintenance, labor, and materials costs, while eliminating brake heads seizures and overriding brake shoes (FRA defect).

Reducing GHG Emissions Through Aerodynamics on North American Railroads

By:
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Gregory Wright, Wabtec, USA

Abstract

Researching and implementing aerodynamic improvements on freight rail cars and locomotives holds significant promise for reducing GHG emissions and operational costs. Simple, lightweight, and inexpensive in-field modifications are possible to most major rail car types such as covered hoppers, autoracks and boxcars. Aerodynamic modifications to the locomotive shape is also discussed and the range of drag reduction and associated fuel savings reviewed. Various tools are available to measure and calculate drag reduction such as Computational Fluid Dynamics (CFD), wind tunnel and full-scale prototype testing both in controlled environments and freight revenue service.

Class I railroads in North America have partnered with the Science Based Targets initiative (SBTi), committing to meeting very aggressive GHG emissions goals by anywhere from 2029 to 2034 depending on the railroad. Three of the six Class I's have committed to a net-zero target emissions profile by the year 2050. Historically, the rail industry has improved fuel efficiency by an average of 0.9% per year going back two decades. If they continue that glide slope to 2030, they will collectively have a 20% gap between where their current improvement trend will take them and where they will need to be in order to meet their SBTi goals. New approaches will be required in the immediate future to help close that gap.

Aerodynamics is one possible solution that the trucking industry has used for decades with the help of DOE funding through different SuperTruck programs. Cumulative fuel economy improvements of 25% or more have been achieved compared to model year 2009 Class 8 tractors and trailers through aerodynamics alone.[1,2,3,4]

There are over one million freight cars in service in North America with 40K to 50K new rail cars being built each year. Introducing simple modifications to the new builds as well as targeting the newer car fleets with in-field modifications can jump start the transition to more aerodynamic rolling stock. While the trucking industry benefited from over $323 million dollars in DOE funding through the

various SuperTruck programs, the rail industry needs to make the investment to move aerodynamic research and implementation forward.

OEMs must drive a proactive approach to introducing aerodynamic concepts into future builds and some of them have already done so in the recent past or have plans to do so in the near future. Customer car owners and leasing entities will also have a role to play as many commercial issues will need to be addressed such as who pays for modifications versus who benefits in terms of fuel savings as well as car interchange issues with multiple railroads sharing associated fuel savings.

The benefit of aerodynamic improvements will last long into the future given that they are fuel agnostic. No matter what fuel source or combination of sources power locomotives far into the future, aerodynamic enhancements will ensure that less energy is consumed as the industry reaches towards a net zero carbon footprint target by 2050. Even under the scenario of zero emissions battery electric locomotives aerodynamic improvements would still help by increasing range and potentially speed.

Historical Fuel Savings Industry Performance

The rail industry commonly uses a fuel efficiency measure of Gallons per Thousand Gross-ton-Miles which has been tracked for many decades. Figure 1 shows each of the seven Class 1 railroads going back to 2001 with KCS only disclosing their fuel efficiency metric starting in 2011. Notice the Canadian railroads have generally been the best performers and starting in 2013 both distanced themselves from their US peers. Most railroads stay in their own fuel efficiency "lane" except for CSX that now looks more like a Canadian railroad in terms of exceptional fuel efficiency. Still, there remains a 31% gap between the best and most challenged railroads looking at the most recent year of 2022.

Figure 2 shows the weighted average performance of the Class I railroads, so it is an industry performance metric that indicates a 0.9% annual improvement going back to 2011. There are some anomalies such as 2018 and 2022 underperforming and 2020 overperforming. If we look at the aggregate SBTi goals out to 2030 and the glide slope required for the industry to achieve that goal, it will require from 2022 forward, a 3.1% year over year improvement in fuel efficiency to meet the SBTi targets. Whereas on the current historical glide slope, that would create a 20% percent gap between where railroads need to be and where they likely will be on their current trajectory or historical glide slope. Per the more challenging 1.5 degree Celsius SBTi goals to be announced by 2025 mentioned earlier, this will likely mean the slope of the line shown in Figure 4 will become even steeper.

Reference LMOA paper[5] for the railroad specific SBTi goals and their various approaches to attain those GHG emissions reduction goals.

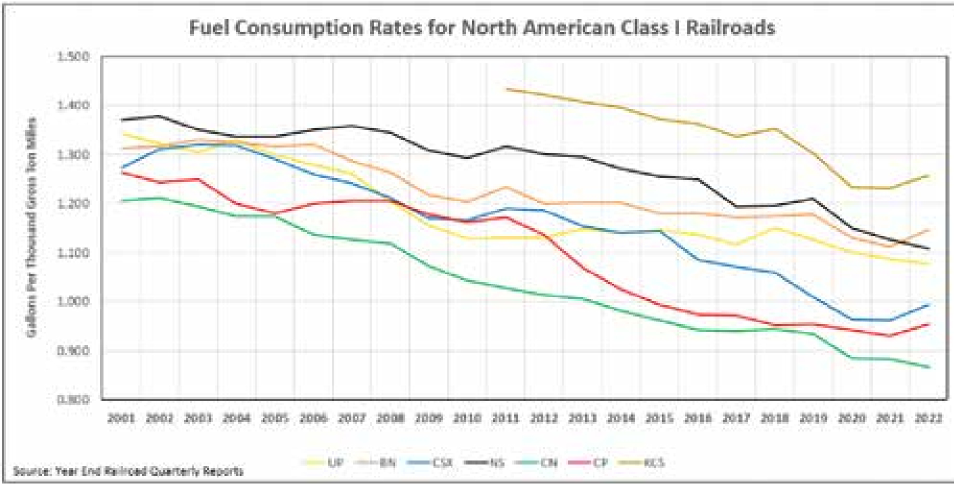

Figure 1 – Fuel Efficiency for Class 1 Railroads

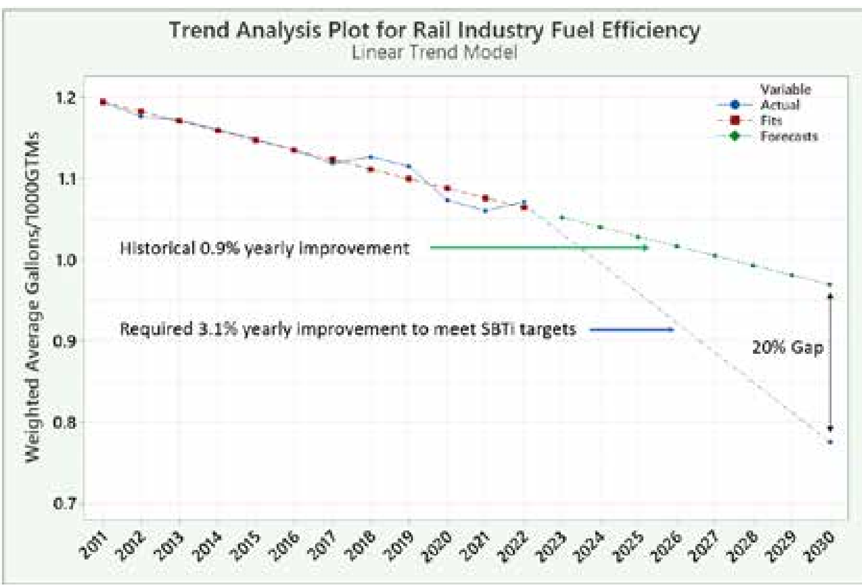

Figure 2 – Historical Glide Slope versus SBTi 2030 Goal

The Power of Aerodynamic Improvements

The shape of rail cars and locomotives within the North American freight industry have not changed in many decades and it is evident that little, if any

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The system, which provides 30 sq. in. more windshield coverage than pneumatics, comes as a complete kit to streamline installation, which can typically be completed in a day.

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678-722-5261 www.acsrail.com Sales@acsrail.com consideration was made for aerodynamic efficiencies in the current and past designs being offered by the major OEMS for cars and locomotives.

A major western Class I railroad has historically performed a considerable amount of research on aerodynamic improvements to both locomotives and freight rolling stock. Many test methods were used including wind tunnel testing, Computational Fluid Dynamics (CFD) research, and full scale testing, both at TTCI in Pueblo, Colorado and in revenue freight service.

Figure 3 shows the curve of aerodynamic and other forces and the resistance required for each, to move trains at various speeds. Given all railroads are focused on increasing network speed and providing stellar service to their customer base, rail aerodynamics should play a future role in helping conserve fuel as network velocity increases.

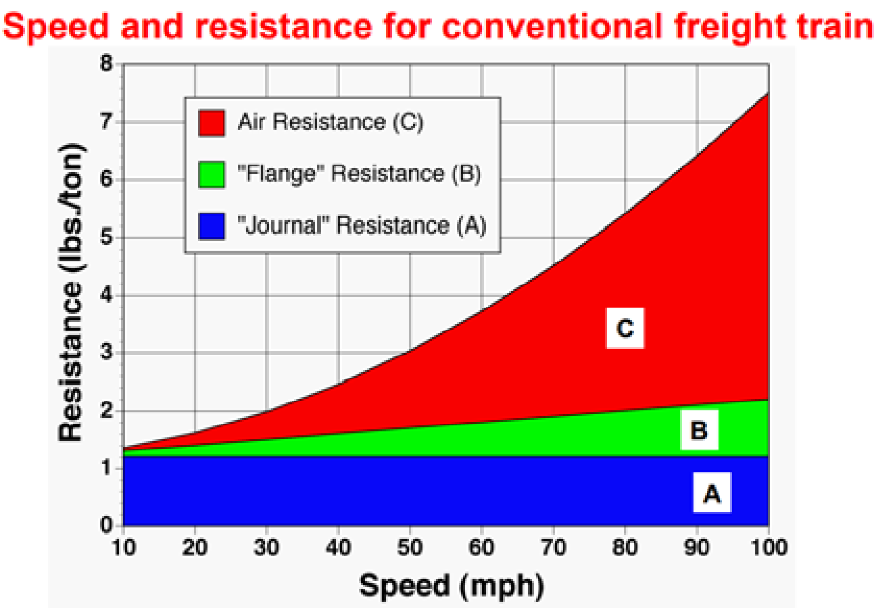

Figure 3 – Resistance Forces for Freight Trains at Various Speeds[6]

There is a precedent for aerodynamics within the rail industry beginning in the late steam locomotive era during the 1930's. Streamlining steam locomotives was an attempt to conserve energy in the form of coal fuel for high speed passenger service.[7] While the aerodynamic improvements were only substantial at higher speeds, it also served as a marketing tool to attract more passengers to travel by rail as the automobile was quickly gaining favor as the preferred mode of personal transport during that time frame. Figure 4 shows a J-3a Hudson on the Twentieth

Century Limited operating between New York and Chicago.

Figure 4 – J-3a Hudson, from Richard Leonard's New York Central Collection[8]

General Motors Electro-Motive Division (EMD) designed the diesel electric F-unit (designation for fourteen hundred horsepower) which was produced between 1939 and 1960 as a freight locomotive with longer EMD E-units designed for passenger service equipped with twin 900-horsepower diesel engines. These F-units were very successful "first generation" road or main line diesel locomotives and were largely responsible for replacing steam locomotives in freight service.[9] Figure 5 shows a typical F-unit locomotive with an aerodynamic front nose design.

Unfortunately, the diesel electric locomotive designs from that point forward were built with little regard to aerodynamics, rather a boxy rectangular design that was the least expensive to manufacture at the expense of energy saving aerodynamic treatments. Freight car designs have also neglected simple aerodynamic principles which if instituted, could save 10% or more in diesel fuel savings and associated GHG emissions reduction.

The sections that follow will outline the simple modifications possible, to both new builds and existing car and locomotive fleets, that could reverse the neglect of aerodynamics. The beauty of aerodynamic improvements is that they are agnostic to fuel source, so they will save diesel fuel today and into the near future and whatever power source(s) are settled on into the distant future as the rail industry moves away from fossil fuels.

Figure 5 ATSF 309L with Train #23 The Grand Canyon in siding at Springer, NM, August 19, 1967, A. Roger Puta[10]

DOE SuperTruck Program

The SuperTruck program was started by the Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) in 2010 as a means of encouraging Class 8 tractor-trailer OEMs for the development of new vehicle technologies aimed at increasing freight efficiency. The program is now in Phase 3 and has awarded $323 million to various OEMs over the last 12 years.[11,12,13]

Phase 1 of the program (2010 to 2015) required the four participating Class 8 OEMs to each produce a technology demonstrator vehicle whose freight efficiency (ton-miles per gallon) was at least 50% higher than their best in class 2009 on-road truck. Phase 2 (2016-2021) increased the goal to a 100% freight efficiency improvement over the 2009 baseline. Most teams achieved over 100% freight efficiency improvement within Phase 1 timelines and further improved vehicle efficiency in Phase 2 through developments in engine and overall vehicle technologies. As part of the program, OEMs also executed a phased adoption of these advanced technologies into their mainstream production vehicles, to ensure efficiency gains for the end consumer.

Aerodynamic improvements of the tractor-trailer system played a major role in achieving these efficiencies, with teams showing an average 25% fuel economy improvement through drag reduction.[1,2,3,4] These improvements consisted of new designs for tractors as well as add-on aero treatments such as side skirts and front/

rear fairings for the trailer.

The overall improvements in freight efficiency have yielded an estimated savings of over 300 million barrels of oil per year or roughly $30 billion per year in fuel savings for the trucking industry,[14] with individual operators saving up to $20k per year. Phase 3 of the program (2022-2030) is now ongoing, focusing on greenhouse gas reduction through supporting the development of battery and fuel cell EVs along with charging infrastructure.

Virtual aero certification for Class 8 Trucks – EPA GHG Regulations

Tailpipe CO_2 emissions from Class 8 trucks are regulated by the EPA through its GHG Phase 1 and Phase 2 standards, issued in 2013 and 2021 respectively. As part of these regulations, Class 8 OEMs are required to provide numerous data points about a given vehicle configuration into an EPA simulation tool which is then used to calculate the vehicle's CO_2 emissions. One of the key inputs in this process is the configuration's aero drag coefficient. Due to the large number of component variants per truck model, each vehicle can have thousands of possible configurations, all of which must be certified in order to be sold and all of which must have their aero drag coefficient evaluated. Moreover, each aero drag evaluation must be carried out at two yaw angles (±4.5°) to produce a yaw-averaged drag coefficient that accounts for real-world wind conditions.

Given the large number of aero drag data points required for vehicle certification, the EPA allows for the use of CFD simulations to obtain this data and regulates the quality of these simulations through the relevant SAE standards. Specifically, SAE J2966 (Guidelines for Aerodynamic Assessment of Medium and Heavy Commercial Ground Vehicles Using Computational Fluid Dynamics) standardizes the requirements for CFD assessments from various technologies in order to be used in the virtual vehicle certification process. Additional CFD specifications are codified in 40 CFR § 1037.532 as part of the GHG Phase 2 rule. Leveraging CFD for virtual certification in place of scale model or full-scale testing has allowed OEMs to save millions of dollars and months of time, allowing them to complete their certification workload without any delays or adverse impacts to ongoing product development cycles.

CFD – History and Applications in Ground Transportation

Modern commercial Computational Fluids Dynamics (CFD) tools have been used among ground transportation industries including automotive, heavy truck and rail for aerodynamic applications since the 1980s. While CFD was initially used as a low-fidelity precursor to wind tunnel or full scale testing, improvements in modeling fidelity and the widespread availability of high performance computing have led to broader adoption of CFD for detailed engineering design and virtual certification.

Today, automotive OEMs leverage CFD as part of analysis-led vehicle development starting at the early concept stage with large-scale parallel Design of Experiment simulations. Such studies enable the OEM to identify regions of greatest aerodynamic benefit within a large design space and pursue further aero drag reduction through optimization at both the component and full-vehicle level. This is especially critical in the design of electric vehicles, which require maximizing operating range while meeting their unique safety and packaging criteria. As the design matures, virtual certification of vehicle configurations is carried out with CFD, adhering to processes and best practices that are approved by regulatory bodies both in the US and globally.

The heavy truck and bus industries also employ CFD widely for aero drag reduction, with OEMs pushed by fleet owners to develop and refine vehicle designs that minimize fuel consumption. In addition to its use as a design and certification tool, commercial vehicle OEMs utilize CFD to analyze scenarios unique to their vehicles including the impact of crosswinds on vehicle stability and tip over and the aero impact of vehicle platooning (drafting).

CFD use in the rail industry has historically focused on high-speed passenger rail, with the need to minimize aero drag and improve vehicle stability. However, with rising rail freight volume and fuel costs, freight rail OEMs and operators have increasingly turned to CFD to improve locomotive and railcar aero drag for fuel savings, while also addressing wind-induced tip over and other safety concerns. These include analyses of the train in isolation and also in relation to its surroundings, including elevated terrain and tunnels.

Outside of aero drag analysis, CFD tools are widely applied across the ground transportation industry to address various design problems in thermal management, cabin airflow, human comfort and aeroacoustic noise suppression.

<u>The Freight Railcar Equipment Universe</u>

There are well over 1 million freight rail cars in service in North America – which cars to begin modifying first and why is not a trivial question. Figure 6 shows the various types of freight cars.

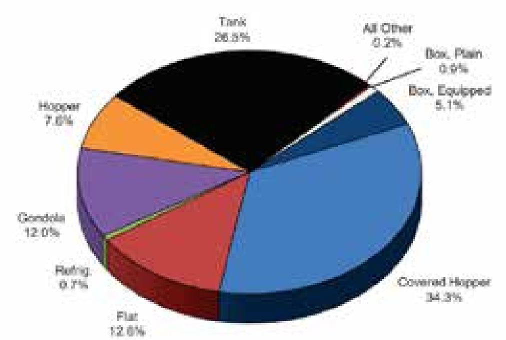

Figure 6 – North American Freight Cars by Type[15]

Simple and lightweight in-field modifications have already been identified for covered hoppers, boxcars, autoracks (a portion of the Flat designation in Figure 6) and intermodal equipment. This represents over half of the different car types currently in service. As to the other half, tank cars are by their shape already the most aerodynamic type of car[16] and the other car types, primarily gondolas and hoppers have opportunities that can also be investigated. Figure 7 shows train drag area by major railcar type where each train consists of 3 locomotives and 90 railcars.

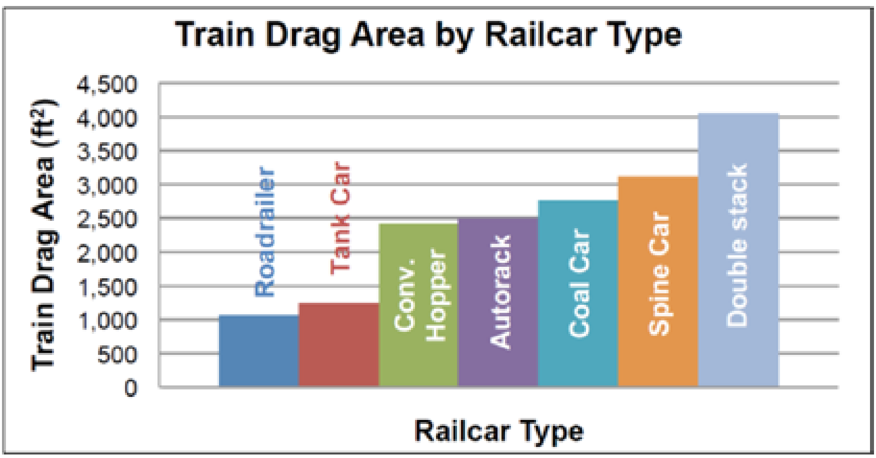

Figure 7 – Train Drag Area by Major Railcar Type[16]

Prioritization should fall along various guidelines for in-service cars while new build cars will benefit from simple shape modifications installed during the build process for perhaps 1% to 2% extra cost. Figure 8 shows a matrix divided into three categories of owned cars, leased cars and new builds. For owned cars, those with high utilization such as covered hoppers and autoracks should be given priority. For leased cars, those which are the newest and commercially viable should likewise have the highest priority for in-field modifications. New builds are among the easiest to change as there is no need to take them out of service, and given the simplicity of the modifications, the time to manufacture should remain unchanged. Also, given there are anywhere from forty to fifty thousand new builds being introduced into service any given year, this helps to quickly introduce more aerodynamic car designs reducing fuel consumption and emissions quickly.

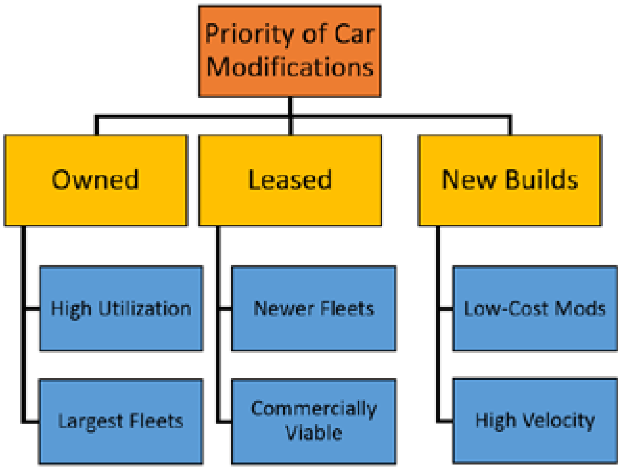

Figure 8 – Prioritization Matrix

Covered Hopper Aerodynamic Modifications

An example of simple modifications made to covered hoppers is shown in Figure 9 where both the cavities around the bottom hopper chute (highlighted in red) and top walkway supports have been enclosed providing a more aerodynamic and smooth side contour, removing sharp angles and open voids which create air turbulence and resulting excessive drag.

These lightweight modifications or aerodynamic treatments were simple to design and install and did not interfere with any visual inspection requirements.

Figure 9 – Covered Hopper with Aerodynamic Modifications Installed (Red Outline Highlighted)

Surface pressure plots shown in Figure 10 indicate far less air impingement due to closing off the gaps between the dump gates. All these seemingly small modifications can add up to a big improvement in fuel efficiency.

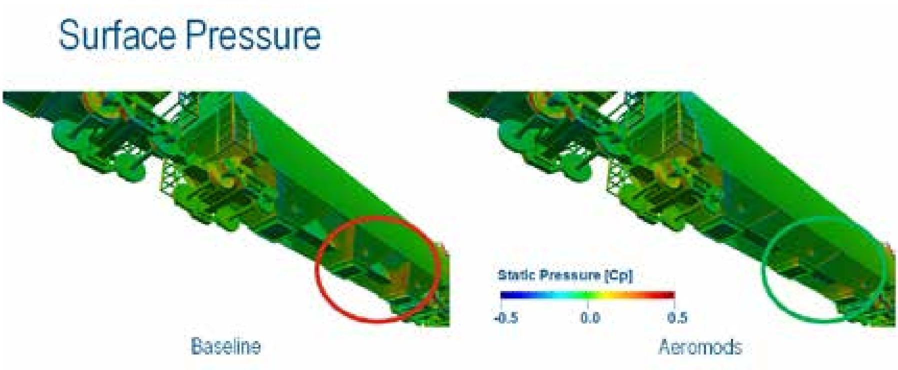

Figure 10 – Surface Pressure Plot Showing Underbody Impingement with/without Aerodynamic Treatment[17]

Revenue field testing was conducted on a unit train of 112 covered hoppers with aerodynamic modifications and a 7% reduction in fuel consumption was measured against similar non-modified unit trains operating over the same territory.

Refrigerated Boxcar Aerodynamic Modifications

Typical boxcar (including refrigerated) designs have a stamped roof structure for rigidity, though having a smooth surface on the exterior and a stamped pattern on the interior would provide a significant drag reduction while maintaining rigidity. Figure 11 shows a CAD model with CFD results showing how the corrugated roof on the outside (right hand side picture) needlessly creates stagnation points and excessive drag denoted by the slower air velocity. In this instance, switching the smooth roof to the exterior (left hand side picture) did not impact the cost for new builds of refrigerated boxcars.

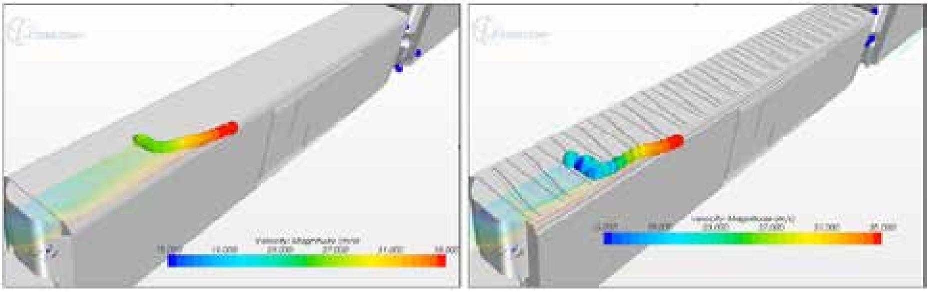

Figure 11 – Surface Velocity Plot Showing Air being Tripped on the Corrugated Roof Exterior[18]

Further, the addition of low profile side skirts between the wheel bogies similarly reduced drag along the bottom of the car as shown in Figure 12. The side skirts and an underbody wheel bogie fairing significantly reduce the drag caused by the impingement of air on the bogie and underbody as can be seen in the higher air velocity (right hand side picture) compared to the conventional car design (left hand side picture) currently in operation.

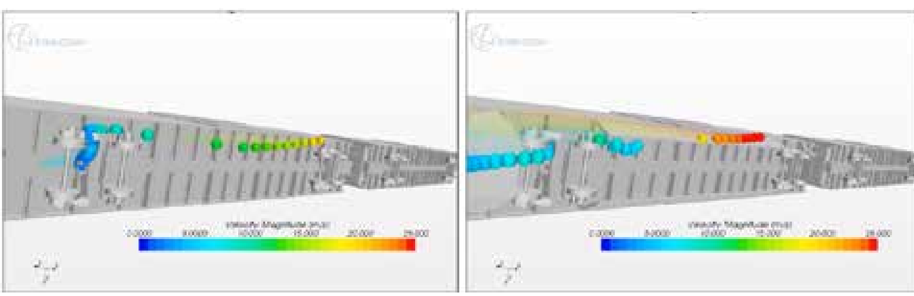

Figure 12 – Surface Velocity Plot Showing Air being Tripped Along the Car Underbody and Wheel Bogies

Another way to reduce drag for many different car types is to change the drawbar coupler design to decrease the car-to-car end wall distance. When this was applied to a new build of refrigerated boxcars, the distance decreased by 14 inches which resulted in less airflow impingement between the cars all along the length of a unit train where all cars have been appropriately modified. This change would likely not incur any extra cost on new builds.

CFD results for all three modifications indicated a drag reduction of almost 30% which translates into a fuel savings of 9% at revenue service speeds.

Autorack / Multi-level Aerodynamic Modifications

Autoracks are another prime candidate for aerodynamic improvements. There are multiple areas of opportunity in terms of drag reduction, namely a smooth roof from the existing corrugated design, a change to the punch hole pattern on the side wall screens and enclosing the underbody chassis voids which act to trip air passing underneath the car. Figure 13 shows the existing car design with the modified side sheet punch hole pattern installed.

Figure 13 – Autorack Vehicles with Doors Open and Aeroscreens Installed on Sidewalls

Extensive wind tunnel testing was performed to determine the extent of drag reduction for each of the three modifications. Figure 14 shows iterations for the smooth roof design, showcasing the coefficient of drag (C_d) as a function of Reynolds number (R_e). A drag reduction of 14% was measured which for a unit train of Autorack cars would equate to approximately 5% in resulting fuel savings.

Full scale testing was conducted on a dozen new car builds with both the smooth roof and modified punch hole pattern for the side walls. An energy reduction of 5% was measured at a track velocity of 40 MPH and over 10% for 60 MPH.

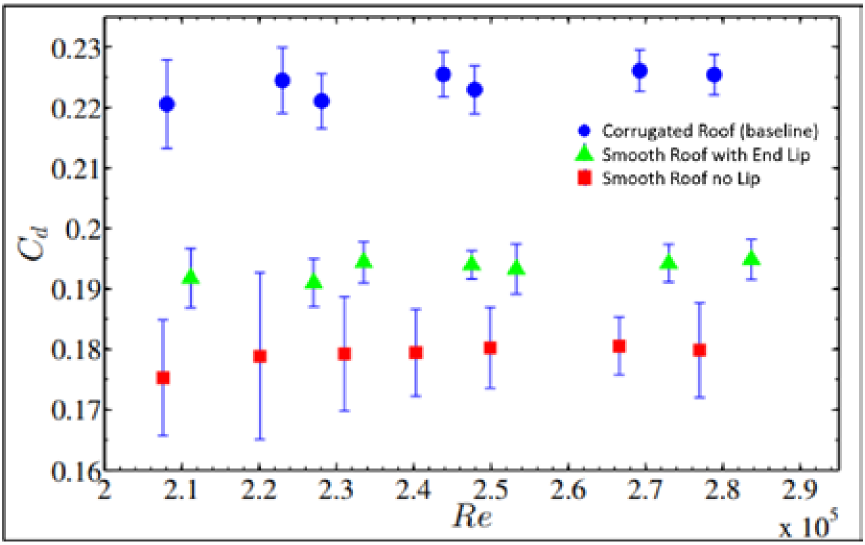

Figure 14 – Smooth Roof Iterations Showing C_d as a Function of R_e [19]

Interomodal Well Car / Container Aerodynamics

Rail transport of containers is three to four times more fuel efficient than truck transportation and a growing business thanks to cost advantages. Unfortunately, intermodal trains tend to have high aerodynamic drag given the wide variability of equipment matching (container size to car well size) and equipment loading (single or empty slots) variability.

An extensive study[20] was performed looking at the impact of equipment slot utilization on aerodynamic drag. Figure 15 shows various configurations for both 48 and 40 foot wells and their corresponding drag coefficients (C_d). A large variation in drag can be seen depending on loading density (minimal single or empty stacks) within a train. The drag differential for a well-built Intermodal train with few gaps or single stacks can be almost half compared to a poorly built train with many empty and single stacks throughout the length of the train.

Most if not all of these aspects of intermodal train make-up can be managed, controlled and optimized during load planning. This could result in substantial fuel savings.

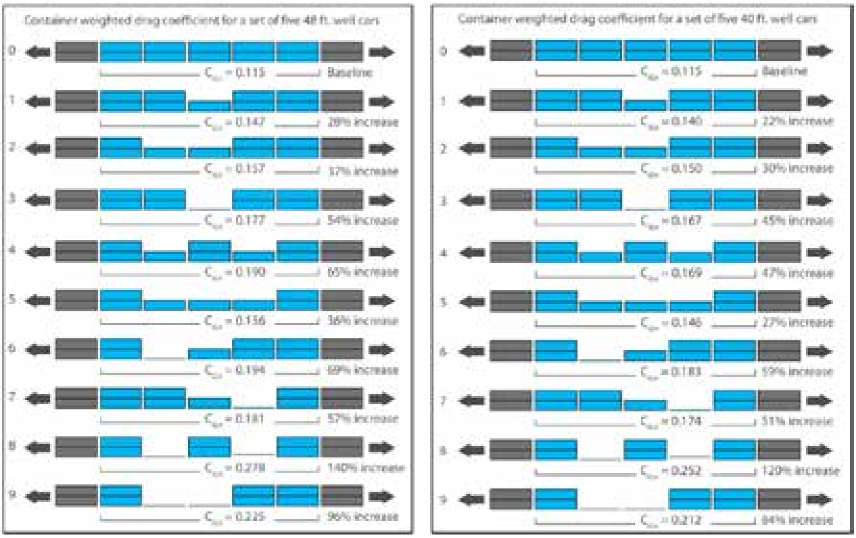

Figure 15 – Cd Variation Depending on Train Loading Density[20]

Further, the gap between containers even when fully double stacked can also cause large variations in train drag. When 40 foot containers are placed in larger wells built for 53' boxes there will be an increase in the size of the inter-car gap and aerodynamic drag. On the other extreme "overhang" placement where the top container is longer than the bottom container will result in lower aerodynamic drag. Figure 16 shows the amount of variability possible with differing gap size depending on how the train is made up.

Figure 16 – Variance of Gap Size Between Top Container Wells

Wind tunnel testing on a variety of container to container gaps revealed the curvilinear relationship shown in Figure 17 between the gap size (L_g) and the coefficient of drag (C_d). Drag virtually doubles between the extremes of a very narrow gap (53 foot containers overhanging on 40 foot wells) and a very large gap (40 foot containers on 53 foot well cars)

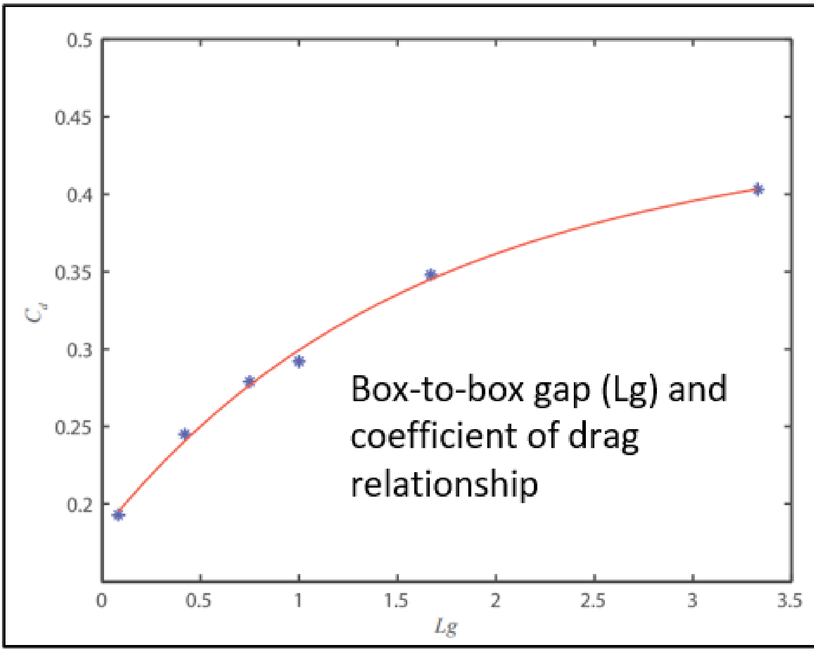

Figure 17 – Relationship Between Top Container Gap and Coefficient of Drag[20]

A summary of operational improvements that can be made are to reduce the top container to container gap, place longer containers on the top position (if able to mix domestic 53 foot with international 40 foot) and group single stacks and spine cars to the rear of the train. Depending on the level of improvement possible against the existing base case, fuel savings approaching 10% can be achieved.

Intermodal Well Car / Container Aerodynamic Improvement

Train make up is where most of the aerodynamic improvements can be made, though there are still opportunities to modify existing equipment for smaller drag reduction and associated fuel savings.

A patented micro-fairing or low profile deflector concept for intermodal containers and freight cars called the RoofRider has been developed using both CFD and wind tunnel testing. Figure 18 shows CFD results indicated less air impingement with the fairing attached to the top ends of the intermodal container. A drag reduction of approximately 5% has been measured which would equal 1.5% fuel savings for a simple, lightweight, and inexpensive addition to container fleets.

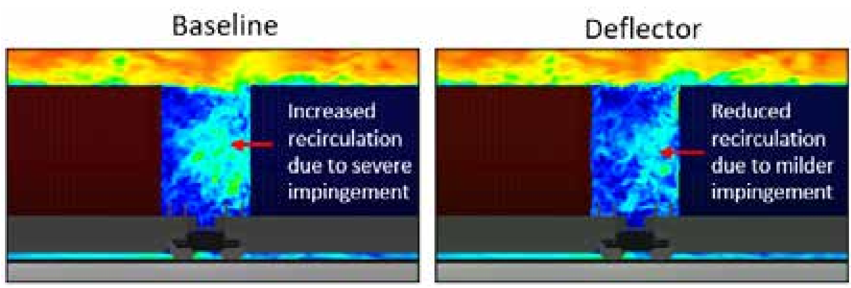

Figure 18 – Technology Deflects Air Over the Inter-car Gap, Reduces the Force on the Following Container[21]

The shape and size of the deflector is shown in Figure 19 and depicted in wind tunnel testing on 1/29th scale intermodal equipment.

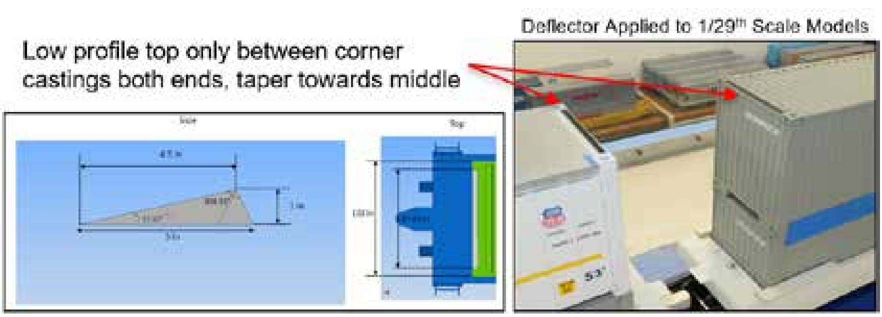

Figure 19 – Size and Shape of Intermodal Container Deflector

Locomotive Aerodynamic Modifications

While aerodynamic improvements to the locomotive can yield a significant reduction in drag for the locomotive itself, the associated fuel savings for the entire train will be relatively small given there is only one front of a train. Still, a 1% to 2% fuel savings for the entire train is possible depending on the degree of modifications introduced and the length and speed of the train.

Numerous studies have been conducted ranging from small shape modifications to an entire locomotive body redesign complete with covered walkways and a passenger locomotive style aerodynamic nose. Figure 20 shows a detailed CAD model of a modern Wabtec Evo locomotive, created and analyzed for CFD analysis by Dassault Systemes.

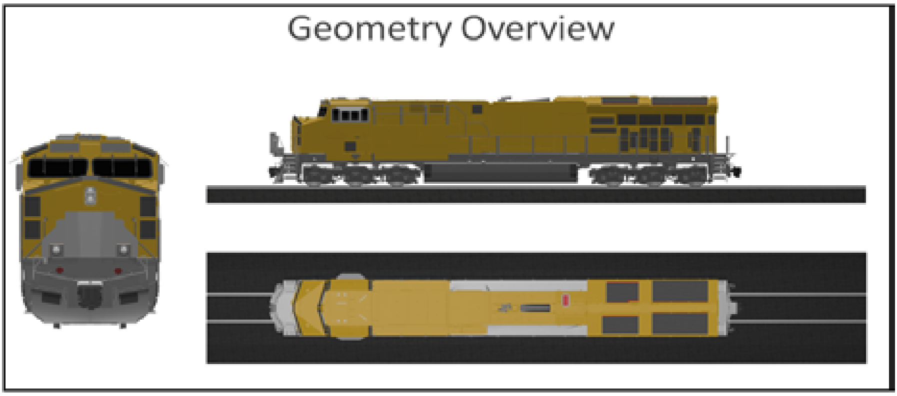

Figure 20 – Detailed CAD Evo Locomotive Model used for CFD Analysis

Figure 21 shows aerodynamic transition concepts on the left hand side, helping to reduce the sharp edges and tripping points which create drag. The right hand side depicts a foldable origami inspired aerodynamic nose cone which reduces the blunt shape of the current locomotive nose face.

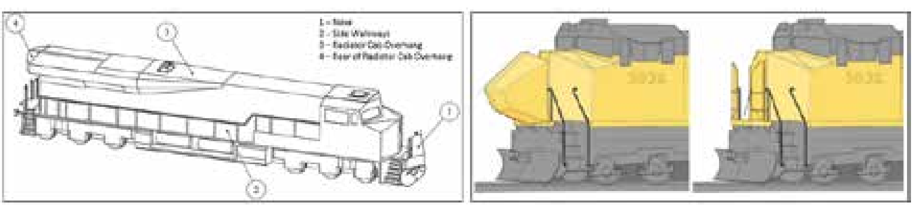

Figure 21 – Various Locomotive Transition and Nose Cone Concepts Tested with Wind Tunnel and CFD[22,23]

Though the fuel savings from the associated drag reduction is smaller than that possible with freight car modifications, there are also far fewer locomotives to upgrade compared to the size of the freight car population within North America. Given aerodynamic improvements are agnostic to future fuel source, it's likely that future locomotive shape design will migrate towards a more aerodynamic shape profile. Whether or not the installed base of tens of thousands of "lead capable" locomotives within the Class I freight universe will see future aerodynamic modifications remains to be seen.

Wind Tunnel History

The first wind tunnels were developed in the late 1800's in France, Great Britain and Russia.[24] In 1901, the Wright brothers created a wind tunnel to test different wing shapes that would eventually carry them into the air.[25]

The first major wind tunnel in the United States was built at NASA's Langley Research Center at Hampton Virginia in 1920.[26] The largest wind tunnel in the world is at NASA's Ames Research Center at Moffett field California which has the capability to test aircraft with wing spans of up to 100 feet. Figure 22 shows the drive fan configuration at the National Full-Scale Aerodynamic Complex.

Figure 22 – Inlet Section of the Largest Wind Tunnel in the World at NASA Ames Research Center[27]

A wind tunnel is often identified by the size of the test section, not the overall size of the wind tunnel itself. The test section is the area or chamber in which models or other objects are placed. The models are typically fitted with sensors that measure the push force against the model of the air drawn through the test section. A common type of wind tunnel is open circuit where air is drawn through the test section by a turbine, having passed first through an inlet screen and a contraction cone to increase the air velocity. After passing through the test section, the air then flows through a diffuser and exits through the turbine blades.

BYU designed and built an open circuit wind tunnel in the late 1950's shown in Figure 23. The device was purchased in 2015 by a major Class I railroad and modified to perform dedicated aerodynamic research on G scale locomotive and freight car equipment. The wind tunnel is equipped with six moveable sensors along the length of the 25 foot plexiglass test section

The wind tunnel was donated and moved to TTCI in 2019 and is now stored at MxV Rail in Pueblo, Colorado waiting for funding (or a paying customer) to put it back into operation. It is likely one of the few medium-sized wind tunnels in North America, if not the only one that is configured for dedicated freight railcar operation and analysis.

Figure 23 – Wind Tunnel Configured for G scale (1/29th) Model Testing

OEM's and Suppliers Beginning to Offer Aerodynamic Choices

There are freight railcar builders who have begun offering more aerodynamic versions of common car types. Some of these offerings are packaged with other improvements such as the Tsumani Gate™ covered hopper shown in Figure 24, which is also designed to offer customized discharge speed control. Further, the industry is looking to move to automated roof hatch covers which would be a huge safety improvement as well as removing the roof walkways which are a large contributor to overall car drag.

Figure 24 – Tsunami Gate™ Car Offering[28]

Other car offerings such as a smooth sided Transverse Ultra-Fast-Flow (TUFF) coal car and a tandem Autorack car are showcased in Figure 25. The aerodynamic drag reduction and associated fuel savings from these relatively new offerings are significant though have not yet been fully embraced by the industry who continue to choose the "lowest cost" version at the expense of long term fuel savings and emissions reduction.

Figure 25 – Smooth Sided Coal Car and Tandem Smooth Sided Auto-Max Car[29,30]

Suppliers to freight railcar builders are also beginning to offer more aerodynamic solutions. Figure 26 shows modified side screen panels. This same vendor is also designing a smooth roof to replace the corrugated roof and other aero treatments for covered hoppers.

Figure 26 – Aeroscreens with a Modified Punch Hole Pattern[31]

How to Approach Given Various Freight Car Owners

Railroads own anywhere from 15% to 40% of the freight cars that they haul with the other cars being either customer owned or leased car fleets. With such a variety of car ownership, the issue of who pays for aerodynamic treatments for operational fleets versus who benefits from the fuel savings will have to be addressed.

Figure 27 shows a possible path forward. There are three main entities that own railcars, the railroads themselves, customers who own fleets for convenience/optimization of operations and leasing entities such as TTX. Some of these fleets will traverse on various railroads as a normal way of doing the business of moving freight.

What is most important is that the path forward accelerates aero modified cars into service while prioritizing newer fleets that have high utilization/mileage. All entities will share in the ESG GHG emissions success spotlight, taking credit where credit is due. The commercial discussions regarding who pays versus who benefits should focus around either fuel surcharge mechanisms or existing rate structures. For leasing entities, aero modified cars will charge a higher lease rate given the lower operating cost in terms of fuel savings.

Leveraging new builds and unit trains are both methods to increase adoption and penetration of aero modified cars in general circulation. Further, where applicable, carbon credits can be generated and leveraged by entities that pursue more aerodynamic friendly options.

The trucking industry has been sharing aero enhanced trailers and trucks for decades. There is no valid reason why railroads can't go down a similar path.

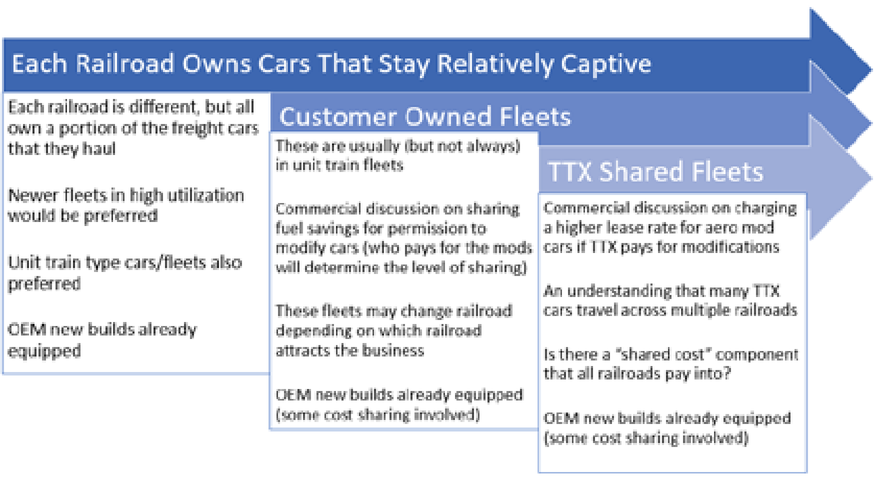

Figure 27 – How Railroads, OEMs and Lease Owners Can Move the Ball Forward

Conclusions

Aerodynamic treatments are available for most major freight car types and involve smoothing roof lines, applying side skirts and underbody treatments to smooth transition and trip points all with the intent of reducing drag and improving fuel conservation. These simple aerodynamic modifications can either be designed and included for new builds or installed in kit form for existing car fleets already in service that are going through periodic maintenance cycles.

There are challenges, as railroads only own a portion of the cars that they haul. Who pays for the modifications versus who sees the fuel savings, will all have to be worked through. At the very least, new builds with aerodynamic modifications should be the first tranche of aerodynamic cars introduced. Recently purchased fleets should then be the next priority with in-field modification kits made available. Customer owned fleets would also be a key opportunity as would leased fleets from TTX and other car owners.

Funding for continued research on aerodynamic opportunities will be key. Government funding through the FRA operated TTC or the AAR operated MxV Rail to perform not only wind tunnel testing, but also full scale energy tests will be a requirement. CFD analysis will also be required, and OEM assistance and support for both locomotives and rail cars will likely help drive needed improvement. A multi-year plan with industry leadership to drive progress and sharing of best practices to accelerate the pace of improvement will be necessary.

As the GHG emissions goals approved through SBTi continue to become more aggressive moving to the preferred 1.5 degree C standard, aerodynamic improvements will become a necessity if these goals are to be met by 2030 and beyond.

Given aerodynamic improvement technologies are agnostic to the fuel type being used to pull freight, they will be just as useful in the future for Battery Electric or Hydrogen Fuel cell powered locomotives pulling revenue freight trains. As railroads set their sights on a net-zero path by 2050, aerodynamics will play a role in helping them transition to whatever future fuel sources the industry chooses in the long term.

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The Discipline of Best Practices for Gaskets and Seals: Design and Use

GASKET AND SEAL DESIGN PARAMETERS FOR LOCOMOTIVE, MARINE, and POWER GENERATION DIESEL ENGINES
It is Always a Materials Choice to Fit the Application

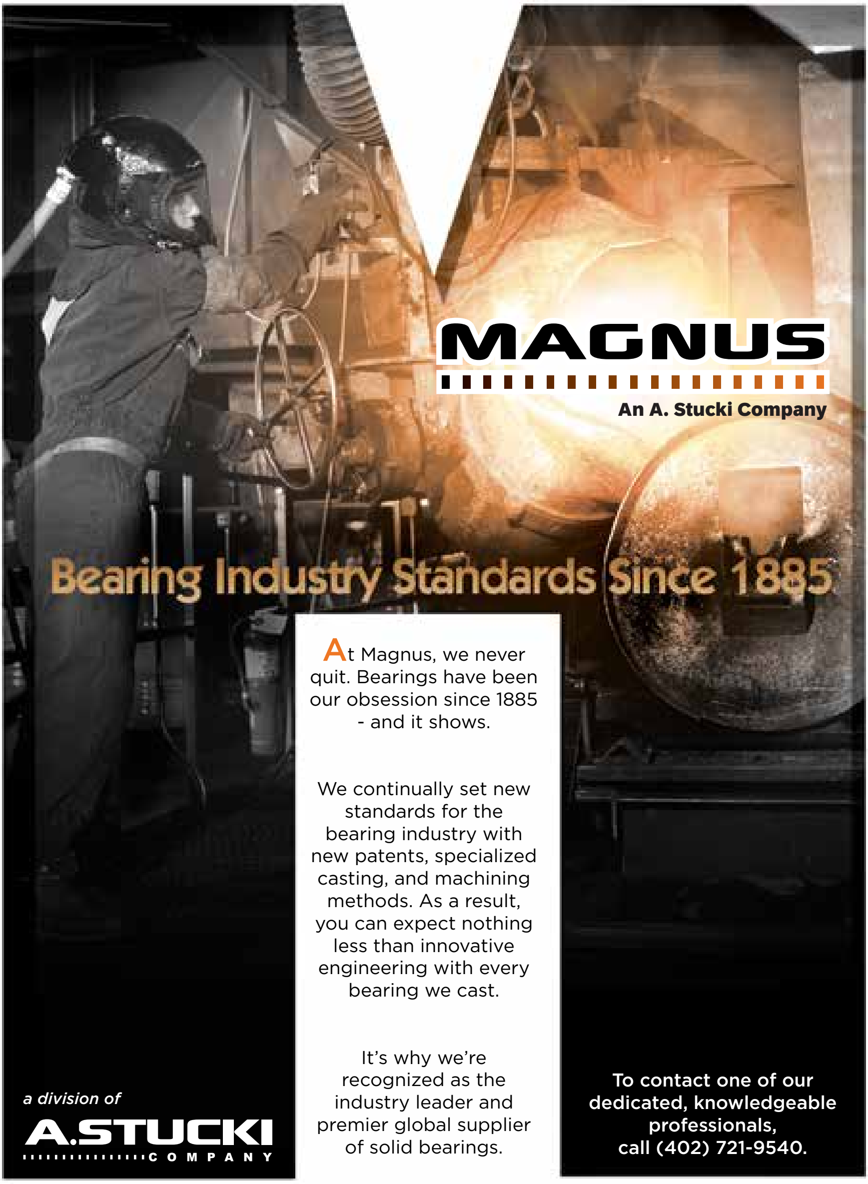
Prepared by Robb Ridgway
Presented by Pat Silvey
Both of Master Packing and Seals

Executive Summary: Defining the difference between Gaskets and Seals

Locomotive, Marine and Power Generation diesel engines in use today can go back to designs from the 1940's. Many of the gasket and seal designs applied to these engines came about because of the materials in use at that time and have in many cases significantly changed or can no longer be legally used, such as asbestos. Metal alloys now are stronger, casting processes have changed, fasteners are stronger, and computer aided design systems now assist in the designing of parts with processes not even thought of back then. In a few areas, materials commonly used today have only been recently invented, discovered, or made, resulting in significant changes in gasket and seal material and design. All these changes must be incorporated to extend the life cycles of all engines whether designed 80 years ago or yesterday. The ultimate design goal should be to extend engine service from overhaul to overhaul, without parts failures and with leak free service. For this paper, these materials and designs for gaskets and seals will be discussed specifically for these large medium speed diesel engines.

GASKETS

Gaskets are usually flat and stationary parts. The success or failure of a gasket is almost always due to material composition and proper loading or assembly torque. During operating service, maintenance procedures are always critical. Fastener application and location play an obvious part and where elastomers are used in the gasket composition, the durometer is also key. Gaskets are designed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to fill a space between two flanges. Those flange surfaces will either be pristine or have some wear or even damage. A good material choice should consider "less than perfect" flange surfaces unless specified otherwise. All gaskets "store energy" to some degree upon compression (material resilience or tension), and almost all gaskets swell to some degree, except for PTFE (Teflon™), graphite, and metals.

At some point, if allowed to remain in service long enough, ALL gaskets will usually fail with time and need to be replaced. It is always helpful to first study a failed gasket upon removal to assess the type of damage that has occurred, such as material failure due to over compression, and then secondly, to observe the flange surfaces that the gasket was clamped between. These two conditions on the flanges and the gasket will almost certainly highlight the leak paths to help determine the problem and the subsequent fix.

As an example, the lube oil pump gaskets applied to these engines tend to leak over time. One issue is during installation, the assembly gasket is applied to a vertical surface, and it is difficult to place and hold the gasket accurately. The bolting pattern is adequate, and the mating surfaces are usually flat and in good condition. But many of these gaskets observed being pulled due to leaking, have predominantly been "high swell" gaskets that contain natural rubber and EPDM binders, two common gasket materials that should not be used with applications involving oil. The chemical reaction produces extreme swell which in turn breaks down the binder preventing the gasket from storing energy. With the significant amount of thermal cycling experienced during service, the gasket becomes flat over time and will not swell further, losing torque compression, resulting in leakage. The drawing shown below, Figure 1, shows the outline of an oil pump assembly gasket removed due to leaking, the actual leak paths, and the inconsistent thickness readings around the gasket. The mounting flange surfaces were indeed flat and in good condition so torque values may not have been achieved accurately, indicating under compression on the left side and over compression on the right side. This gasket material failed on the right side after many thermal cycles. The gasket illustration, Figure 2, shows a redesign in red that provides for better loading over the entire gasket surface by decreasing the gasket area. It was also designed to "sit" on the ledge of the pump body for easier installation.

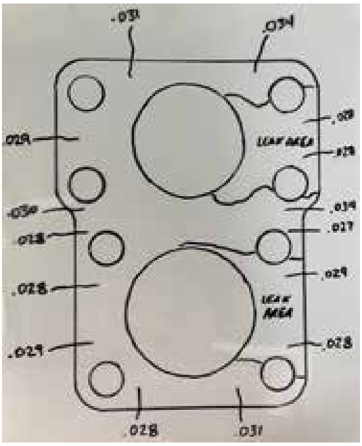


Figure 1

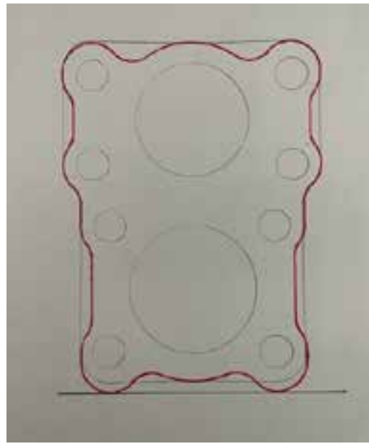


Figure 2

Another gasket design question is what the flange finish should be for the gasket application and how much deflection can a gasket absorb when the flanges are not parallel. Short answer is that for non-metallic gaskets such as compressed fiber gasket materials, the best finish is a smooth surface of 125 to 250 RMS finish. For a metal gasket such as copper gaskets, a smoother finish is better, 60 to 90 RMS. All gaskets require a little "tooth" between the flange surfaces and the gasket for a friction grip, especially for the non-metallic materials as the gasket can otherwise extrude. For deflection, a gasket can normally handle up to about 10% of the gasket thickness for flanges that are not parallel. Most metal gaskets will take some deflection although not that much, 2-4% at maximum.

Soft gaskets such as compressed fiber sheet, graphite, PTFE, and rubber that are more compressible are generally more forgiving to misalignment and to flanges that are out of parallel on closure. However, these materials, with the exception of graphite, to varying degrees, are more susceptible to creep relaxation and movement while under a load. The flange surface finish can play a critical role in the gasket's service life and long-term reliability. A very smooth surface finish will not create the necessary friction between these mating surfaces, making the nonmetallic gasket more susceptible to creep under load. This creep can translate to a loss in bolted joint tightness and potential leakage. A rougher surface finish is generally recommended for soft, non-metal reinforced materials to create the necessary friction for stability and compression between the mating surfaces. A typical surface finish recommendation for these materials is Ra 3,2 to 12,5 μm.

Defining the Gasket Application

Gasket materials offered today can handle most conditions. The three biggest concerns would be temperature, pressure, and the pH of the medium being sealed. The fourth concern is the loading, (assembly torque) of the gasket material and the assembly bolt pattern. A normal bolt pattern for a standard flange gasket is where even loading occurs. An irregular design in the flange bolting pattern is susceptible to leaks. And the fifth and final concern is the fastener and assembly method.

- Temperature: This is usually one of the first concerns when choosing a gasket material as it must handle the extremes in actual operating temperature as well as those experiencing regional climates. For instance, moving a consist in southern Mexico during winter where it is hot and then running through the USA and up into Canada where it can be sub-zero, or vice-versa can create leaks, normally due to fastener stretch or relaxation. This severe temperature swing places serious constraints on the gasket if the material does not have enough resilience to operate in the extremes of weather. A chart is provided in Appendix A to help in those choices.
- Pressure: There are two pressures that gasket materials must deal with: a) the internal fluid or gas operating pressure and b) the assembly fastener pressure or clamp load/bolt torque that needs to be applied to compress the gasket enough to negate the blow-out force of the internal operating pressure. The current engine operating pressures, fluid, or gases are not much of a problem today in these engines; however, the design consideration is for material that has good resilience to resist the degradation from stress relaxation and loss of clamp load, both due to fastener yield, temperature, and engine vibration.
- Fluid / Media pH: The chemistry of the fluid or gas being sealed will always be critical to the success of the gasket. As mentioned earlier, almost all gasket material will swell to some degree so material composition of the gasket must be based on the fluid chemistry it will seal so that any adverse reaction is held to a minimum. As an example, sealing in an oil application will fail prematurely if EPDM was the chosen elastomer as it swells from the exposure to the oil.
- Flange type and Available Clamp loading: Design of the flange surface is a big consideration along with the actual surface finish. Standard ASA designed flange gaskets are easier to work with as the clamp load is totally symmetrical. All fasteners are equidistant around the bolt circle for even distribution of the gasket assembly clamp load. Flange thickness is also critical for proper gasket loading and we find that in some cases the thickness will change, making it difficult to properly load. Many OEM designs are difficult to properly load because the bolt holes are

predetermined locations and not always evenly spaced. Flange widths can also change up from wide to narrow and back to wide. Fastener sizes can also vary in certain applications, usually due to flange design.

As a result, the gasket flange design and material choice become just as critical to a long leak free operation. Two examples; a) Figure 3 shows a gasket that is easy to load with bolts equally spaced and b) Figure 4 illustrates a gasket with irregular bolt holes and thinner flanges making it difficult to load the gasket evenly.

Figure 3

Figure 4

- <u>Fasteners – Installation Procedures:</u> A fifth concern for the sealing of gasket materials, is the critical selection of fasteners by metal type, hardness, and other characteristics. One of the biggest factors for premature leakage is either a lack of proper clamp load or over-torquing the fastener, regardless of any of the other factors. Gasket clamp loading requires proper procedures for the torquing of the fasteners, usually in three passes of an exact pattern for even distribution of the clamp load. Fasteners should also be lubricated as unlubricated threads never achieve a true torque reading by as much as half. While there are charts for torquing an unlubricated bolt you will not achieve uniform load. A graphite/oil lubricant is highly recommended, but the OEM recommendation takes precedence. Lastly, if an impact gun is used during assembly, only use it for the first pass and use a torque wrench properly set after that. If the bolt is over-torqued, it can quickly crush the gasket in the area around the fastener and cause a leak.
- <u>Gasket Design Process:</u> Existing locomotive and marine diesel engines were designed in the past with different standards than those followed

today. There was, and still is, a propensity for the design engineers to just "follow the flange" for the gasket design. Bolt pattern also can be an issue where even spacing and different bolt sizes were used for many legitimate design reasons. If asked to fix a consistent "leaker", the gasket designer should ask for a drawing of the flanges so that an FEA (finite element analysis) can be conducted to help in redesigning the gasket to best respond to the existing flange condition and bolting situation. This is a service that should be available with fluid sealing specialists.

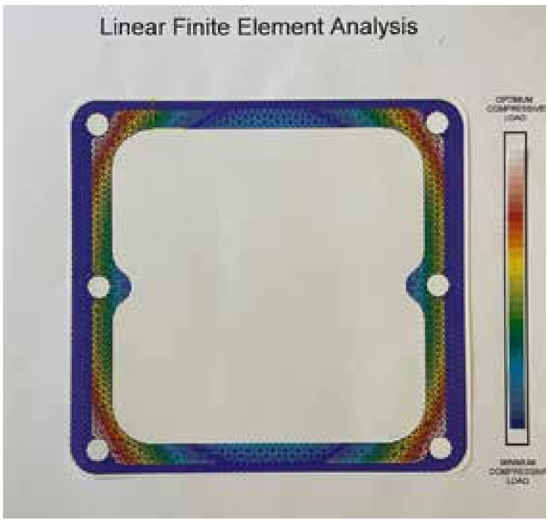


Figure 5

In Figure 5, the minimum compressive loading can be clearly seen along the top and bottom flange because of the lack of a bolt in the middle of the flange, as compared to the left and right flange design. In this case, by narrowing the gasket width and providing the addition of "stabilizing" embossments, a better load is created.

- <u>Material Choice Example:</u> With all the above criteria, a design decision on the choice of material to use can be made. As an example, assume an application that involves diesel oil with a maximum operating temperature of 220°F, 60psi pressure, a square flange with bolts in the corners, standard Grade 5 fasteners torqued to 35 lbs/ft. This would be a simple application with many options. In this case the temperature and operating pressure is easily accommodated by most materials, either straight elastomers or a compressed fibered sheet. Some experienced mechanics may have a preference from experience, but the current service goal is Overhaul to Overhaul unless it has a maintenance requirement for periodic change. Because almost all gasket materials will swell to some degree, it should be controlled by staying away from any elastomer that shows a high swell in oil (in oil service). That eliminates EPDM, EPT, EPR (ethylene Propylene) and natural rubber. Best choice would be a Compressed Synthetic Fiber sheet with a nitrile binder. Identify a gasket sheet from suppliers using ASTM Line Callout: F712100A9B2E23K7M5 or F712100A9B4E22K5M6. Both are Nitrile bound fibers with great resistance to oils, temperatures well above the application, and pressures from vacuum to 1,200 psi (83 bar). Vendors who understand the business will use a sheet that meets this callout. An explanation on the break-down of the codes is provided in Appendix B to help understand and define the right choice for the seal application.

Fluid sealing specialists will also tell you that <u>THINNER IS ALMOST ALWAYS BETTER THAN THICKER,</u> except for flanges that are warped and those that are not flat, or those not able to be exactly parallel to each other upon closure. Although most engine internal pressures, other than around the cylinders, are usually under 100 psig, the operating pressure pushes against the thickness of the gasket material, referred to as the blow out force. The loading on the gasket creating the compressive force, also must be greater than the internal pressure. The lower the profile, the less the pressure impacts on the gasket. Thinner material is also preferred as thicker materials show a greater decrease in torque retention over time. And in applications with increasing temperatures, torque retention worsens. This can be seen below in the definitions of compressibility and recovery. The biggest reason for failed gasket applications is lack of load and second is poor choice in material.

STANDARDIZATION OF PHYSICAL CHARACTERISTICS

The following are industry standards that should help in picking and comparing materials to ASTM standards (American Society for Testing and Materials). These standards help to fairly compare gasket materials and can help in determining what should work for a particular situation. However, these are standard lab tests that help to establish and compare materials. They are not indicative of a successful leak free application. Please consider these as just a start to an application.

SEALABILITY

Sealability is measured according to the **ASTM F37** specifications. It is an indication of the materials sealing ability under a set of conditions. A seating stress of 2000 psi is imposed through the flanges on the material sealing iso-octane at an internal pressure of 14.7 psi. The test is done at ambient temperature and the number shown is the amount of leakage in milliliters per hour. **The lower the number the better the material.**

COMPRESSIBILITY

Compressibility is measured according to the **ASTM F36A** specifications. A load of 5,000 psi is imposed on the material and the loss of thickness is measured and expressed as a percentage of the original height. The compressibility of a material indicates, to a degree, its ability to fill flange scratches, nicks, or voids and to flow or move to assist in sealing misaligned or warped flanges. **In general, the higher the number, the easier it is to seat the material.**

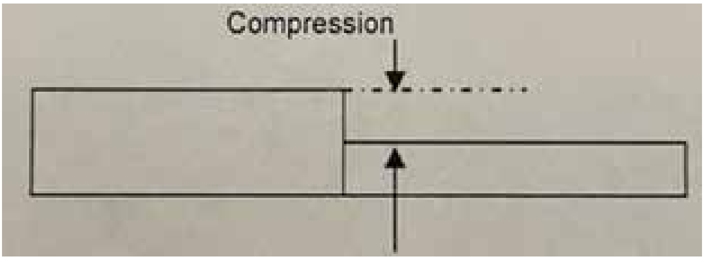


Figure 6

RECOVERY

Recovery is also tested under the **ASTM F36A** specifications. Recovery is the measured rebound or increase in thickness from the compressed measurement once the load is removed. It is written as a percentage of increase over the compressed measurement and indicates the ability of the material to resist temperature and pressure. **The higher the number, the better the material is at holding torque.**

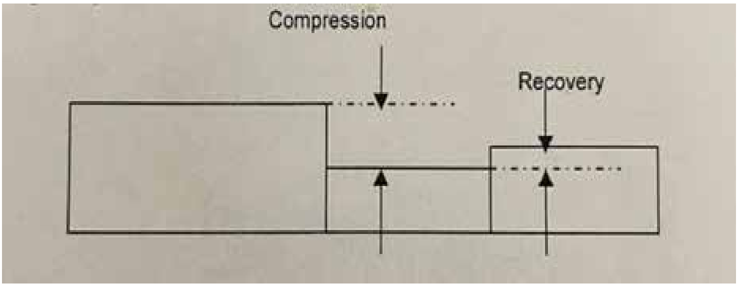


Figure 7

CREEP RELAXATION

Creep Relaxation, also referred to as Torque Retention, is measured according to the **ASTM F38** specification and indicates the materials ability to hold stress or bolt load over a specific period. It is expressed as a percentage of the original load and shows the amount of lost stress from that load. **A lower number indicates a more stable material retaining torque and resisting leakage.**

TENSILE STRENGTH

Tensile Strength is measured under **ASTM F152** and is given in pounds per square inch. It is the total force required to pull the material apart and is not related to the sealing function of the material. It relates more to the manufacturing process.

HOT COMPRESSION TEST

One of the other tests that is used as a standard, although many don't use it, is the HOT COMPRESSION TEST. This is used in the auto industry and is considered a "force to failure" test.

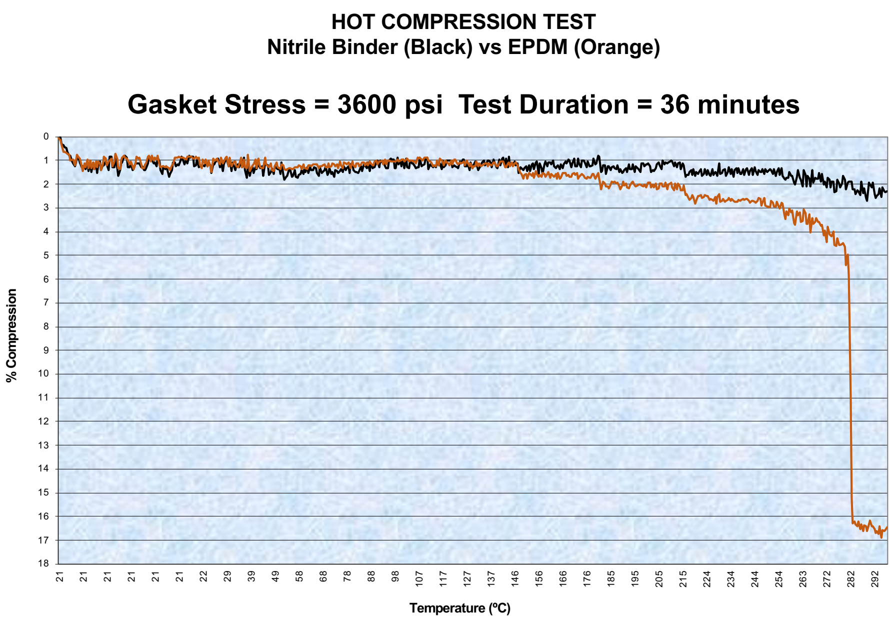


Figure 8

After the first 7 minutes at 21°C, the temperature increases every minute until it reaches 291°C. The test is to measure the loss of compression through the material as a percentage of the original height. This test shows a clear loss of bolt load, or loss of torque. This helps pick the best elastomer for the application, whether as a homogeneous material or a compressed sheet with fibers and fillers.

OIL SWELL TEST

As stated above, but worth repeating, ALL gasket materials swell except for PTFE and GRAPHITE. The following test, illustrated in Figure 9, was done for a Class One RR with a gasket material that was currently being used, sealing well initially and then after a period in service, started to show leakage. Both the Nitrile gasket and the EPDM gasket were tested which showed the EPDM material tripling in load through swelling of the elastomer, starting at 20 lbs. of imposed load and after 80 hours measured 73 lbs. of load. The NITRILE material doubled from 20 lbs. imposed at the start to 46 lbs. at 72 hours and held that through 120 hours. The problem is that the swelling is caused by a breakdown of the polymer connections which eventually causes the gasket to fail through constant thermocycling of the engines as shown in the hot compression graph shown above in figure 8.

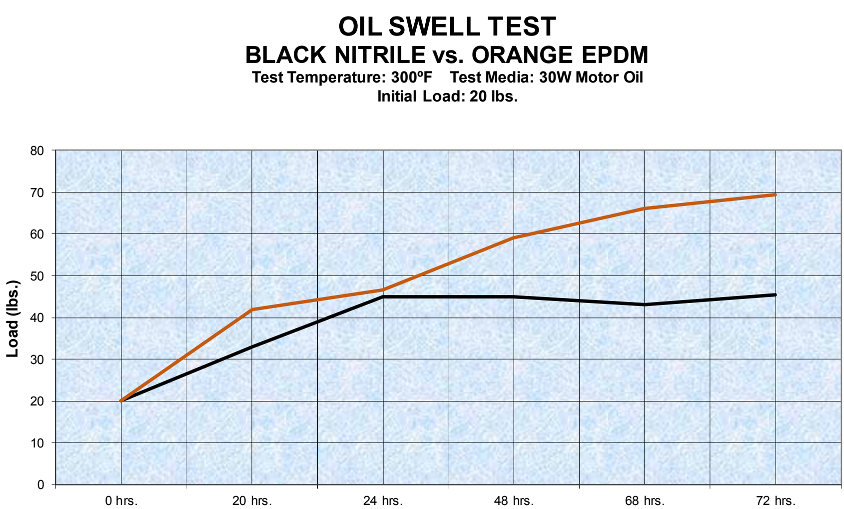


Figure 9

SEALS

Seals are somewhat different than gaskets because of their material composition and that their general shape conforms to either a cavity or rotational surface and are used in both static and dynamic applications such as reciprocating rods and rotating shafts. They cover a broader area of materials and shapes and are usually activated by pressure ranging anywhere from vacuums to very high pressures. The most common would be the O-ring that can operate as a stationary seal (like a gasket) under compression, or as a dynamic seal handling rotational or reciprocal sliding movement. Other types of designs can also handle rotational movement. There are all kinds of designs, shapes, and materials used for hydraulic and pneumatic applications in cylinders, and other types of equipment. Seals are generally designed for motion, pressure, and temperature and the selection of materials is almost limitless.

Most of the seals on these engines are O-ring in shape and design although there are some square O-ring applications and extrusions as well. The bottom oil pan seal is a lengthy round cross section extrusion which should be a simple application to seal if the material, diameter, and durometer are correct.

SEAL MATERIALS AND THEIR PROPERTIES: The most common materials used today are Nitrile, EPDM, Silicone, and Viton™ . Elastomers must be chosen by service: fluid, air, or gas to be sealed, operating temperatures and consideration for outside temperatures when shut down. Engine thermocycling must also be considered.

NITRILE (BUNA-N) is one of the most useful, general-purpose oil resistant synthetic polymers used on the engines. It can be used in oils, solvents, hydraulic fluid, and water. It is acceptable for temperatures ranging from -50°F. to +250°F. Although it should not be used in highly polar solvents like acetone and MEK, ozone, chlorinated and nitro hydrocarbons. It is not recommended for ethanol.

EPDM (Ethylene Propylene) is also a synthetic polymer that shows excellent resistance to aging through a combination of exceptional resistance to sunlight, ozone, water, and low (-70°F) and high (+325°F) temperatures. However, it does not have good resistance to fuels, oils, and solvents and is not recommended for aromatic hydrocarbons. It is approved for alcohols and ketones and recommended for ethanol.

Silicone is a unique elastomer that shows very low compression set with excellent resilience. It is excellent in resistance to water, weather, and sunlight aging, heat ozone, and oxidation. It has a temperature range of -150°F to +500°F. It is not recommended for use in solvents and oil.

FKM (Viton™) FKM's generally have a wide range of chemical resistance and high service temperatures to +400° to 500°F with time limits, but low temperatures only to -20°F. FKM's are used extensively in industry as O-rings, hydraulic seals, rod and shaft packings, diaphragms, gaskets, and pump parts. There are three families of FKM's, A, B, and F. The A family is the universal choice for most applications and most OEM's will almost always have it generically written in as Viton™ or FKM. However, any application where hot aqueous solutions are involved, only the F family should be considered as the A family type will crack over time and fail. B family is best for diesel oils and fuels, especially when at or above 250°F.

ENGINE SEALING RECOMMENDATIONS AND APPLICATION DESIGN EXAMPLES:

WATER JUMPER ELBOW

O-rings used on locomotive, marine and power generation diesel engines are designed mostly for static applications. As an example, the water jumper elbows on the EMD engines, Figure 10, provides a perfect illustration. The nozzle side has two O-rings that are static, do not physically move but compensate for the vibrational movement from contact with the cylinder head itself. They seal the coolant water cycling through the power packs and has been a problem. The OEM has specified these to be FKM from the "A" family. The problem is that they are not designed to handle hot water for any length of time. Only FKM from the "F" family can handle hot aqueous solutions and should have been specified for long life cycle. The flange side of the elbow is completely static and used as a gasket under compression. The OEM supplies those as Silicone. The flange mounted O-rings do not have to be lubricated as the force is only through compression. The OEM design size for all of these is slightly different. The nozzle side O-rings, regardless of material, must be lubricated prior to power pack assembly being dropped into the block. If applied dry they will roll, twist, and will split causing failure. Any application where motion will be created on or by the O-ring, especially a rolling motion, must be lubricated. After analyzing the material and dimensions it is possible to get all three in the same size and material. Part of the design criteria was to change the size so that both locations could be handled with one O-ring. The other was to change the sizes, durometer, and the material to help eliminate the fretting damage being done to the block where the nozzle O-rings encounter the block drilling.

Figure 10

VALVE COVER SEALS

A particularly difficult sealing application or "headache" for the EMD engines is the top deck valve covers that sit atop the engine. Mechanics have gone through several iterations of seal designs over the years to get the proper material and seal design. One current valve cover elastomeric seal that has successfully solved this application is by using the correct seal material and shape, and has been known to actually pull a slight vacuum indicating a tight seal and no leaks.

Figure 11

FINALLY, AN EXAMPLE OF A FUEL LINE INJECTOR SEAL

The fuel lines are often handled roughly during re-use and the bulbs at the end at times need to be smoothed out with crocus cloth. Now with this non-OEM seal, that step can be eliminated.

Figures 12 (A & B)

GASKET and SEAL DESIGN FACTOR SUMMARY

<u>**GASKET DESIGN FACTORS**</u>

Temperature: Pick a material that allows both lower and greater temperature range required. If your application will run hot oil at +240° pick a material that will take more than that so that you don't risk an engine malfunction that will push the temperature past the design designation.

Pressure: Important to make sure that your loading through the gasket exceeds the operating pressure (blow out force) over time.

pH: Know your material so that you don't choose one that will not hold up to the medium that you are sealing.

Flange surface finish: Friction between the gasket surfaces and the flange surfaces are far more critical than believed. DON'T USE OILS, GREASES, ANTI-SEIZE PASTE, OR RTV SILICONE SEALANT ON GASKETS. You can use 3M Spray #77 or Permatex #2 gasket adhesives.

Fasteners: Should be lubricated for proper torque readings, however, torque can be specified as wet or dry. You should always use a torque wrench on the last pass to be accurate.

Torque: Proper loading requires a "star pattern" on round gaskets and "opposing crisscross patterns on rectangles and odd patterns. Uniform clamping force is required to prevent leaks.

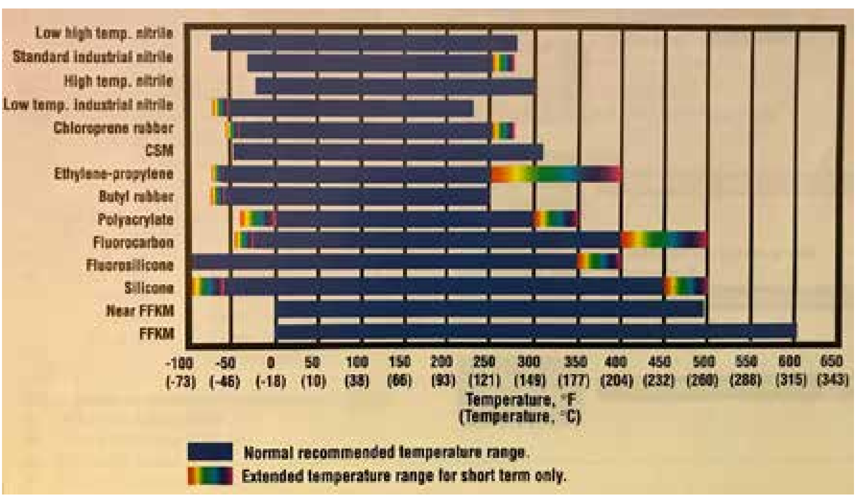
SEAL DESIGN FACTORS

Static O-rings: If the ring is just to be laid flat and compressed, no lubricant is needed. If it will be mounted into grooves, either in a cylinder wall or rod to be pushed into place, then you must lubricate those O-rings.

Dynamic O-rings: MUST be lubricated so that they do not roll, twist, and split. Lubricants should be either silicone or ester-based lubricants as they offer the best reduction of friction while not compromising the elastomeric polymer used in the O-ring. DuPont Molykote is one example but there are many offerings in industry.

To reiterate the purpose of this narrative, all these changes to both gaskets and seals must be incorporated today to extend the life cycles of all engines whether designed 80 years ago or just yesterday. The ultimate design goal should be to extend engine service from newly manufactured to the first overhaul and then subsequently overhaul to overhaul, without parts failures and with leak free service

APPENDIX A: TEMPERATURE EFFECT ON GASKETS



APPENDIX B: ASTM F104-11 Standard Classification System for Nonmetallic Gasket Materials

(**The pdf for this can easily be pulled up on the internet.** Since I have not received approval to reprint their 12 page material. I can only explain the overall line callout system. Specifics will have to be found from the ASTM web site. I am going to make up a number for these purposes.

F712100A9B2E23K7M5

First number 7 calls out the TYPE of Material. 7 is for NON-ASBESTOS material.

Second number 1 calls out the method of process of manufacture. 1 is for COMRESSED SHEET

Third number 2 calls out the compressibility under Test Method F36. 2 = 5 to 15%

Forth number 1 calls out thickness increase when immersed in IRM 903 Oil. 1 = 0 to 15%

Fifth number 0 calls out the weight increase when immersed in IRM 903 Oil. 0 = Not Specified

Sixth number 0 calls out the weight increase when immersed in water. 0 = Not Specified

A9 calls out the sealability characteristics by Test F37 and those details will go on Engrg. Dwg.

B2 calls out Creep Relaxation by Test F38. B2 represents 15%

E23 calls out weight and thickness increase from immersion in ASTM Fuel B. The first number represents the weight increase, and the second number represents the thickness increase.

K7 calls out Thermal Conductivity characteristics as determined by Practice F433. Those results will usually be placed on an engineering drawing. This is not used as a certifiable requirement unless agreed to between the manufacturer of the sheet and the buyer/end user.

M5 calls out the Tensile strength of the material determined by Test F152. In this case M5 represents 1,500 psi.

When looking for a material, it is best to go through the actual F104-11 Line Callout to understand what you are going to run on your engine. It is helpful to be able to compare the sheet characteristics of various suppliers and understand how the material might react to your application with all of the above information. Every supplier can supply the line callout at request and that should be required to assist engineering and purchasing.

Report on the Committee on Fuel, Lubricants and Environmental

TUESDAY, OCTOBER 3, 2023

1:45 PM

Chair

Chris Miller

Senior Director-Service Product Management

Wabtec Corporation, Chicago, IL

Vice Chair

S. Fritz, P.E.

Senior Manager-R&D

Southwest Research Institute, San Antonio, TX

Commitee Members

B. Amen	Manager-Mechanical Engineering	Union Pacific RR	Omaha, NE
J. Barnes	Chief Chemist	Norfolk Southern	Chattanooga, TN
D. Beebe	Technical Director	Temple Engineering	Liberty, MO *Past President*
M. Brinkman	Sales Manager-Engineering	Boll Filter	Novi, MI
D. Cook	Chief Technical Officer	Rail Propulsions Systems	Fullerton, CA
T. Degerness	Manager Fuels	CPKC	Calgary, Alberta
R. Denton	Corp Chemical Technology Manager	Cummins, Inc	Columbus, IN
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R. Flott	Chief Fuel Chemist	BNSF Railway	Topeka, KS
P. Fontecchio	Engrg Mgr-Engine Cooling & Lube	Wabtec Corporation	Erie, PA
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R. Garver	Sales Manager	Innospec	Englewood, CO
F. Girshick	Lubricants Technology	Infiineum	Linden, NJ
R. Hays	Director-Sales	Red Gian Oils/HF Sinclair	Council Bluffs, IA *New Member*
J. Heywood	Senior Fuels and Lubricants Engineer	Wabtec Corporation	Fort Worth, TX Regional Executive
S. Jaworski	Application Advisor	Exxon Mobil	Williamstown, Ontario *New Member*
C. Koglin	OEM Relations Specialist	Afton Chemical Corporation	Southfield, MI
S. Koshy	Mechanical Engineer	Amtrak	Wilmington, DE
T. Mack	President/Owner	Zero Emission Loco Technology	Blue Ash, OH
J. Meinhardt	Applications and Service Engineering	Cummins, Inc	Columbus, IN
R. Modiyani	Senior Manager Emerging Markets	Chevron Renewable Energy Group	Ames, IA
S.Nevin	Managing Director-Supplies & Material	CPKC	Calgary, Alberta
R. David Pelletier	OEM Technical Advisor	Exxon Mobil	Durham, ME
L. Rasmussen	Product Engineer-Engine Systems	Progress Rail-Electro Motive Diesel	LaGrange, IL
L. Rawding	RR Product Manager	American Refining Group	Bradford, PA
C. Ruch	Director-Technical Research & Development	BNSF Railway	Topeka, KS *2nd Vice President*
G. Smith	Project Manager	Argus Consulting, Inc	Overland Park, KS

Note: Dave Tuttle of American Regiining Co and James Klaus of Cummins, Inc. recently retired-we wish them a happy/healthy retirement

PERSONAL HISTORY

Chris Miller

Senior Director of Product Services Management
Wabtec
Chicago, IL

Chris is a versatile professional with experience in product management, employee development, problem solving, strategic planning, carbon reduction, sustainability, and customer service. He enjoys learning about new concepts and techniques, especially in the energy systems space to be a resource for others. Chris works cross functionally to develop innovative and pragmatic solutions for customers that create win/win solutions.

Chris spent 12 years at multiple North American Class 1 Railroads in operations, reliability, and mechanical engineering. He is now at Wabtec as the Senior Director of Product Services Management where he is developing the roadmap and strategy for the energy systems powering the world's existing freight locomotives. His products push the existing diesel-burning locomotive fleet to be more reliable and fuel efficient while growing to include energy sources such as alternative fuels, batteries, and hydrogen that are needed to support the industry's transition to carbon neutrality.

Chris has three children aged 10, 8 and 4 with his wife, Liz. They moved to Chicago in 2021 and love the city and suburbs. He enjoys running when there is free time from all the kid's fun activities (soccer, dance, swimming, and basketball).

THE FUEL, LUBRICANTS AND ENVIRONMENTAL COMMITTEE WOULD LIKE TO EXPRESS THEIR SINCERE APPRECIATION TO METROLINK (MICHELE STEWART, CARLOS PEREZ, ERIC POGHOSYAN AND EMMANUEL VALLES) FOR HOSTING OUR FEBRUARY 22, 2023 MEETING IN BLOOMINGTON, CALIFORNIA AND TO THE UNION PACIFIC (BRETT AMEN, JUSTIN HENDRICKSON AND STEVE CAIRNS) FOR HOSTING A TOUR OF THEIR FACILITY IN BLOOMINGTON, CALIFORNIA.

THE COMMITTEE WOULD ALSO LIKE TO THANK CUMMINS (SCOTT FILES AND JIM KLAUS) FOR SUPPORTING US IN SEYMOUR, INDIANA ON JUNE 22, 2023 AND FOR GIVING US A TOUR OF THEIR FACILITY. ALSO, SPECIAL THANKS TO AMTRAK (DEVON PARSONS, DAN RIMER AND BOB HAGLEY) FOR THEIR HOSPITALITY AND FOR PROVIDING A TOUR OF THEIR BEECH GROVE, INDIANA FACILITY ON JUNE 23, 2023.

COMPANIES, SUCH AS THE ONES MENTIONED ABOVE, PROVIDE A VENUE SO THAT OUR COMMITTEE CAN CONDUCT IMPORTANT MEETINGS IN PREPARATION OF RAILWAY INTERCHANGE 2023 TO BE HELD IN INDIANAPOLIS, INDIANA ON OCTOBER 2-4, 2023

The EPA Diesel Emissions Quantifier (DEQ) – Time For a New Approach

By:
Tom Mack, Zero Emission Locomotive Technologies, LLC

Abstract

The federal government and many states use the EPA Diesel Emissions Quantifier (DEQ) to calculate emissions reduction and grant cost efficacy. Based on the information entered into the DEQ, emissions output, including NOx, PM2.5, HC, CO, and even CO2 are calculated. Based on the calculated emissions and the cost of a new locomotive, emissions reduction efficacy costs are then determined. These efficacy costs are used by many grant providers to determine if a project will be cost effective in its emissions reduction, or whether one project is more cost effective than another, allowing projects to be ranked for grant awards.

The DEQ is an online tool provided by the EPA. It can be accessed at: https://cfpub.epa.gov/quantifier/

Problem Statement

While using the DEQ itself is a fairly simple and straightforward process, the results of the DEQ do not match what would normally be expected for emissions calculations. For example, the DEQ uses a locomotive's *rated* horsepower and annual hours of operation to determine the estimated annual emissions, rather than the locomotive's actual annual fuel use. As such, no consideration is given to whether the locomotive spends most of its time in lower throttle notch settings or whether it runs primarily at higher horsepower settings. A lower horsepower locomotive, despite using the same amount of fuel and operating for the same number of hours annually as a higher horsepower locomotive, will be assessed as emitting significantly less pollution than its higher horsepower counterpart

For example, consider a 900 HP EMD SW900, 1200 HP EMD SW1200, and 1750 HP EMD GP9, all of which use the EMD 567C engine, just with different numbers of cylinders. Comparing these three units using the same amount of fuel and working the same number of hours, the DEQ shows the 900 HP SW900 (with a 8-567C engine) produces just 75% of the emissions of a 1200 HP SW1200 (with a 12-567C engine). The 1750 HP GP9 (with a 16-567C engine) would produce almost double the emissions of the SW900. Yet, it is entirely possible that all three locomotives use the same amount of fuel annually, and would be expected to produce the same amount of emissions, simply due to different duty cycles.

LMOA Paper Justification

This paper highlights the results of the current DEQ and why the results do not match either accepted practice or even the EPA's own accepted emissions calculations based on fuel usage. This paper attempts to clarify exactly how the DEQ calculates its emissions and why the current approach may not be optimal for allocating locomotive emissions reduction funding. It will also show how these emissions could be better calculated and include suggestions to modifying the DEQ. This is critical for the fair comparison of emissions from different locomotive operations and to support the best use of limited publicly supported grant funds for locomotive emissions reduction.

Real World DEQ Scenarios

To start with, it is important to see exactly what results the DEQ produces with different rated horsepower locomotives in the same operating scenarios. The following DEQ case study is run with information on two very similar locomotives; one is a 900 HP switcher (an EMD SW900) and the other a 1,200 HP switcher (an EMD SW1200). Both locomotives were listed as having the same age, annual fuel usage, and annual hours of operations. The results of the DEQ can be seen in the following two reports. These scenarios assume that both locomotives would be replaced with 100% battery-electric locomotives, thus eliminating 100% of the EPA regulated mobile source emissions. (See Figures 1 and 2)

Group Name: EMD SW900

Type Locomotive	**Engine Model Year** 1956	**Fuel Type** ULSD (diesel)
Target Fleet Switch Locomotive	**Tier** Uncontrolled	**Annual Fuel Gallons** 30,000
Sector Freight	**Horsepower** 900	**Diesel-equivalent Gallons** 30,000
Quantity 1	**Upgrade Year** 2021	**Annual Usage Hours** 2,000
	Remaining Life 1	

Edit Group | Copy This Group | Delete

Upgrades to EMD SW900

Action	Upgrade	Cost per Unit		Percent Reduction				
		Upgrade	Labor	NO_x	PM2.5	HC	CO	CO_2
Edit Delete	Locomotive Replacement - All-Electric	$1,163,231	$0	100	100	100	100	100

Emission Results

Here are the combined results for all groups and upgrades entered for your project.[1]

Annual Results (short tons)[2]	NO_x	PM2.5	HC	CO	CO_2	Fuel[3]
Baseline for Upgraded Vehicles/Engines	2.856	0.061	0.166	0.300	337.5	30,000
Amount Reduced After Upgrades	2.856	0.061	0.166	0.300	337.5	30,000
Percent Reduced After Upgrades	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Lifetime Results (short tons)[2]						
Baseline for Upgraded Vehicles/Engines	2.856	0.061	0.166	0.300	337.5	30,000
Amount Reduced After Upgrades	2.856	0.061	0.166	0.300	337.5	30,000
Percent Reduced After Upgrades	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Lifetime Cost Effectiveness ($/short ton reduced)						
Capital Cost Effectiveness[4] (unit & labor costs only)	$407,339	$19,155,928	$7,017,518	$3,873,057	$3,447	
Total Cost Effectiveness[4] (includes all project costs)	$585,140	$27,517,387	$10,080,627	$5,563,625	$4,951	

Figure 1: DEQ Results for 900 HP EMD SW900 using 30,000 gallons of fuel annually

Group Name: EMD SW1200

Type Locomotive	**Engine Model Year** 1956	**Fuel Type** ULSD (diesel)
Target Fleet Switch Locomotive	**Tier** Uncontrolled	**Annual Fuel Gallons** 30,000
Sector Freight	**Horsepower** 1,200	**Diesel-equivalent Gallons** 30,000
Quantity 1	**Upgrade Year** 2021	**Annual Usage Hours** 2,000
	Remaining Life 1	

Edit Group | Copy This Group | Delete

Upgrades to EMD SW1200

Action	Upgrade	Cost per Unit		Percent Reduction				
		Upgrade	Labor	NO_x	PM2.5	HC	CO	CO_2
Edit Delete	Locomotive Replacement - All-Electric	$1,163,231	$0	100	100	100	100	100

Emission Results

Here are the combined results for all groups and upgrades entered for your project.[1]

Annual Results (short tons)[2]	NO_x	PM2.5	HC	CO	CO_2	Fuel[3]
Baseline for Upgraded Vehicles/Engines	3.808	0.081	0.221	0.400	337.5	30,000
Amount Reduced After Upgrades	3.808	0.081	0.221	0.400	337.5	30,000
Percent Reduced After Upgrades	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Lifetime Results (short tons)[2]						
Baseline for Upgraded Vehicles/Engines	3.808	0.081	0.221	0.400	337.5	30,000
Amount Reduced After Upgrades	3.808	0.081	0.221	0.400	337.5	30,000
Percent Reduced After Upgrades	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Lifetime Cost Effectiveness ($/short ton reduced)						
Capital Cost Effectiveness[4] (unit & labor costs only)	$305,504	$14,366,946	$5,263,139	$2,904,792	$3,447	
Total Cost Effectiveness[4] (includes all project costs)	$438,855	$20,638,040	$7,560,470	$4,172,718	$4,951	

Figure 2: DEQ Results for 1,200 HP EMD SW1200 using 30,000 gallons of fuel annually

Using the EPA's accepted 15.2 bhp-hrs per gallon of fuel used conversion to horsepower-hours (for a switcher locomotive), one would expect the emissions results, and therefore cost effectiveness, to be same for both locomotives. After all, both locomotives use the same 567 engine, except that one is an 8-cylinder and the other a 12-cylinder. But the overall fuel efficiency of the 8-567C vs. the 12-567C engine would be expected to be the same, regardless of number of cylinders or Notch 8 HP. Supporting this emissions assumption is an actual study by Southwest Research Institute of four locomotives – one (an EMD MP15) uses a 12-cylinder EMD 12-645E and three (EMD GP38-2's) use a 16-cylinder EMD 12-645E. All locomotives tested use Tier 0 roots blown engines without turbochargers. The study results, shown in Figure 3, clearly show the NOx profile of the two engines to be virtually identical. Also, the EPA diesel gallons used for hp-hrs conversion uses a standard conversion factor for switcher locomotives that assumes the overall efficiency of any switcher locomotive's diesel engine will be fairly the same. Therefore, if both locomotives used the same amount of fuel in a given year, the amount of work (hp-hrs) produced from the fuel would be the same.

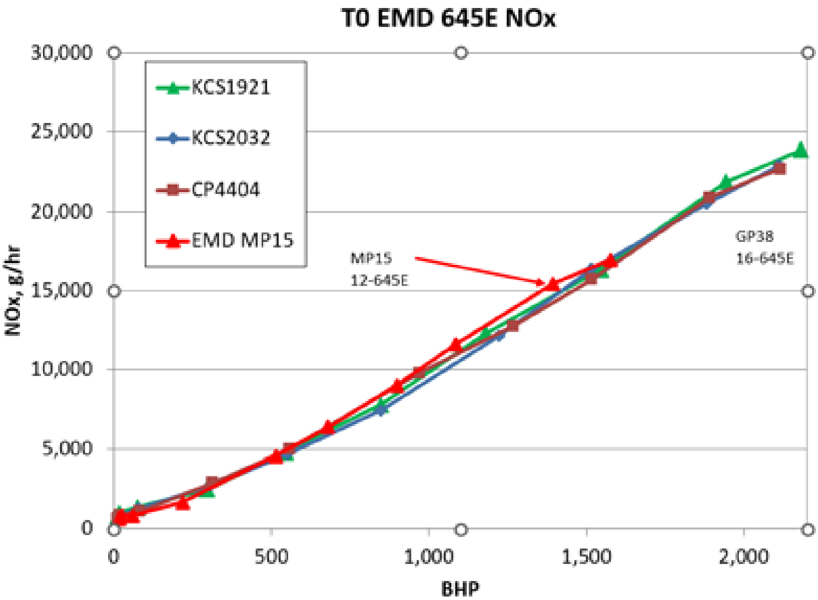

Figure 3: Southwest Research Institute Published NOx Output Results for Roots Blown EMD 645E Engines

It should also be noted that a difference in duty cycle can easily account for the 900 HP SW900 using the same amount of fuel as the 1,200 HP SW1200. In the same usage scenario, the 900 HP SW900 could easily replace the 1,200 HP SW1200 except for being unable to reach the full HP of the SW1200 in N7 and N8. But since N7/N8 only account for 1% of the EPA switcher duty cycle, assuming that an operator can get by without having to go above 900 HP for that 1% of the duty cycle, an SW900 can easily do the work of an SW1200, and would consume virtually the same amount of fuel as its more powerful counterpart. Vice versa, an SW1200 could definitely replace an SW900, but simply never be run above N6. Assuming the same amount of fuel is used in diesel engines of the same efficiency, the hp-hrs of the two locomotives should be virtually identical, with the emissions levels being virtually identical.

However, when we run the EPA DEQ, the calculated emissions levels for the SW900, using the same amount of fuel and working the same number of hours per year as an SW1200, are only 75% of the emissions of the SW1200. For example, the SW900 is calculated to produce only 2.856 tons of NOx per year from 30,000 gallons of fuel consumed, while the SW1200 is calculated as producing 3.808 tons of NOx per year from 30,000 gallons of fuel consumed (this also does not make sense based on the EPA's own fuel to power calculations). At first glance, this seems to indicate that the DEQ utilizes the N8 HP of any given locomotive for the emissions conversion, rather than the fuel burned. Just because a locomotive is higher horsepower in N8 has little bearing on its emissions output if the two locomotives work the same number of hours and use the same amount of fuel.

Furthering this example to now include a 1,750 HP GP9 (which has a 16-567C engine), as shown in Figure 4, the emissions output of the 1,750 HP GP9 is calculated as nearly twice that of the 900 HP SW900. The SW900 was calculated to produce only 2.856 tons of NOx per year from 30,000 gallons of fuel consumed, while the GP9 is calculated as producing a significantly higher 5.553 tons of NOx per year from 30,000 gallons of fuel consumed. Again, this shows the EPA DEQ calculation uses the horsepower rating of the locomotive, which has little to do with its overall emissions profile. Clearly annual fuel consumption is the prominent factor in estimating annual emissions from a given locomotive.

Group Name: EMD GP9

Type Locomotive	**Engine Model Year** 1956	**Fuel Type** ULSD (diesel)
Target Fleet Switch Locomotive	**Tier** Uncontrolled	**Annual Fuel Gallons** 30,000
Sector Freight	**Horsepower** 1,750	**Diesel-equivalent Gallons** 30,000
Quantity 1	**Upgrade Year** 2021	**Annual Usage Hours** 2,000
	Remaining Life 1	

Edit Group | Copy This Group | Delete

Upgrades to EMD GP9

Action	Upgrade	Cost per Unit		Percent Reduction				
		Upgrade	Labor	NO_x	PM2.5	HC	CO	CO_2
Edit Delete	Locomotive Replacement - All-Electric	$1,163,231	$0	100	100	100	100	100

Emission Results

Here are the combined results for all groups and upgrades entered for your project.[1]

Annual Results (short tons)[2]	NO_x	PM2.5	HC	CO	CO_2	Fuel[3]
Baseline for Upgraded Vehicles/Engines	5.553	0.118	0.322	0.584	337.5	30,000
Amount Reduced After Upgrades	5.553	0.118	0.322	0.584	337.5	30,000
Percent Reduced After Upgrades	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Lifetime Results (short tons)[2]						
Baseline for Upgraded Vehicles/Engines	5.553	0.118	0.322	0.584	337.5	30,000
Amount Reduced After Upgrades	5.553	0.118	0.322	0.584	337.5	30,000
Percent Reduced After Upgrades	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Lifetime Cost Effectiveness ($/short ton reduced)						
Capital Cost Effectiveness[4] (unit & labor costs only)	$209,488	$9,851,620	$3,609,009	$1,991,858	$3,447	
Total Cost Effectiveness[4] (includes all project costs)	$300,929	$14,151,799	$5,184,322	$2,861,293	$4,951	

Figure 4: DEQ Results for 1,750 HP EMD GP9 using 30,000 gallons of fuel annually

This anomaly affects the cost efficacy of replacing two different horsepower locomotives. An operator who only needs a locomotive producing about 1,000 HP and thus runs a 900 HP SW900 would seem to produce significantly lower emissions than an operator who also only needs about 1,000 HP but had bought an over-powered 1,750 HP GP9. Both locomotives should be putting out virtually the same amount of emissions if they use the same amount of fuel per year.

Does the EPA's own data suggest that two locomotives of even greatly different rated horsepower can produce basically the same emissions output? The answer is yes. The EPA clearly states in *EPA-420-F-09-025 April 2009 Emission Factors for Locomotives*, Table 3 Conversion Factors (bhp-hr/gal), that one gallon of diesel used in a locomotive in a switcher duty cycle produces 15.2 bhp-hrs. By EPA standards, there is no difference in the number of bhp-hrs produced by 30,000 gallons of diesel fuel (30,000 x 15.2 = 456,000 bhp-hrs) whether it is burned in an 8-567C engine, a 12-567C engine, or a 16-567C engine (or a GE FDL or Alco 251 for that matter). They would all calculate out to 456,000 bhp-hrs. Since emissions are then calculated by multiplying bhp-hrs by the Tier standard of the locomotive, a Tier 0 switch cycle 14.0 g/bhp-hr NOx locomotive, for example, would produce 456,000 x 14 = 6,384,000 grams of NOx (7 short tons of NOx). That would be regardless of what model locomotive is operated.

Let's take a real world scenario of how this might play out. A quarry starts out with an EMD SW900, runs it in N1-N8, and it works fine for their needs. They work 2,000 hours a year and the loco consumes 30,000 gallons of fuel annually to switch cars around the quarry. The SW900 gets wrecked so the quarry purchases a nice used SW1200. The SW1200 per published information produces 885 HP at N6, so the quarry likely never needs to run its "new" SW1200 above N6, and this becomes the actual situation. They still work 2,000 hours a year, and since the engines in their wrecked SW900 and current SW1200 are both 567C's with virtually the same overall engine efficiency, their fuel consumption remains at 30,000 gallons per year to do the same work. Unfortunately, the quarry operator blows the generator in the SW1200, so the owners of the quarry decide to simply move a nice GP9 from another of their operations that is shutting down and use it to replace the SW1200. A 1750 GP9 produces 960 HP at N5, so now the quarry crews only have to operate their "new" GP9 in N1-N5 to do their daily chores. Again, they still work 2,000 hours per year, and we would expect the fuel consumption to remain at right around 30,000 gallons per year. Under the DEQ the GP9 will produce almost double (1.94x) the amount of NOx as the SW900, but this doesn't match the reality of the situation.

Emissions calculations are critical right now because, under the Biden administration Bi-Partisan Infrastructure Law (BIL) and the Inflation Reduction Act (IRA), billions of dollars of funding will become available to many locomotive operators to purchase new, low emission locomotives, including both Tier 4 diesel and zero-emission battery locomotives. Several states have already historically based their cost effectiveness calculations to award emissions reduction funds, such as the VW settlement funds, on the EPA DEQ calculation. And as one state official said, "the EPA DEQ is only an estimate but gives the state an apples to apples comparison between locomotives to determine emissions and cost effectiveness." However, from what can be seen from previous DEQ reports and the real world operations scenario, the DEQ does not provide accurate "apples to apples" comparisons.

Imagine, for example, if the previously mentioned quarry had bought a cheap 3,000 HP EMD SD40-2 for its operation. They still only need 900 HP, so they would probably never operate the SD40-2 above N3 (790 HP) or N4 (1180 HP).

But the DEQ would peg the emissions for an SD40-2 at over 3.3 times of an SW900. Or suppose a grain elevator operator who bought an SD40-2 to pull a unit train during grain season through the loadout, and uses 12,000 gallons per year of fuel, and never operates above 3-4 MPH (hence doesn't need the 3,000 HP, just the 6-axle tractive effort), applies for a locomotive replacement grant. The grain elevator's grant request would be rated as more cost effective for emissions removal than a railroad replacing a 1,500 HP MP15 using 30,000 gallons of fuel per year.

Basis for EPA's Current DEQ Calculation

According to the EPA, its locomotive DEQ is based on the calculations found in RIA EPA420-R-08-001a. However those calculations are for wide-area fleets, such as might be found in a city or state. As such, these are utilized for large area emissions calculations where multiple different types of locomotives might be found. But for grant purposes, usually single or a few locomotives are used. At that point the DEQ becomes pointless since it assumes that the load factor of every individual locomotive of the same EPA Tier (emission factor) is identical and thus the horsepower rating of the locomotive is what determines the emissions output, rather than its annual fuel consumption. The problem with this assumption is that it implies that the diesel engine efficiency of a locomotive is directly related to its horsepower rating in view of the fact that a lower horsepower locomotive will always show lower emissions, even if it works the same amount of time as its higher horsepower counterpart and consumes the same amount of fuel, which is a fallacy. Contrary to what was said by an EPA representative that, "user-reported power and usage hours… is a more precise method of estimation than using an average bhp-hr/gal conversion factor from fuel usage", this paper asserts that a more precise assumption is that the diesel engines of two different locomotives are very close in efficiency, especially when these are from the same locomotive manufacturer. The majority of switchers in service and available for replacement are EMD products with a 567 or 645 engine. As such, it is the fuel consumption of the locomotive, not the rated horsepower, that is far more precise in comparing two locomotives' annual work output, from which emissions are then calculated.

Additional calculations to illustrate the issue are shown below. In this scenario, a 1956 vintage 900 HP EMD SW900 with an 8-cylinder 567C engine is compared to a 1956 vintage 1750 HP EMD GP9 with a 16-cylinder 567C engine. When brand new, the 900 HP engine would produce 112.5 HP per cylinder and the 1750 HP engine would produce 109.4 HP per cylinder. The fuel efficiency of the two engines would be expected to be within a couple of percentage points of each other. For purposes of the following scenario, a publicly available grant application which was awarded to a rail operator using the DEQ calculator is used. The rail operator reported the use of a 1956 1,750 HP GP9 working 2,500 hours per year and consuming 35,000 gallons of diesel fuel. The locomotive was in use 300 days per year, which calculates to a reasonable 8.33 hours per day. Using the DEQ calculation, ***Annual Emissions*** $_{(grams)}$ $= N \times HP \times LF \times AH \times EF$, for these two locomotives each working 2,500 hours per year, would yield the following results:

Annual Emissions						
Tons =	grams =	N x	HP x	LF x	AH x	EF
3.569	3,237,705	1	900	0.0827	2,500	17.4
6.940	6,295,538	1	1,750	0.0827	2,500	17.4

Figure 5: Results for SW900 and GP9 Emissions Calculations

Additional documentation on the actual grant shows that the grant awarder, using the DEQ, calculated the annual NOx emissions at 6.941 tons, so the above calculations are valid for this scenario.

Since the DEQ does not use the annual fuel consumption in its calculation, it does not matter whether the 900 HP locomotive uses more fuel to work the same hours as the 1,750 HP locomotive. As shown in the above calculation, as long as the two locomotives work the same amount of time, the DEQ will always calculate the 1,750 HP locomotive as producing 1.94x more emissions than the 900 HP locomotive. This is a false assumption that grossly underestimates the emissions inventory for lower horsepower (e.g. <= 1200 HP) switcher locomotives, which comprise a large amount of the industrial switching fleet, compared to higher horsepower (e.g. 1750-2300 HP) switcher locomotives.

For the DEQ to argue that a 900 HP locomotive utilizing the same amount of fuel and working the same amount of hours as a 1750 HP will always do about 50% of the work of a 1750 HP locomotive would imply either:

1. All locomotives are operated at the same duty cycle by every owner, irrespective of locomotive's horsepower rating or industry served, or
2. Locomotive engine efficiency is directly proportional to the rated horsepower (i.e. a 900 HP locomotive will always be only ~50% the efficiency of a 1750 HP locomotive) and a 900 HP locomotive will thus always have to work twice as many hours to produce the same amount of hp-hrs and emissions as its 1750 HP counterpart.

It can most readily be recognized that both of the assumptions above are unfounded in real world locomotive operation.

DEQ and Idle Reduction

Another major weakness in the DEQ calculation involves idle reduction technologies installed on a locomotive. Under the current DEQ, the use of anti-idling devices, such as AESS or APU's, has no effect on emissions reduction. Yet it should be pointed out that the EPA offers incentives for "emissions reductions" using these devices.

Interestingly, in many cases, the use of an APU or AESS by a locomotive operator will have no effect on the number of hours a locomotive is “used” (operated) annually. If a railroad is running a GP9 2500 hours per year, with a 70% idle rate, just because the railroad installs an AESS to turn the engine off and on when in idle, an 8-hour switching shift will still take 8 hours. In this case the locomotive’s Annual Usage Hours entered into the DEQ would not be any different from a locomotive without an APU or AESS.

For example, if a railroad has a crew assigned to work 8-hours per day, 5 days per week, the crew’s locomotive is operating 40 hours per week, 2,080 hours per year. If the railroad installs an AESS system, the crew still operates the locomotive 40 hours per week, 2,080 hours per year. They are still out working, it’s just that when they are stopped for a signal, or in between switching moves, the AESS can shut down the engine until they resume activity. The throttle is in idle and the locomotive is ”operating”, awaiting a movement of the throttle, but under the DEQ, despite the fact that the AESS will decrease fuel usage and emissions, the locomotive, with identical operational hours and rated horsepower will still show the same emissions output as the non-AESS equipped locomotive.

So by the current EPA DEQ calculations, the DEQ will show that there is no emissions advantage to an AESS or APU. This simply is not the case. But utilizing fuel usage for the emissions equation will clearly show a reduction in emissions if an AESS or APU is installed on a locomotive.

DEQ Emissions Calculations – A Better Way?

The most logical basis to estimate the amount of work of a single locomotive compared to another locomotive is its fuel consumption, since fuel energy will convert directly to work energy using the formulas:

BTU / 3412.1416416 = kWH

kWH x 1.341 = hp-hrs

Work output (WO) can then be calculated by multiplying the hp-hrs content of the fuel by the engine efficiency (EE): *hp-hrs x EE = WO*

Based on the above, if we use the DOE LHV value of 127,500 BTU per gallon of diesel, the average efficiency of a switcher locomotive diesel engine is 30.3%, as shown by the following three calculations:

127,500 BTU / 3412.1416416 = 37.4 kWH

37.4 kWH x 1.341 = 50.1 hp-hrs of total energy in 1 gallon of diesel fuel

15.2 EPA hp-hrs/gal / 50.1 = 0.303 (30.3% efficiency)

As can be seen, the locomotive diesel engine is already given a rather low efficiency rating for switching. For example, a 2,000 HP GP38-2 in switching service would use the 15.2 HP per gallon EPA conversion (30.3% efficiency), whereas the same locomotive in Class III line haul service would produce 18.2 hp/gal = 36.3% efficiency, and in Class I/II line haul service would produce 20.8 hp/gal = 41.5% efficiency. The EPA assumes that engine efficiency will change based on line haul vs. switching duty cycles. Interestingly, calculations based on actual horsepower and fuel consumption at throttle notch data shows that common EMD switcher locomotives (e.g. SW900, SW1200, SW1500, MP15) do run at an efficiency level of between 29% and 35% in the EPA switcher duty cycle. The EPA's 15.2 hp-hrs per gallon for switchers is a reasonable representation for emissions calculations purposes. In fact, published data for an EMD GP9's fuel consumption and power at notch utilizing the standard EPA switcher duty cycle extrapolate to 14.8 hp-hrs/gal, within 2-3% of the EPA projection.

Using the EPA 15.2 hp/gal factor, the following NOx emissions would be calculated on two unregulated 1956 era locomotives using the same amount of fuel per year:

900 HP SW900 using 35,000 gallons of fuel = 35000 x 15.2 =
532,000 hp-hrs x 17.4 g/bhp-hr = 9,256,800 grams NOx = **10.20 tons**

1700 HP GP9 using 35,000 gallons of fuel = 35000 x 15.2 =
532,000 hp-hrs x 17.4 g/bhp-hr = 9,256,800 grams NOx = **10.20 tons**

However, assuming that both locomotive use 35,000 gallons per year (which can be empirically extrapolated to hp-hrs) working 2,500 hours per year (which cannot be empirically extrapolated to hp-hrs), the current DEQ will calculate the NOx emissions as follows:

1 SW900 x 900 HP x 0.0827 Load Factor x 2,500 hours x 17.4 g/bhp-hr =
3,237,705 grams NOx = **3.57 tons**

1 GP9 x 1750 HP x 0.0827 Load Factor x 2,500 hours x 17.4 g/bhp-hr =
6,295,538 grams NOx = **6.94 tons**

Notice how grossly underestimated the EPA DEQ emissions are vs. the EPA hp-hrs calculation. The DEQ only calculates NOx output for the 900 HP locomotive at 3.57 tons, whereas the NOx output based on fuel consumption is 2.9x higher. Even the NOx output for the 1750 horsepower is underestimated, with actual emissions being 47% higher than the DEQ estimate.

To extrapolate this out to engine efficiency, we can reverse calculate the DEQ emissions output to hp-hrs and hp-hrs per gallon for an unregulated (pre-Tier 0) locomotive:

900 HP SW900 = 3,237,705 grams NOx / 17.4 g/bhp-hr = 186,075 hp-hrs / 35,000 gallons = **5.32 hp-hrs/gal**

1750 HP GP9 = 6,295,538 grams NOx / 17.4 g/bhp-hr = 361,813 hp-hrs / 35,000 gallons = **10.34 hp-hrs/gal**

Applying the empirical value shown above of 50.1 hp-hrs of total energy available in one gallon of diesel fuel, the overall efficiency rate of the two locomotives calculates as follows:

900 HP SW900 = 5.32 hp-hrs/gal / 50.1 hp-hrs/gal available = **10.6%** diesel engine efficiency

1750 HP GP9 = 10.34 hp-hrs/gal / 50.1 hp-hrs/gal available = **20.6%** diesel engine efficiency

It can easily be argued that even for a 1956 locomotive, the efficiency level of the GP9 at 20.6% is far too low, considering a normal truck diesel engine fuel efficiency of ~40%. Even compared to the EPA estimation of 30.3% would indicate the current locomotive is only about 66% as efficient as it should be. But to suggest that a 900 HP locomotive, just by nature of its lower rated horsepower, will be only 33% of the standard EPA switcher efficiency is incorrect.

Conclusion

This paper illustrates that while the DEQ may have merits for estimating emissions for larger fleets, it is unsatisfactory for calculating single locomotive emissions levels. Since the EPA DEQ accepts the users annual fuel usage input as one of its parameters, it can easily be reworked using the EPA's existing standards to provide better estimates of actual locomotive emissions. This is critical for future funding requests as well as to establish correct emissions reporting right now for locomotives in service on railroads and in industrial settings throughout the U.S.A. The EPA is encouraged to revise the DEQ for emissions calculations as soon as possible and LMOA suggests/recommends the use of a fuel consumption based calculation, such as those used by California or other states for locomotive emissions estimates.

[The author would like to thank Steve Fritz of Southwest Research Institute for the time he spent long before this paper was actually written reviewing and evaluating much of the data and concepts found herein. His prior review of much of the information presented in this paper was a big driver in this topic being submitted to the LMOA FL&E Committee for consideration for publication.]

ALTRIOS - Advanced Locomotive Technology and Rail Infrastructure Optimization System, Exploring Pathways to Freight Rail Decarbonization

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ABSTRACT

The Advanced Locomotive Technology and Rail Infrastructure Optimization System (ALTRIOS) is a unique, fully integrated, open-source software tool to evaluate strategies for deploying alternative energy locomotive technologies and associated infrastructure for cost-effective decarbonization. ALTRIOS simulates freight-demand driven train scheduling, mainline meet-pass planning , locomotive dynamics, train dynamics, energy conversion efficiencies, and energy storage dynamics of line-haul train operations. This paper includes information on where to get and how to use the tool. ALTRIOS development was funded by the Department of Energy Advanced Research Projects Agency – Energy (ARPA-E) through a collaboration between NREL, the University of Illinois Urbana-Champaign RailTEC, University of Texas at Austin, Southwest Research Institute (SwRI), and BNSF Railway.

BACKGROUND

The U.S. freight rail system consumes roughly 13 billion liters of diesel a year, with associated criteria (HC, CO, NO_X and PM) and greenhouse gas (GHG) emissions from locomotives and other maintenance and freight handling equipment. All six Class-I North American railroads have signed up for Science Based Targets initiative (SBTi) decarbonization goals, with commitments to reduce GHG emissions on the order of 40 percent by 2030. However, the path to reach these goals remains uncertain. The challenges to decarbonization include capital costs, high instantaneous power requirements for locomotives, large energy demand, the need for that energy in remote locations, and interoperability of locomotives throughout North America. The industry has a large installed base of diesel-electric locomotives (appx. 22k) and the need for high reliability. Many potential decarbonization technologies exist such as hydrogen, biofuels, and batteries, and are being heavily promoted as the solution, but the question still remains about how each should be used to minimize cost, environmental impacts, and potential decreased operational efficiency.

The many options available for decarbonization lack a clear way to apply them, and highlights the need for a modeling tool that could help railroads determine their technology path; however a modeling tool like this did not exist. ARPA-E recognized this gap in technology and funded the LOCOMOTIVES program to spur the development of open-source tools to help solve this problem[1].

An open-source approach was chosen for these tools because it helps accelerate the decarbonization of the U.S. freight-rail system for several reasons.

First the tool is freely available to potential users. However, this does not mean that the end user will not incur costs while using it. There may be a need for development of additional features, training, and support; however, these could be internal or external resources that each railroad chooses to use.

Second, the details of the implementation can be understood because the source code is available for all users. This includes details like numerical details of the solver, modeling assumptions, and exact calibration values. These public features could enable a standard for virtually benchmarking technologies in the decarbonization marketplace. For instance, a technology, energy, or locomotive provider could demonstrate an incremental reduction in carbon usage over a specific route. These results could be shared and reproduced with a user at a railroad who understands what assumptions went into generating these results. This common standard of modeling will help to iterate through new technologies more rapidly.

The availability of source code also allows for implementation of new features by all users that could be incorporated into the public framework or kept proprietary for internal development. New features could be items like battery health modeling, catenary charging throughout the network, and MW-hr tracking for locomotives.

ALTRIOS is one of four open-source frameworks that was developed as part of the LOCOMOTIVES program. It uses a 1 Hz, physics-based simulation of individual trains and infrastructure within a rail network to evaluate decarbonatization pathways prior to investing in them. The framework includes many details like powertrain component efficiencies, time of day electrical grid carbon intensity, fuel carbon intensities, infrastructure costs, physical track layout, speed limits, and servicing times for different technologies. The model provides default values for these details that will work for most users but can be fine-tuned for each user dependent upon their use case.

The potential use cases for this modeling framework are quite broad. The most obvious use case is helping railroads understand what technologies to deploy, where to use them, and how to integrate them within their network. Locomotive OEMs could use this tool to develop specifications for their locomotives in collaboration with railroads. Electricity providers and fuel suppliers can gain a better understanding of the additional demand for their services in a geospatial context. Researchers and technology providers have a framework to experiment with proposed new technologies and network optimization, hopefully resulting in specific proposals for decarbonization that are more realistic. The diagram in Figure 1 shows how ALTRIOS framework fits into decarbonization strategy development for the freight rail industry.

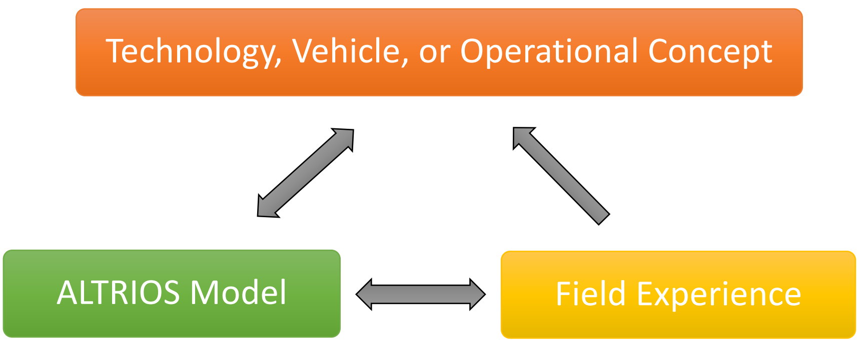


Figure 1. Diagram showing how the ALTRIOS framework could fit into the U.S. freight rail decarbonization strategy development.

Deploying new technologies is time consuming, difficult, and expensive. Its best to screen, qualify and propose new technologies prior to any field testing so that a better trial can be conducted. It is often not feasible to conduct field trials across an entire network. The ALTRIOS framework can facilitate improving the initial specifications, **how** to use it within a network, and **where** to best deploy each technology. The tool can also benefit from field data to improve the model calibration and understanding **why** in-use performance was achieved. ALTRIOS can do this with several software components that are described in the following section.

ALTRIOS Framework Components

The ALTRIOS framework was designed to support five simulation modes. These modes are locomotive/consist, single-train, network, technology rollout, and calibration simulations. Each of these modes have been designed to capture different aspects of the model. The block diagram in Figure 2 describes everything needed for a network simulation. A subset of this diagram is needed for a single train simulation.

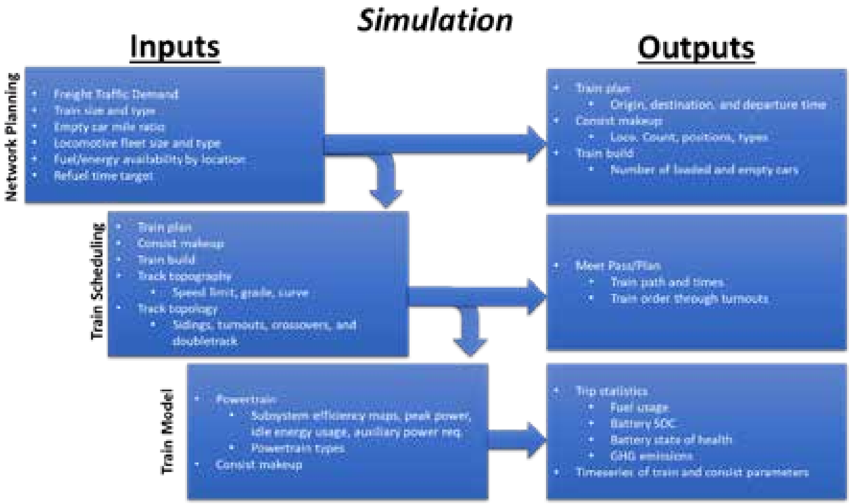


Figure 2. Overview of the ALTRIOS Modeling Framework

The locomotive or consist simulation is the simplest simulation mode. This mode uses a subset of the "Train Model" to simulate a single locomotive or consist based on a required power trace. The inputs for this mode would be locomotive type (conventional, hybrid, fuel cell, or battery-electric locomotive [BEL]). The power trace is specified in watts. The outputs of this model will be a timeseries of powertrain performance data. It will also include aggregate data like total fuel or energy usage. This mode is intended to verify locomotive performance and operation prior to using it in full scale simulations.

There are also many parameters that are not required as inputs to execute this simulation. These include items like internal battery resistance, alternator efficiency, engine efficiency, and auxiliary loads. These parameters have been calibrated using experimental data to model current production locomotives and components. Modifying these parameters could be useful for modeling a specific locomotive model or component.

The single train simulation is used to simulate a single train along a specified route. The inputs for simulation are the network, locomotive type and count, railcar type, count, load, and an optional speed trace for a given territory. If a speed trace is not specified, the maximum speed limit is followed as closely as physically possible. The output of this model includes aggregate and timeseries data that includes powertrain performance and train dynamics. The simulation mode is intended to help understand train performance in a single configuration on a specific route. This may include something as basic as if the route can be completed with the selected locomotive lineup.

The network simulation mode will allow a user to schedule, configure, and simulate a fleet of locomotives and cars based on origin/destination freight demands. This type of simulation can be used to understand how a fixed locomotive pool can be used to move a fixed freight demand within a network. It can help to answer questions like how BEL charging time or infrastructure location will impact the required locomotive pool size.

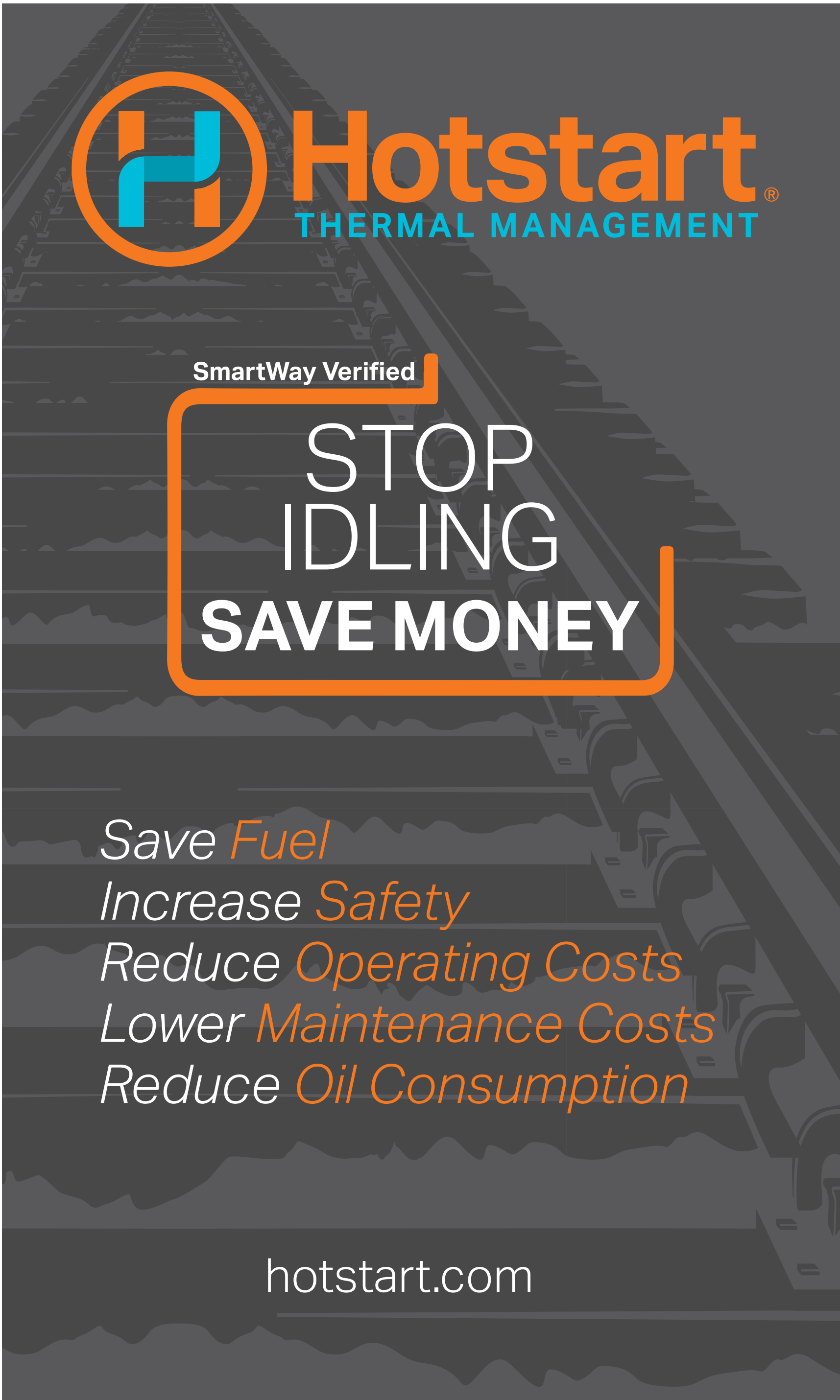
The inputs that are required for this simulation mode are locomotive fleet size and type, locomotive servicing intervals, rail network definition, infrastructure location and type, and freight demands. The outputs for this mode will include aggregate and timeseries data for each train that can be processed using the lifecycle analysis (LCA) calculator described later in this document.

The rollout simulation is used to understand what adoption rates are needed for various technology to achieve desired decarbonization rates. For example, how many new BELs are purchased, delivered, and deployed per year over a user-defined number of years. The inputs for this simulation mode are the same as the network simulation, but it will also include parameters that may change with time. This can include locomotive fleet composition, energy cost, energy GHG emissions, and freight demand.

The outputs for this simulation will include costs, GHG emissions, energy usage by type and location, and detailed train performance. These outputs are all grouped by year. This data can then be used by the life cycle analysis (LCA) calculator to calculate the marginal GHG abatement cost in \$/MtCO_2e (US dollars per metric ton of CO_2 equivalent).

The final simulation mode is the calibration simulation. This simulation mode was developed to calibrate rail car, locomotive, and component models against actual test data. These simulations use a single train or locomotive simulation to fit the model to test data. The exact inputs will vary based upon what is being calibrated. This simulation mode is not covered in the remainder of the report because it is most likely of interest to only a small subset of end-users.

The diagram shown in Figure 2 shows conceptually how the framework ties together from a user perspective. The diagram in Figure 3 shows the major software components that were developed to realize the framework depicted in Figure 2. The core software components are the train consist planner, meet/pass planning, train performance calculator, the powertrain model, and the simulation manager. Each one of these components generates the inputs for the next component so that the output performance metrics can be generated for use with the LCA calculator.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SAVE MONEY
Save Fuel
Increase Safety
Reduce Operating Costs
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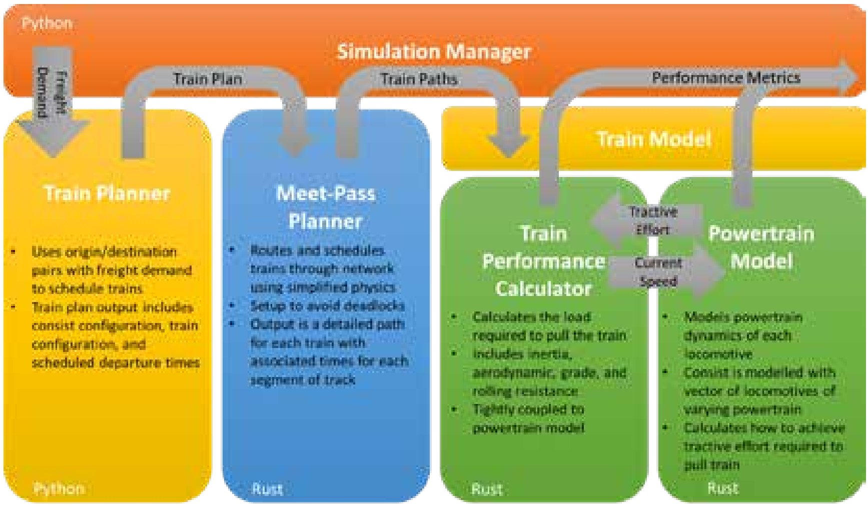

Figure 3. ALTRIOS: Train Corridor Simulator

Each block in Figure 3 identifies the applicable open-source coding language as either Python or Rust. Python was used where ease of use was required. Rust was used where code execution performance was important.

Access to this software is provided in two forms. The first form is a web interface that can be found at (PUT URL HERE ONCE LAUNCHED). This interface captures some of ALTRIOS's functionality and is meant to familiarize a user with the framework and provide non-programmers a way to interact with the framework. The second interface is a Python API that will allow a user to fully interact with the framework. This will allow for implementation of different rollout strategies, optimization strategies, and different powertrain architectures. Python API will allow for exploring more detailed scenarios using the framework. Both interfaces are covered in detail later in this document.

Train Consist Planner

The train consist planner builds the trains virtually. It assigns locomotives, loaded cars, and empty cars to build a train. The high-level inputs for this module are shown in Table 1. These inputs will be what the user will most likely interact with when performing a network simulation. There are additional inputs that can be configured for each locomotive, rail vehicle, and network, but the default values for these items will be satisfactory for most users.

Table 1. High-level inputs for train consist planner

Input	Description
Manifest Empty Return Ratio	Ratio of cars that must returned to original location empty.
Locomotive Pool	This is a list of locomotives that are available to pull trains. The locomotives in this group type and power rating.
Locomotive Types	This includes specifications for each locomotive type. These specifications include servicing (refueling) time and capacity. Each type can have a different servicing time to capture different behaviors.
Simulation Days	The number of days to simulate. The default is 21 days so that the middle week can be used as an average/ steady state snapshot for the network.
Freight Demand	These are origin/destinate pairs for each train type with number of cars.

The inputs provided to this software module can be supplied in a few different ways. The freight demand is supplied in a text file that can be edited with Microsoft Excel. An example of this file is shown in Figure 4 for a route between Barstow, CA and Stockton, CA. This file can be configured to have more than two destinations if needed.

	A	B	C	D	E
1	Origin	Destination	Train_Type	Number_of_Cars	Number_of_Containers
2	Barstow	Stockton	Unit	798	0
3	Barstow	Stockton	Manifest	863	0
4	Barstow	Stockton	Intermodal	740	740
5	Stockton	Barstow	Unit	777	0
6	Stockton	Barstow	Manifest	1076	0
7	Stockton	Barstow	Intermodal	707	707

Figure 4. Example demand file shown in Microsoft Excel for route between Bartow, CA and Stockton, CA.

The remaining inputs for the train consist planner module will either be provided through the web interface or Python API. These inputs are then fed into the train consist planner algorithm shown at a high level in Figure 5.

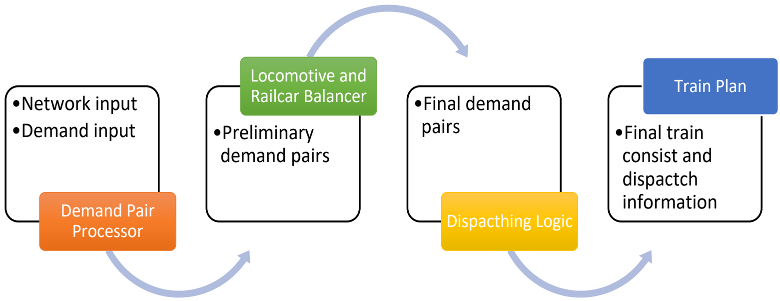

Figure 5. Diagram showing Train Consist Planner algorithm at a high level

Locomotive tracking is an important feature of the train consist planner because the servicing time of new locomotive types may have implications for train scheduling and locomotive fleet size. For example, today's diesel-power locomotives can be refueled in 20-minutes, where a BEL may take 4-8 hours to charge the batteries. The train planner tracks each locomotive as it arrives or departs each location. Departing locomotives are removed from the front of the locomotive queue. Locomotives are then placed at the end of the queue when they arrive at their destination. As each train is planned, the origin pool planner runs a pre-check to determine the locomotive(s) to assign to the train based on train size/ weight and power requirements, and available locomotive charge and fuel refill status, etc. This strategy is depicted in Figure 6.

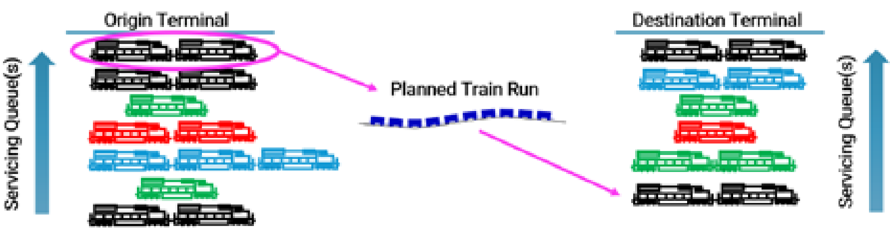

Figure 6. Diagram showing the locomotive tracking that is contained in the Train Consist Planner

The output of the train consist planner is a set of scheduled trains. Each scheduled train includes a departure time, consist of specific locomotives, and a set of cars. This information will be used by the meet/pass planner.

Meet/Pass Planner

The meet/pass planner is shown schematically in Figure 7. It uses the train schedule developed by the train planner. This tool develops the path each train will take through the track network along with estimated times for traversing each segment. It uses a high-performance free-path-based deadlock avoidance algorithm to coordinate train movements within the network. The "stringline" diagram in Figure 7 shows how the algorithm optimizes train trajectories to "meet" trains at passing sidings that generally minimize total overall delay. The trains pass in this diagram where the lines cross. The horizontal portions of the line are where the train is waiting for another train to pass.

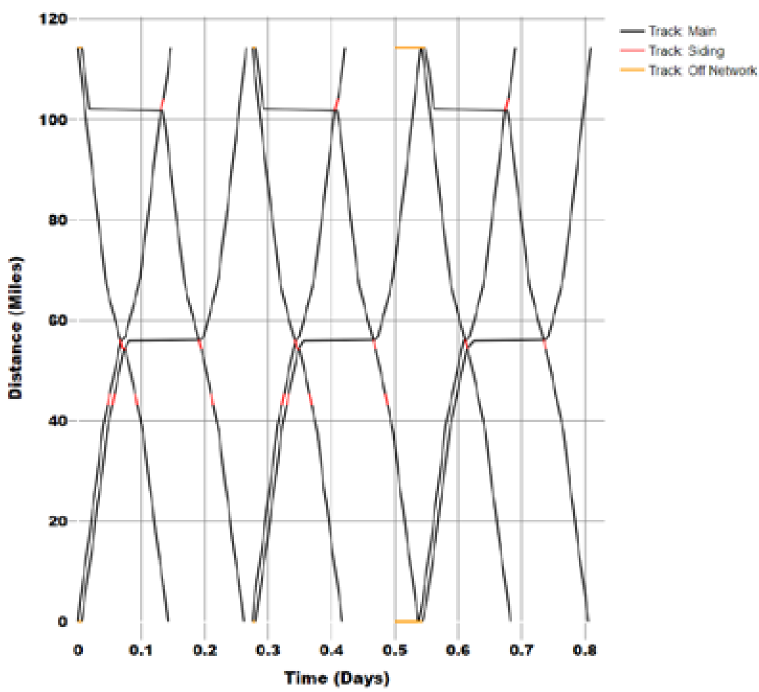

Figure 7. Stringline diagram showing how trains are scheduled to meet and pass as they traverse the network

The output of this module generates a simplified model to estimate times through network. This output is passed back to the simulation manager for use by the train performance calculator and powertrain model to simulate each train within the network. These two modules will use a detailed model to accurately predict train performance.

Train Performance Calculator & Powertrain Model

The train performance calculator is the software module that calculates the resistance created by the train. This module is tightly coupled to the powertrain model which captures locomotive dynamics. The two modules execute concurrently to execute each train simulation. Both modules have been highly optimized so that simulations execute very rapidly. Rapid execution was prioritized for these software modules so that more in depth studies could be executed to understand these technologies more fully.

The train resistance calculator has several parameters to approximate the complete train load. Grade resistance for the train is modeled as uniform mass strap. Rolling resistance is a constant value, recalculated only if train mass changes. Aerodynamic resistance is a function of the square of speed and air density, with air density estimated from front of train elevation. The curve resistance has been implemented using the tabular approach from the AAR Train Energy Model (TEM). Each of these terms is configurable by train type.

The powertrain model uses a component-based approach. This approach simplifies the calibration process and enables flexibility when creating different powertrain architectures. The component types were designed to capture classes of subsystems to enable modeling of a broad range of technologies. There are four main component types that exist with this module and are depicted in Figure 8.

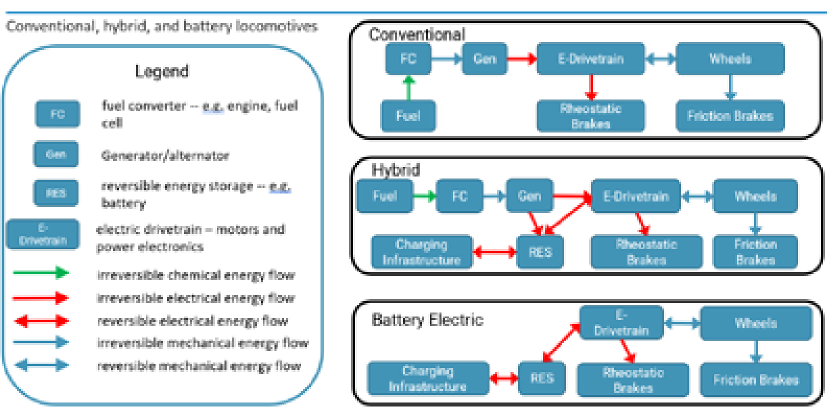

Figure 8. Diagram showing powertrain component types and example powertrain architectures which can be realized with these components

The first component type is the fuel converter. This object type is meant to capture subsystems that convert chemical energy in a non-reversible way. A diesel engine or a hydrogen fuel cell are examples of fuel converters.

The second component type is a generator or alternator. This is required to be used with some fuel converters like engines to convert mechanical power to electrical power. Power can only flow in one direction with this object type.

The third component type is reversible energy storage. This component type represents systems that can store and release energy. Lithium ion batteries have been the focus for the current scope of work, but this component type could be expanded to include mechanical or other energy storage technologies.

The final component type is an E-drive. This is simply the motor that drives the axle. The current version of the framework assumes that this motor will be used across all locomotives.

Each locomotive that is created using these components is added to a vector of locomotives to model the consist. This allows for multiple locomotive types to be used within a single consist as shown in Figure 9. Tractive power is distributed based on positive tractive power capacity and regenerative braking capacity. If any BELs are present in the consist, the current approach is that power is taken from or provided to BELs preferentially while respecting battery state of charge limits. However, the control approach to BEL power utilization is user customizable.

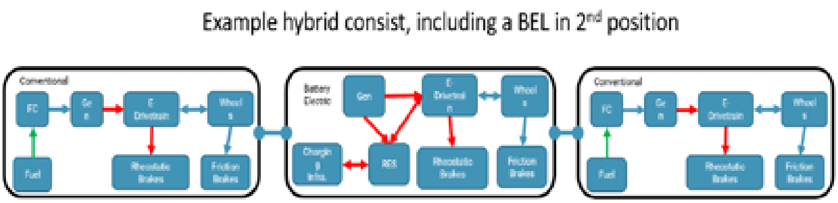

Figure 9. Example of a hybrid consist, with a BEL in the 2nd position

LCA Calculator

The Life Cycle Analysis (LCA) calculator uses the outputs from the train model to calculate total energy usage location, GHG emissions, and financial costs. A diagram of its inputs and outputs are shown in Figure 10. The calculator can be used with the output from the rollout or network simulations.

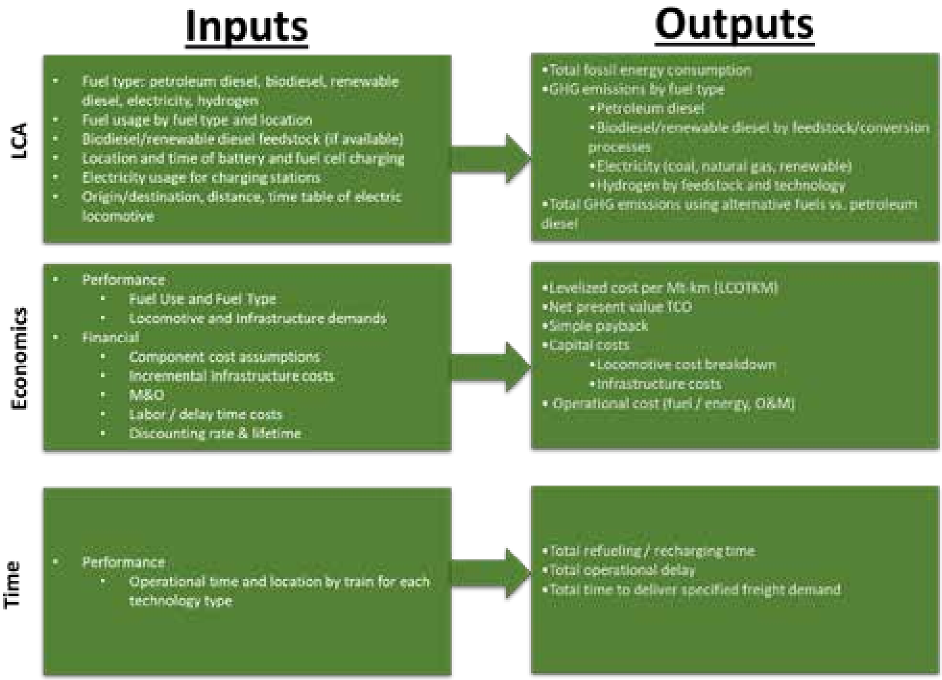

Figure 10. Block diagram describing LCA calculator

The inputs for this model are generated from the output of the train model. There are also many parameters for emissions factors that can be edited to model specific regions or alternative fuels. These parameters are contained in a text file that can be edited with Microsoft Excel. An example of this file type is shown in Figure 11.

	A	B	C	D	E	F	G	H	I	J	K
1	Year	Name	LowHeatingValue	Density	Density Units	Type	Region	TOD	Pollutant_Name	Value	Units
2	2020	ultra low sulfur diesel	42.6	3206	[g/gal]	Liquid	California	NA	GHG_LCA	100.5	gCO2 eq/MJ
3	2020	Grid elec	NA		NA	Electric	California	0:00	GHG_LCA	81.5	gCO2 eq/MJ
4	2020	Grid elec	NA			Electric	California	1:00	GHG_LCA	80.7	gCO2 eq/MJ
5	2020	Grid elec	NA			Electric	California	2:00	GHG_LCA	80.2	gCO2 eq/MJ
6	2020	Grid elec	NA			Electric	California	3:00	GHG_LCA	80.5	gCO2 eq/MJ
7	2020	Grid elec	NA			Electric	California	4:00	GHG_LCA	80.7	gCO2 eq/MJ
8	2020	Grid elec	NA			Electric	California	5:00	GHG_LCA	83.9	gCO2 eq/MJ
9	2020	Grid elec	NA			Electric	California	6:00	GHG_LCA	98.3	gCO2 eq/MJ
10	2020	Grid elec	NA			Electric	California	7:00	GHG_LCA	91.2	gCO2 eq/MJ
11	2020	Grid elec	NA			Electric	California	8:00	GHG_LCA	62.3	gCO2 eq/MJ
12	2020	Grid elec	NA			Electric	California	9:00	GHG_LCA	48.9	gCO2 eq/MJ
13	2020	Grid elec	NA			Electric	California	10:00	GHG_LCA	42.5	gCO2 eq/MJ
14	2020	Grid elec	NA			Electric	California	11:00	GHG_LCA	55.5	gCO2 eq/MJ
15	2020	Grid elec	NA			Electric	California	12:00	GHG_LCA	52.3	gCO2 eq/MJ
16	2020	Grid elec	NA			Electric	California	13:00	GHG_LCA	61.6	gCO2 eq/MJ
17	2020	Grid elec	NA			Electric	California	14:00	GHG_LCA	70.7	gCO2 eq/MJ
18	2020	Grid elec	NA			Electric	California	15:00	GHG_LCA	77.9	gCO2 eq/MJ
19	2020	Grid elec	NA			Electric	California	16:00	GHG_LCA	79.4	gCO2 eq/MJ
20	2020	Grid elec	NA			Electric	California	17:00	GHG_LCA	98.9	gCO2 eq/MJ
21	2020	Grid elec	NA			Electric	California	18:00	GHG_LCA	124.5	gCO2 eq/MJ
22	2020	Grid elec	NA			Electric	California	19:00	GHG_LCA	134.6	gCO2 eq/MJ
23	2020	Grid elec	NA			Electric	California	20:00	GHG_LCA	125.4	gCO2 eq/MJ
24	2020	Grid elec	NA			Electric	California	21:00	GHG_LCA	105.8	gCO2 eq/MJ
25	2020	Grid elec	NA			Electric	California	22:00	GHG_LCA	89.2	gCO2 eq/MJ
26	2020	Grid elec	NA			Electric	California	23:00	GHG_LCA	83	gCO2 eq/MJ
27	2020	Soybean biodiesel	37.8	3335	g/gal	Liquid	California	NA	GHG_LCA	56.3	gCO2 eq/MJ
28	2020	H2 from natural gas	120	90	[g/m^3]	Gas	California	NA	GHG_LCA	117.7	gCO2 eq/MJ

Figure 11. Example file for LCA calculator emissions factors, showing time-of-day dependency of the Carbon Intensity of Electricity from the California Grid

All emissions are reported in units of carbon dioxide equivalent (CO_2e), calculated using the global warming potentials of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) of 1, 25, and 298 g CO_2e per g of greenhouse gas, respectively, for a 100-year time horizon, per California GREET (CA-GREET 3.0) model. The economics model calculates the levelized cost of GHG per million Tonne-Km, a Net Present Value, and an internal rate of return.

NETWORK GENERATION

The physical layout of the rail network is required to accurately model train performance and accurately schedule trains. A utility within ALTRIOS enables all users to create representative network models. The key items needed to define these networks are grade, curvature, speed restrictions, and track layout. There will be two different options to create these networks based upon the data available to the user.

- Option 1: Use railroad proprietary XML network files that conform to AAR S-9503.V2.0
- Option 2: Compile publicly available data sources to create realistic network

Option 1 is the easier of the two methods to generate a network. This approach will work well for routes that have PTC implemented. The main drawback to this approach is that the user must be part of a railroad or supported by a railroad to have access to this data. The route being studied must also have PTC implemented over its entirety.

Option 2 will use publicly available data sources to model the network. This approach will require more work, but it enables all users to have access to a representative network. The utility to create networks using this approach is implemented in QGIS. QGIS is an open-source GIS editor. This editor simplifies the process of joining multiple geospatial data sources to create a single network. A specific example of a relatively short network will be included in the ALTRIOS rollout so that new users can run the program with the sample network, then adapt as needed for their particular scenario.

Model Validation:

The ALTRIOS model was validated over the ~ 375-mile route between Barstow and Stockton, California. Detailed data for 1 BEL & 2 Wabtec Tier 4 ET44C4 diesel locomotives was used, covering seventeen round trips with a total of 6,375 miles traveled. The total duration of the data recorded is 900 hours.[2]

The geography is well suited for validation, including mountains which provide opportunities for high power traction or regenerative braking for long durations. The route also included long flat plains between Bakersfield and Stockton to provide another extreme in topography.

The BEL hybrid consist within the train performance calculator has been calibrated against this test data. These models continue to be refined as the code is updated. A more thorough review of the process is planned to be released in the future once the framework is officially released.

Getting Started With ALTRIOS

There are two options to get started with ALTRIOS. The first option is to use the web interface that can be found at https://altrios.nrel.gov. This interface enables users to simulate a single train or a rollout of BELs into a locomotive pool over specified interval. The intent of this interface is to allow new users to familiarize themselves with the framework with no programming required. However, it does not cover all features of the framework.

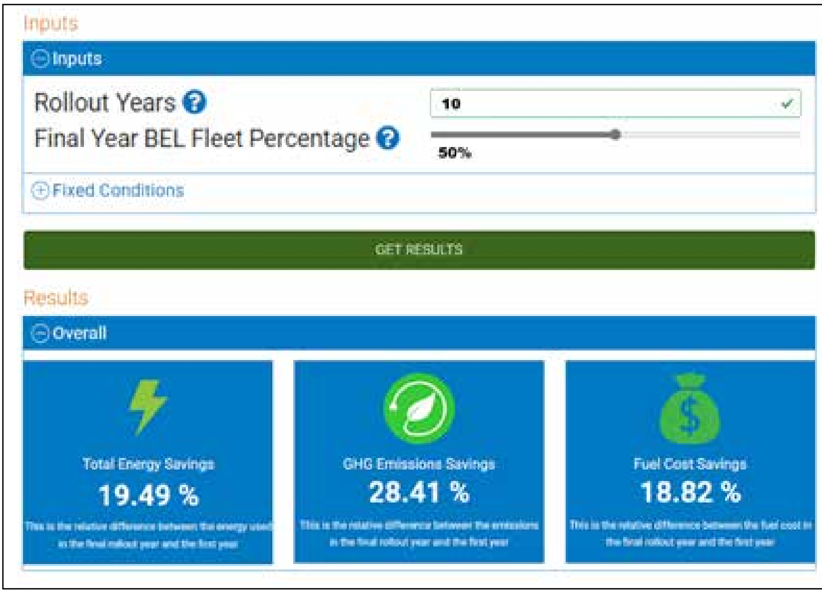

Figure 12. Screen clipping from ALTRIOS-LITE web interface show the single-train (top) and rollout simulation (bottom)

The second interface option is the Python API. This API exposes all features of the framework to the user through a Python module. This interface does require the user to understand programming and will take more time to get started. However, this interface will allow the user to perform more advanced studies by performing parameter sweeps or applying optimization techniques to find more optimal solutions.

Conclusions

ALTRIOS is an open-source framework that was released in June of 2023. The web interface is accessible at http://ALTRIOS_IS_THE_BEST.com. The framework has many features that can be useful for simulating various decarbonization pathways, but it is not fully populated with the many technologies that currently exist.

The team is actively pursuing opportunities to support future development of this tool through additional government funding, private projects, and an industry consortium. Potential features that could be implemented include catenary charging, more alternative fuel data, locomotive MW-hr tracking, tender car modeling, and network resiliency modeling

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Evaluation of Emissions and Engine Wear with 100% Soy Methyl Ester Biodiesel on an EMD567 Switcher

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Abstract

This report documents the effects of B100 (100% Soy Methyl Ester biodiesel) on emissions and engine component wear on a legacy switching locomotive. A 1-year evaluation was conducted by Southern Railway of British Columbia (SRY) on a pre-Tier 0 EMD SW900 switching locomotive. Near the end of the evaluation period, the University of British Columbia (UBC) conducted steady-state emissions measurements on the locomotive using both B100 SME and No. 2 diesel as a comparison baseline. The objective of this study was to determine the relative change in tank-to-stack emissions and identify any engine component compatibility issues caused by operating on B100 SME in a legacy switching locomotive.

All fuel system seals were replaced with Viton equivalents, one power assembly (cylinder #5) was replaced, and new fuel injectors were installed prior to the study. All other engine components were left in as-is state prior to commencing the B100 trial. After 2432 hrs of operation no abnormal degradation was observed in the fuel system, oil, filters, seals, or cylinder assembly. Some coking was observed on the injector tips, however all other injector components were unaffected. Gelling of B100 SME was observed in the on-shore storage tank when ambient temperature was -6°C, however on-board fuel was not affected due to engine recirculation.

Steady-state emission rates were measured at notches idle—8 for both B5 and B100 SME in addition to repeat measurements on a different day (total of 4 measurement days). Relative to B5, when operating on B100 the following engine performance and tank-to-stack emissions changes were observed:

- Engine output decreased by 2—9%. A temporary adjustment of the governor load-balance point successfully recovered the lost power at notch 8.
- Brake-specific CO emissions were reduced by 24—76% at notch 5 and above, and increased by 46% at notch 1, otherwise similar
- Brake-specific NOx emissions were increased by 13—26%
- Brake-specific particulate emissions (black carbon) were decreased by 51—83%
- Brake-specific tank-to-stack CO_2 emissions increased by 1—9%
- Brake-specific well-to-stack CO_2 emissions were decreased by a calculated 94%

Introduction & Background

Transport Canada's Clean Transportation Systems – Research and Development Program funds projects to help reduce air pollutants and greenhouse gas (GHG) emissions from the rail, marine, and aviation sectors. Southern Railway of British Columbia (SRY) was awarded a matching fund from this program to test the performance of 100% biodiesel (B100) as a solution for reducing GHG and air pollutants from switching locomotives. Soy methyl ester (SME) biodiesel was selected due to its availability and low life-cycle carbon intensity of 3.49g/MJ, compared to the 2023 limit of 81.76g/MJ for standard petroleum diesel (as certified through the BC Low Carbon Fuel Standard, BCLCFS).

The chemical properties of B100 SME are known to produce different engine and emissions performance relative to conventional fossil diesel. Typically, increased NO_X and decreased PM emissions reported for B100 are attributed to the increased proportion of fuel-bound oxygen [1]. Increased NO_X emissions may also be partially caused by more advanced ignition timing due to higher cetane number [1,2]. Differences in the viscosity and compressibility (speed of sound and bulk modulus) may also result in advanced injection timing for mechanical injection systems operating on B100 compared to conventional diesel. The reduced heating value of the fuel also reduces the maximum output of the engine at a given notch. Material compatibilities with B100 also differ from conventional diesel and must be considered for engine and fuel system degradation. In particular rubber and copper alloys are adversely affected by B100. Better characterization of these engine emissions, performance, and wear properties for B100 SME is needed to support assessment of this fuel as an appropriate GHG and air pollutant reduction approach in legacy switching locomotives.

SRY conducted a long-term study on the emissions performance and engine wear effects caused by switching from No. 2 diesel to B100 SME. By local legislation, the standard petroleum diesel is a 5% biodiesel blend, which will be referred to as B5 throughout the rest of this report. A switcher locomotive (EMD SW900) was operated on B100 fuel for approximately 2500 hrs starting in July

2022 to the writing of this report in June 2023. It is planned for the locomotive to remain operating on B100 for the rest of 2023. The objectives of this study were to:

- Determine the compatibility of B100 with engine and fuel system components, and identify any necessary component modifications
- Evaluate the relative change in tank-to-stack emissions of CO_2, NO_x, CO, and particulate matter (PM) from the switcher locomotive when operating on B5 vs B100 under steady state conditions. Note that certification of fuel and engine performance was not pursued in this study.

Test Locomotive & Engine

Testing was performed using SRY900, an EMD SW900 switcher locomotive operated by SRY in New Westminster, BC where all testing reported here was performed. This locomotive is a pre-'Tier 0' vehicle (build year of 1957). SRY900 is a powered by a diesel-electric assembly using an EMD 567C 2-stroke engine as the prime mover. Details of the engine configuration are given in Table 1.

Table 1: Locomotive and engine specifications

Parameter	Specification
Road Number	SRY900
Manufacturer	EMD
Model	SW900
EPA Tier	Pre Tier 0
Build year	1957
Lifetime engine hours	Over 200,000 hours
Fuel Injection	Unit Injector
Idle – Full Speed	275 – 835 RPM
Governor	Woodward Model PGR (Electro-Hydraulic)
Displacement per cylinder	567 cu. In.
Generator	EMD D15

Figure 1: EMD SW900 switcher locomotive used in fuel-switching study. Custom exhaust system used for emissions sampling and exhaust flowrate measurement shown installed.

Tested Fuels

Soybean Methyl Ester was selected for evaluation as it provides a significant life-cycle GHG benefit compared to conventional diesel and could be directly sourced from SRY's sister company Seaspan Ferries. However, this fuel is otherwise in very limited supply in BC. The fuel also carries a significantly increased cost; at the time of writing SME B100 costs approximately 70% more than standard no. 2 diesel. A comparison of typical chemical properties of SME B100 and B5 diesel is given in Table 2. Fuel analysis in Table 2 was conducted by AGAT Laboratories for B5 (marine) fuel and B100 SME (same fuel supplier as the current study) under the direction of Seaspan Ferries prior to the current study. Life-cycle carbon intensity in Table 2 is taken from the BC Low Carbon Fuel Standard (BC LCFS) approved carbon intensities records. In Table 3, fuel composition and calorific data is presented for B5 and B100 fuel samples taken on-site during the emissions testing campaign. Fuel C, H, N, O were measured using a Euro Vector Element Analyzer by Econotech Services Ltd. (Delta, BC). It should be noted that the measured oxygen content in the B5 fuel is significantly higher than is typically reported, and further investigation is required. The fuel composition analysis is considered valid for cumulative compositions ranging from 96—104% (per Econotech Services Ltd.).

Table 2: Typical fuel properties. B5 (marine) diesel and B100 SME (same source as the B100 from this study) analyzed by AGAT Laboratories. Fuel analysis conducted prior to this study.

Property	Test Method	Units	B5	B100 SME
1. Kinematic Viscosity (40C)	ASTM D7042	mm^2/s	3.6	4.3
2. Cetane Index	ASTM 6890	-	51.2	56.9
3. Acid Number	ASTM D664	mg KOH/g	0.07	0.28
4. Cloud Point	ASTM D2500	°C	-12	1
5. Cold Filter Plugging Point	ASTM D6371	°C	-17	-4
6. Pour Point	ASTM D97	°C	-15	0
7. Lubricity, corrected wear scar diameter @ 60°c	ASTM D93	µm	220	150
8. Life-Cycle Carbon Intensity	BC LCFS – GHGenius LCA	g-CO2e/ MJ-fuel	81.76	3.49

Table 3: Comparison of B5 and B100 fuel composition and higher heating value from samples taken in this study.

Property	Test Method	Units	B5	B100 SME
1a. Higher Heating Value	Parr oxygen bomb calorimetry	kJ/kg	43960	38929
1b. Volumetric higher heating value	Parr oxygen bomb calorimetry	Btu/gal	137818	128437
2. Carbon Content	Automated flash combustion & Gas chromatography Econotech standard method 410D, ASTM D 5291, ASTM D 5373 (oxygen measured separately using same method)	%	84.5	77.5
3. Hydrogen Content		%	13.7	11.5
4. Oxygen Content		%	3.2	8.5
5. Nitrogen Content		%	< 0.1	< 0.1

TECHNICAL APPROACH

This section discusses the engine preparation, emissions testing methods and instrumentation used in this study.

Engine Preparation & Inspection

Several modifications to the locomotive engine were made prior to the B100 trial to address material compatibility. All O-rings and rubber gaskets in the fuel system were replaced with VITON O-rings and gaskets, including fuel tank sight glass O-rings. Spin on fuel filters and suction strainer filters were replaced. The fuel pump was replaced with one equipped with VITON seals.

All but one of the power assemblies were left in the engine to provide an assessment of engine performance in an 'as-is' state. The cylinder #5 assembly (furthest from the blower) was replaced to establish a clear baseline for piston ring and liner inspections. Eight new Interstate-McBee Ecotip Utex fuel injectors (part number 40078995) were installed, such that inspections could be performed by the injector manufacturer at regular intervals. Both airboxes were cleaned, lower main bearings were inspected, and engine oil (Chevron 20W40) was changed. No mini-overhaul or other major maintenance activities were conducted other than regular 182-day inspections.

Additional inspections of certain engine components were performed to identify necessary modifications to regular maintenance schedules. Oil samples were analyzed (analysis performed by AGAT Laboratories) every 14 days. Sets of 2 injectors were sent to Interstate-McBee at 210hrs, 410hrs, and 2432hrs. Cylinder #5 was removed and inspected at 2432hrs. Fuel filters were replaced and cut open for inspection at 210 and 1889hrs.

Exhaust Measurements

Emissions measurements were conducted by connecting the locomotive generator leads to a passive resistance load-box at the SRY yard, which is typically used for annual inspection of switcher engines. The load-box permitted steady-state operation of the locomotive engine at full load at idle and notch 1 to 8. The priority of these measurements was to determine the relative difference in emission rates of Greenhouse gases (GHGs; CO_2) and criteria air contaminants (CACs; NOx, CO, particulate matter) as a function of engine output power for the B5 and B100 fuels. The exhaust measurements conducted were intended to evaluate the relative difference in tank-to-stack emission rates between the B5 and B100 fuels under in-use conditions. The conducted measurements were not intended to provide EPA certification data. The limitations of the methods used and their impact on reported values are highlighted throughout this section.

Testing protocol

Exhaust emissions measurements were conducted over a period of one week in April 2023 by UBC staff and graduate students. Two measurements were taken at each notch on each day, except for notch 4 which was repeated more frequently to further characterize experimental variability. A repeat day of measurements was conducted for each fuel to assess the day-to-day repeatability of measurements and engine operation. Notches were tested in a different sequence on each measurement day to avoid introducing bias from testing hysteresis. Day 1 and 2 testing was done with B100 fuel (on which the locomotive had been operating for several months). The fuel tank was subsequently drained as best possible given the internal baffling of the fuel tank, and then filled to approximately half (800 liters) with B5 fuel. Day 3 and Day 4 were B5 emissions testing with approximately 2 hours of notch 4 operation prior to measurements on Day 3 to consume any remaining B100 fuel.

At each measurement point, the exhaust temperature, NOx and CO concentrations were monitored to indicate achievement of steady-state operating conditions following a change of notch. Depending on the notches being transitioned to and from, this required 10-20 minutes of engine operation per operating condition. Data presented in this report is a 1-minute average of the recorded values after steady-state conditions were achieved.

Table 4: Ambient testing conditions

	Temperature [C]	Pressure [mbar]	Relative Humidity [%]
B100 (Day 1)	8—17	1006—1010	38—79
B100 (Day 2)	9—18	1017—1020	35—62
B5 (Day 3)	8—21	1027—1028	38—92
B5 (Day 4)	14—18	1017—1019	43—59

Instrumentation

To improve exhaust sampling access and flow measurement conditions, the standard exhaust stack was replaced with a custom exhaust test section with 10-inch diameter (see Figure 1). Up to a 5bhp reduction of engine output was observed at notch 8 (approximately 0.5% of total output) with the exhaust test section installed. This is within the day-to-day variability of the engine and considered negligible in this study. The exhaust test section was fitted with a pitot tube, thermocouple, 1 gas-phase sampling probe, 2 particulate sampling probes, and an absolute pressure sensor port. Additionally, engine speed, generator current, and generator voltage were monitored to establish the engine operating condition. The configuration of the exhaust sampling system is presented in Figure 2.

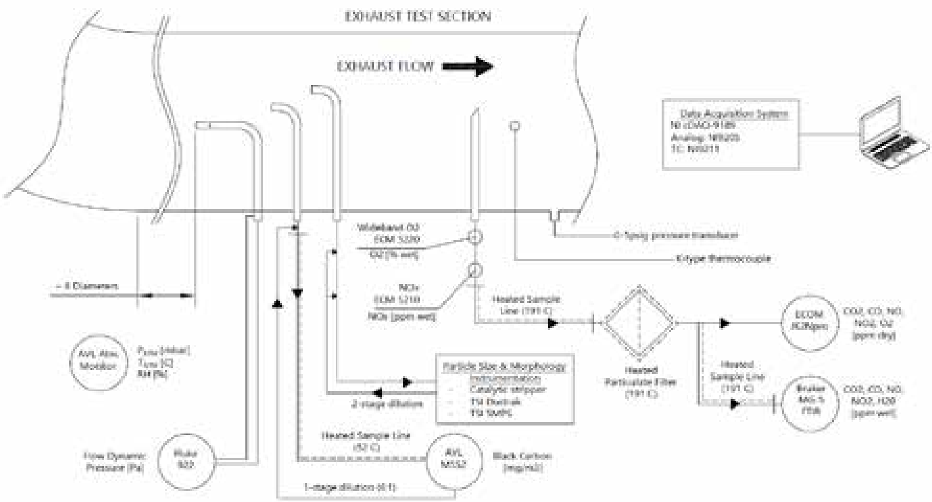

Figure 2: Exhaust sampling instrumentation diagram.

Exhaust Flowrate

Exhaust flowrate was measured to calculate emission rates. Practical constraints prevented the measurement of either fuel or intake air flows, so total exhaust flowrate was measured using a pitot tube and measured exhaust thermodynamic conditions. Exhaust centerline velocity was measured using a Dwyer 160-12 pitot tube and Fluke 922 differential pressure transducer. The exhaust test-section provided 8 diameters (limited by locomotive bodyworks) of unimpeded flow upstream of the pitot tube, so a fully-developed turbulent flow profile was assumed reasonable.

Exhaust flowrate calculation is considered a source of systematic error in the emissions factors presented in this study. The assumption of a perfectly uniform and well-developed turbulent flow introduces some error that could not be validated against either intake air or fuel flow measurements. Using the measured exhaust velocity, fuel composition, and exhaust composition (O_2, CO_2, CO) to estimate fuel flow, a peak brake thermal efficiency for the engine-generator combination of 34% (in notch 3) was calculated. This value approximately matches the manufacturer data for this engine without the efficiency loss of the generator. It is therefore considered likely that the exhaust flow measurement systematically underestimates the true exhaust mass flowrate. However, exhaust centerline velocity measurements recorded with the pitot tube were highly repeatable. Considering a linear fit between generator power and exhaust centerline velocity shows an R^2 of 0.995 for both fuels. This demonstrates that relative comparisons of emission flowrates for the B5 and B100 fuels can be reliably made.

Gas-phase emissions

All gas-phase emissions were sampled using diaphragm vacuum pumps drawing from a single probe in the exhaust test-section. Electrochemical O_2 and NOx sensors (ECM 5220 and ECM 5210, respectively) provided wet concentration measurements immediately at the exhaust sample point. A 5m heated sample line and particulate filter, each controlled to 191C, transported the sample gas to the gas analyzers. An ECOM J2KNpro portable emissions analyzer provided dry concentration measurements of CO2 (NDIR), CO (NDIR), NO (electrochemical), NO_2 (electrochemical), and O2 (electrochemical). A Bruker MG-5 Fourier Transform Infrared (FTIR) provided redundant measurements of CO_2, CO, NO, NO_2, in addition to H_2O, HCs, HCHO. Development of improved FTIR post-processing methods is on-going, so FTIR data are currently only considered to support analysis of other instruments.

Particulate emissions

Two independently sampled particulate measurement streams were employed in this study. The first system uses an on-road industry-standard photoacoustic instrument (AVL MSS2) to measure the black carbon concentration. The second system was used to analyze particulate numbers, size distributions, morphology, and volatile fractions. Only results from the black carbon measurements are presented here.

The black carbon sampling system used a sample probe oriented into the flow without upstream obstructions. A single stage of cold, filtered dilution air was introduced at the sample point to provide a sample dilution ratio of 6:1 for all measurement points. A 4m heated sample line controlled to 52C transported the sample gas to the analyzer. A standard temperature loss correction was applied

Engine operating condition

The engine operating condition was monitored by instrumenting the generator output current (ATO-CUS-DC1500) and voltage (ATO-VOS-DC1000). Calibration of the measured generator outputs was verified to be within 1% of the corresponding load-box readings. A non-contact tachometer was used to monitor engine rpm. Instrumentation of engine shaft torque was not possible, so all emission rates are presented with respect to the generator output. Uncertainty in the measured generator power measurement will also impact absolute values of emission factors reported. Note that neither generator efficiency nor auxiliary loads (i.e. auxiliary generator and compressor) are accounted for in any of the presented results. Brake specific emissions are therefore presented normalized to units of tractive generator power (i.e. g/trac.hp-hr). Variation of generator efficiency as a function of engine speed is a significant source of uncertainty in the absolute values of presented emission factors. Neither generator efficiency nor auxiliary loading is expected to change between fuels, therefore conclusions regarding the relative impact of B100 with respect to B5 are not impacted by this uncertainty.

TEST RESULTS

This section presents the results of engine component inspections and steady-state emissions measurements.

Effects of B100 on Engine Components

An inspection of engine components was performed after 2432 hours of operation on B100 (approximately 7370 gallons of fuel burned). Viton seals exhibited no excessive wear or softening, and airboxes were clean with very little carbon. All lab reports of oil analysis (14-day intervals) showed nominal results, very similar to B5. Cylinder head #5 was removed and no carbon was seen on the piston crown or fire deck. Inspection of the cylinder revealed no excessive wear, or build-up of varnish on the cylinder wall.

Some sludge was visible on spin-on paper fuel filter elements at 210hrs, but it was not sufficient to impact fuel system performance. At 1889hrs filter elements showed minimal sludge. No contaminants were found in the suction strainer housing.

Injector inspections at 210hrs, 410hrs, and 2432hrs showed some minor coking on the nozzle, but no abnormal effects on any other injector internals (e.g. plunger, needle valve). After inspection, all injectors were reassembled and passed standard production tests before being returned to service at SRY.

Fuel flow in the onshore storage tank and onboard tank were qualitatively evaluated when the ambient temperature was -6°C. Gelling was observed in the onshore tank, which significantly reduced the fuel flowrate. No evidence of gelling in the onboard tank was observed, likely due to engine return fuel flow agitation and heating. Preventative fuel blending of B5 with the B100 was conducted through the coldest months as a precaution. Establishing best practices for maintaining cold flow fuel properties will be the subject of future efforts in this project.

After 11 months, the rubber fuel line on the on-shore fuel storage tank began weeping and required replacement. Fuel cranes with B100-compatible hoses should be installed.

Engine Performance

Engine performance was assessed by measuring the output power of the main traction generator. The lower heating value of B100 fuel resulted in de-rating of the engine output at all notches compared to operation on B5. The de-rating of the engine is similar to the reduction in the volumetric heating value of the fuel (7% reduction in volumetric higher heating value). The coefficient of variance of output power (COV = standard deviation of generator power divided by average generator output) was observed to be higher at lower notches, which is an expected due to the increased significance of auxiliary power requirements at lower notches (note that compressor and auxiliary generator remained engaged throughout emissions measurements). This variability is also expected to contribute to emission factor variability and error for lower notches.

The governor load balance point was adjusted at notch 8 on day 1 of B100 testing to assess the possibility of recovering lost engine output through increased fuelling. This adjustment successfully returned notch 8 engine output to the B5 baseline, within the range of day-to-day engine variability. This increased engine output was only maintained for approximately 10 minutes of operation before the governor was reset to the original load balance point.

Table 5: Comparison of generator output power (hp) at full load for all notches operating on B5 and B100.

Notch	B5 avg [hp]	B5 COV	B100 avg [hp]	B100 COV	% Change
1	18	0.09	17	0.02	-6.4
2	85	0.07	82	0.06	-3.9
3	208	0.08	204	0.02	-2.2
4	333	0.02	304	0.01	-8.7
5	444	0.01	412	0.01	-7.4
6	553	0.01	518	0.00	-6.3
7	663	0.01	623	0.01	-6.1
8	772	0.00	728	0.01	-5.7

Steady-State Emissions

This section presents the steady state emissions for full load operation at notches 1 to 8. Brake specific emission factors are presented in units of g/trac. hp-hr. At idle, the generator output power is zero, so no emission factors are shown for the idle operating condition. The minimum and maximum measured emission factors are also presented to provide a measure of the test condition variability and uncertainty in the results.

An increase in the tank-to-stack brake-specific CO_2 emissions was observed for all notches. This increase is similar to the loss in engine output power noted at each notch, but is not consistent across all notches. Increased tank-to-stack CO_2 emissions are likely result of the decreased H/C ratio of 1.78 from 1.93 (calculated from fuel composition in Table 2) for B100 and B5, respectively.

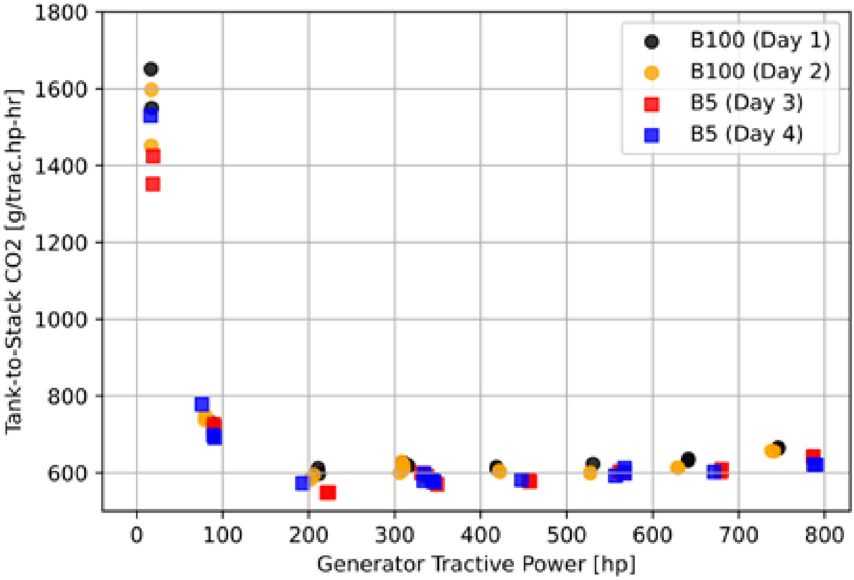

Figure 3: Steady-state brake-specific CO_2 emission factors at full-load.

Table 6: CO2 emission factors in g/trac.hp-hr. Percent change calculated based on average measurement from both testing days for each fuel. The % change in emission factor is calculated based on the average values for B100 with respect to B5.

Notch	B5 min.	B5 avg.	B5 max	B100 min.	B100 avg.	B100 max	% change
1	1351	1436	1531	1451	1562	1651	8.8
2	692	723	777	703	730	749	1.0
3	548	556	573	583	597	611	7.3
4	570	584	599	600	617	629	5.7
5	577	579	581	602	608	614	5.0
6	592	601	612	600	607	623	1.0
7	602	604	609	613	623	636	3.1
8	620	631	641	655	661	665	4.7

When considering biofuels, the life-cycle (well-to-stack) CO_2 emissions must be considered to quantify the total impact and potential for CO_2 reductions. In

Figure 4 the life-cycle CO_2 emissions are calculated using well-to-tank emission factors for western Canada provided by GHGenius 5.02 (current edition of LCA tool used for carbon intensity calculations by the BC LCFS) and the measured tank-to-stack emissions from this study. A summary of the well-to-tank emission factors is provided in Table 6. A standard lube oil emission factor for heavy-duty diesel vehicles of 11.6g-CO_2/GJ was also included. Based on this analysis, the well-to-stack CO_2 emissions are reduced by approximately 94%, which agrees closely with the general certified carbon intensity provided for the B100 SME in the BC LCFS (see Table 2).

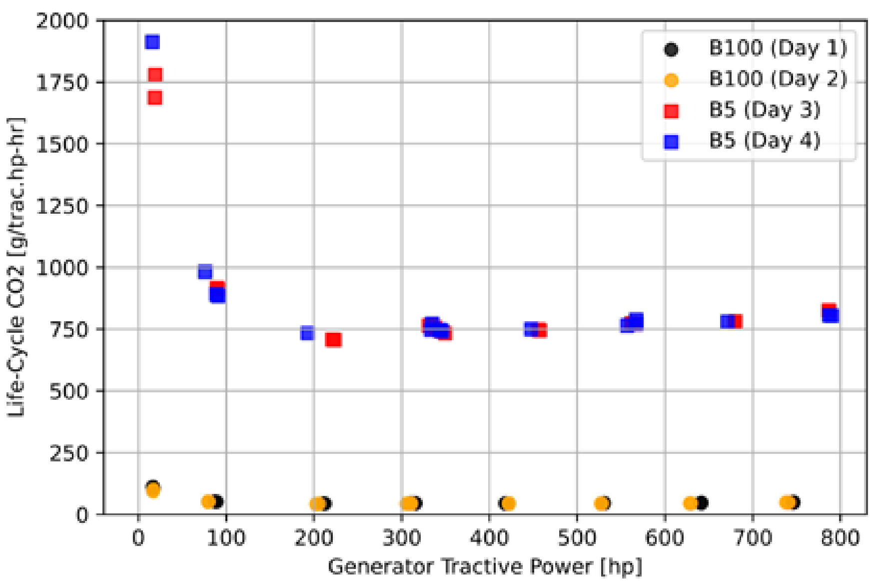

Figure 4: Life-cycle CO_2 emissions for B5 and B100 SME based on standard emission factors for western Canada used in GHGenius 5.02 (life-cycle analysis tool used by the BC LCFS).

Table 7: Upstream emission factors (g-CO_2e/GJ-fuel) from GHGenius 5.02 as used in the BC LCFS.

Fuel (Feedstock)	Rail Diesel (Crude Oil)	Biodiesel (Soy Oil)
Fuel dispensing	305	350
Fuel distribution and storage	680	1,127
Fuel production	11,921	3,560
Feedstock transmission	269	2,002
Feedstock recovery	7,998	6,174
Feedstock upgrading	2,408	13,292
Land management emissions	0	17,341
Direct land use change	205	0
Fertilizer manufacture	0	7,225
Feedstock coproducts	0	-36,978
Avoided emissions	0	0
Fuel coproducts	-127	-9,382
Total [g-CO_2/GJ-fuel]	23,660	4,710

CO emissions are approximately the same between the two fuels for notches 2—4. At notch 1, operation on B100 yields a significant increase in brake-specific CO emissions. At notches 5—8, B100 provides a significant reduction in brake-specific emissions, which may result from the fuel-bound oxygen enhancing oxidation of CO for the longer injection durations at higher notches. High variability of the measured CO concentration was observed between day 3 and 4 (B5 testing) at notches 6—8. Similarly high variability was observed in the FTIR CO measurements, indicating that instrument error is not likely. Furthermore, particulate concentrations (sampled independently from the gas-phase emissions) showed high variability for the same range of notches between day 3 and day 4 of testing. The cause of this variability between day 3 and 4 is not clear, but may be related to the fuel draining and re-filling that occurred between day 2 and day 3 of measurements or differences in ambient conditions.

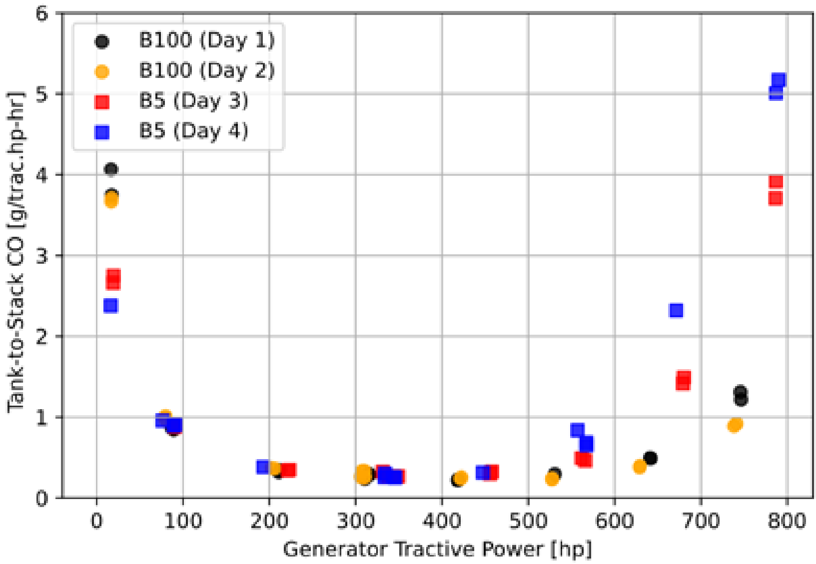

Figure 5: Steady-state brake-specific CO emission rate at full load.

Table 8: Comparison of brake specific CO emissions in units of g/trac.hp-hr. Percent change calculated based on average measurement from both testing days for each fuel. The % change in emission factor is calculated based on the average values for B100 with respect to B5.

Notch	B5 min.	B5 avg.	B5 max	B100 min.	B100 avg.	B100 max	% change
1	2.4	2.6	2.8	3.7	3.8	4.1	46.1
2	0.9	0.9	1.0	0.8	0.9	1.0	1.9
3	0.3	0.4	0.4	0.3	0.4	0.4	-1.5
4	0.3	0.3	0.3	0.2	0.3	0.3	1.9
5	0.3	0.3	0.3	0.2	0.2	0.3	-24.4
6	0.5	0.6	0.8	0.2	0.3	0.3	-59.1
7	1.4	1.7	2.3	0.4	0.4	0.5	-74.7
8	3.7	4.5	5.2	0.9	1.1	1.3	-75.6

Brake-specific NO_x emissions measured in the wet exhaust (electrochemical sensor) near the sample point are shown in Figure 6. NOx emissions increased for B100 by 14—26% across all notches. The current measurements alone can not definitively identify the cause of these increased emissions. However, research elsewhere on oxygenated biofuels has identified increased fuel-bound oxygen and higher cetane number of the B100 relative to B5 as potential mechanisms for increased NOx production [1,2].

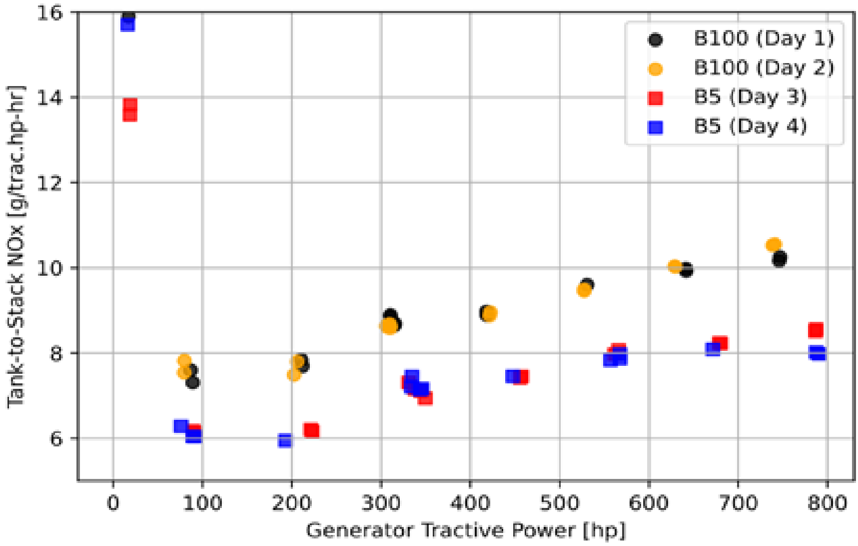

Figure 6: Steady-state brake-specific NOx emission rate at full load.

Table 9: Brake specific NOx emissions in units of g/gen.hp-hr. Percent change calculated based on average measurement from both testing days for each fuel. The % change in emission factor is calculated based on the average values for B100 with respect to B5.

Notch	B5 min.	B5 avg.	B5 max	B100 min.	B100 avg.	B100 max	% change
1	13.6	14.4	15.7	15.9	16.3	16.9	13.5
2	6.1	6.1	6.3	7.3	7.6	7.8	23.3
3	5.9	6.1	6.2	7.5	7.7	7.8	26.2
4	6.9	7.2	7.5	8.6	8.7	8.9	20.9
5	7.4	7.4	7.5	8.9	8.9	9.0	19.9
6	7.8	7.9	8.1	9.5	9.5	9.6	19.8
7	8.1	8.2	8.2	9.9	10.0	10.0	22.1
8	8.0	8.3	8.6	10.2	10.4	10.6	25.4

Brake-specific emissions of particulate (black carbon) when operating on B100 were reduced at all notches by 51—82% with respect to B5. This agrees with observations by other experimental research studies [1]. Complementary particulate measurements comparing particulate concentrations with and without a catalytic stripper indicate that the volatile component (i.e. non black carbon component) of the particulate matter constitutes the majority of the particulate mass, especially at notches 6—8 for both fuels. Further analysis of the particulate number concentration, size distribution, and morphology are in progress. As noted for the CO emissions, significant day-to-day variability was observed between day 3 and day 4 testing on B5. Given the independent sampling locations of the particulate and gas-phase emissions, this emissions variability is considered to be real (i.e. not a sampling system issue). A possible cause of this variability may be residual B100 remaining in the fuel system on day 3, or due to differences in ambient conditions.

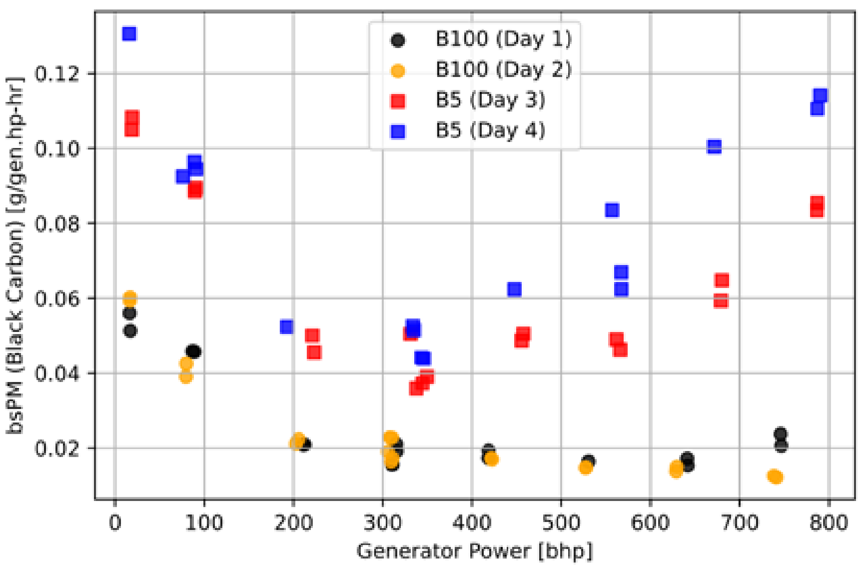

Figure 7: Steady-state black carbon emissions at full load.

Table 10: Brake specific PM (black carbon) emissions in units of mg/gen.hp-hr. Percent change calculated based on average measurement from both testing days for each fuel. The % change in emission factor is calculated based on the average values for B100 with respect to B5.

Notch	B5 min.	B5 avg.	B5 max	B100 min.	B100 avg.	B100 max	% change
1	105.0	114.6	130.6	51.3	56.7	60.3	-50.5
2	88.5	92.3	96.4	39.1	43.3	45.8	-53.1
3	45.5	49.3	52.3	20.9	21.3	22.4	-56.7
4	35.9	44.3	52.5	15.6	18.9	22.9	-57.4
5	48.7	53.8	62.3	17.0	17.7	19.4	-67.1
6	46.2	61.6	83.5	14.7	15.3	16.4	-75.2
7	59.3	74.8	100.4	13.8	15.3	17.2	-79.5
8	83.5	98.4	114.2	12.2	17.3	23.7	-82.5

Conclusions & Recommendations

Engine hardware compatibility and emissions performance were evaluated on a SW900 switcher locomotive operated on B100 SME for approximately 2500hrs of regular commercial operations. If fuel system components are replaced with equivalents having appropriate materials (i.e. Viton seals), this study indicates that no other significant changes to regular maintenance should be necessary to operate on B100 SME. In locations where ambient temperatures consistently drop below freezing (such as at Southern Railway of British Columbia), measures such as fuel blending with B5 will be necessary to prevent gelling. Assessing appropriate blend ratios and storage solutions for winter operations are the focus of future work on this project.

Tank-to-stack emissions of CO_2 are slightly increased when switching from B5 to B100 SME, however there is approximately a 94% reduction in the total life-cycle (well-to-stack) CO_2 emissions (as assessed for British Columbia). The deep decarbonization offered by B100 operation is additionally accompanied by significant (50-83%) reductions in the black carbon emissions, and some CO emissions reductions (24-76%) at higher notches. These reductions in CO_2, CO, and black carbon must be weighed against increased NOx emissions (13-26%) at all notches.

Operationally, a slight loss of output power (2—9%) is incurred when switching from B5 to B100, however this loss of power appears recoverable with adjustment of the governor balance point. Such an adjustment presents an increased risk of engine durability and likely excessive smoke opacity at high-load in the event that the engine is inadvertently fuelled with B5, which must be carefully considered. The data presented in this study are limited by unavailability of fuel flow measurements, however it is expected that increased fuel consumption comparable to the loss of output power was incurred.

B100 SME presents a viable pathway to deep decarbonization in the short- to mid-term for legacy switcher locomotives without significant capital expenditures, or adjustments to maintenance programs. The primary obstacles remain trade-offs with increased NOx emissions, and fuel supply and cost.

Acknowledgments

The authors of this work would like to acknowledge the technical and financial support provided throughout this project. Primary project funding was provided by Transport Canada's Clean Transportation Systems – Research and Development Program. Financial support of the emissions measurement program was provided by Environment and Climate Change Canada's Climate Action Awareness Fund and the Southern Railway of British Columbia. The technical support of the maintenance team at Southern Railway of British Columbia and colleagues in the Clean Energy Centre and Department of Mechanical Engineering at UBC are also gratefully acknowledged.

Supplemental Information

Emission Rates

This section provides the emission rate (kg/hr) results to complement the emission factors presented above.

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[1] Jiaqiang, E., et al. "Effect of different technologies on combustion and emissions of the diesel engine fueled with biodiesel: A review." *Renewable and Sustainable Energy Reviews* 80 (2017): 620-647.

[2] Thangaraja, J., K. Anand, and Pramod S. Mehta. "Biodiesel NOx penalty and control measures-a review." *Renewable and Sustainable Energy Reviews* 61 (2016): 1-24. best

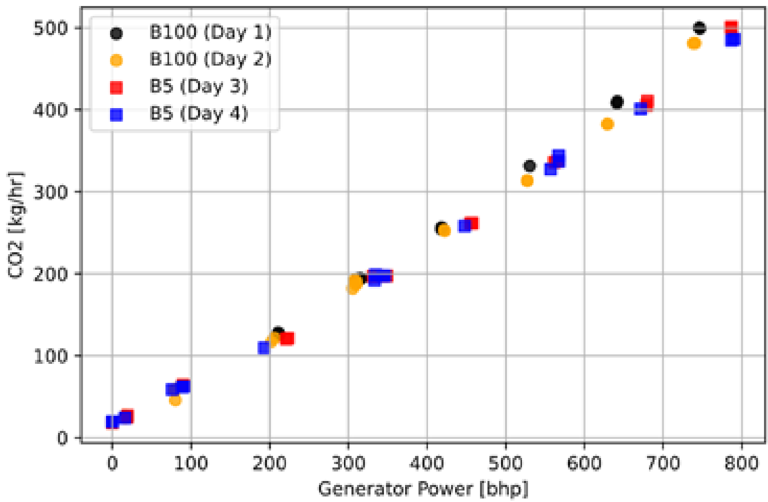

Figure 8: CO_2 emission rates at full load.

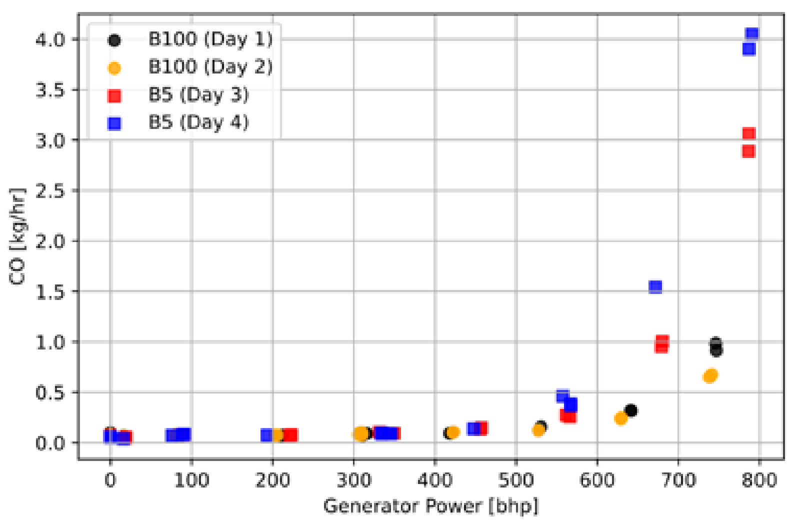

Figure 9: CO emission rates at full load.

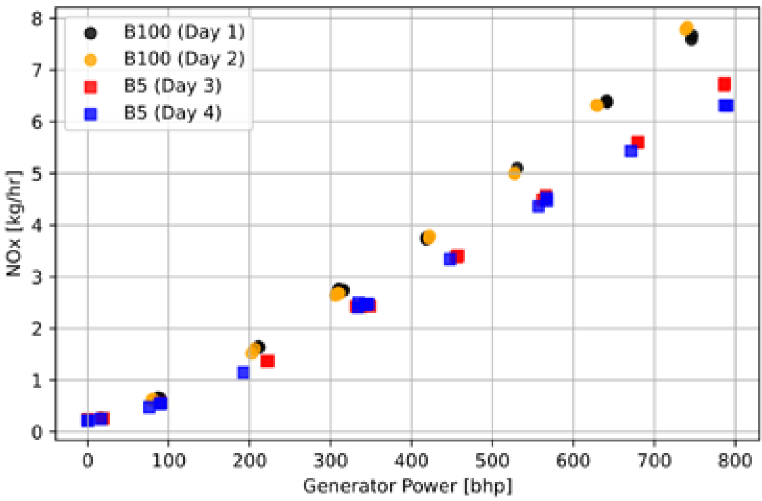

Figure 10: NOx emission rates at full load.

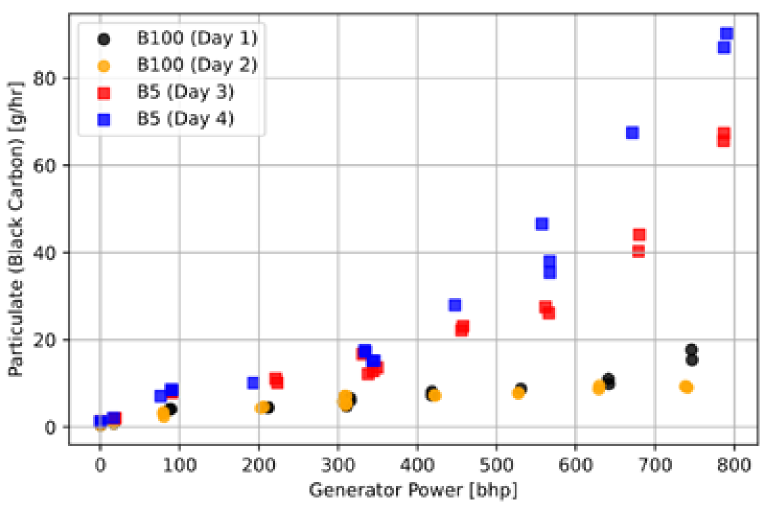

Figure 11: Black carbon emission rates at full load.

Report on the Committee on Electrical Maintenance

TUESDAY, OCTOBER 3, 2023

3:15 PM

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PERSONAL HISTORY

Jason Fox

Senior Director-Locomotive Engineering and Quality
Union Pacific RR
Omaha, NE

Jason Fox was born and raised in Hampton. Virginia. He went to school at Virginia Tech in Blacksburg, VA where he received a Bachelor of Science degree in Electrical Engineering. Jason moved to High Point, North Carolina where he worked as a Design Engineer at Thomas Built Buses. Jason integrated engine, transmission, and air brake systems into the school bus chassis.

After earning his Master of Business Administration from the University of North Carolina-Greensboro, Jason took on a Quality Assurance role at Thomas Built Buses where he was responsible for the quality programs for transit style school bus manufacturing. Jason moved to Omaha, Nebraska and worked as an Electrical and Hydraulic Controls Engineer for Elliot Equipment Company, a manufacturer of serial platform trucks and boom trucks.

Jason joined Union Pacific RR in 2011 and currently holds the position of Senior Director-Locomotive Engineering and Quality. He is responsible for the reliability and maintenance of Union Pacific's locomotive fleet. His interests include watching live music, barbequing, and travelling.

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Using Locomotives as Emergency Generator Backup Power

Prepared by:
Tom Bourbeau – Enerpro, Inc.
Keith Mellin – Peaker Services

Abstract

U.S. Department of Energy studies suggest the risk of electrical grid outages will increase in the future due to many factors. These include natural disasters (ice storms, wild fire), terrorist attack, increased use of renewable energy, and reduction in base load coal fired steam plants and nuclear plants. The potential black outs and brown outs on railroad and customer plant operations should be addressed.

Critical infrastructure facilities such as hospitals, airports, emergency service centers, etc. typically have permanent emergency backup power installed while most railroad shops do not. Once a power failure has occurred, demand for portable backup generators will greatly exceed supply and they should not be counted on to support continued operations.

Locomotives offer a potential source of emergency backup power for facilities critical to railroad operations. They are essentially standalone power plants complete with an onboard fuel source. Locomotives have been used during emergencies for backup power in the past and electrical grid conditions in the future may warrant their use again.

Past Uses of Locomotives as Emergency Backup Power

In 1998 a series of severe ice storm devastated the power grid in parts of southwest Quebec, Canada, leaving 1.5 million people without power in the middle of winter. The town of Boucherville requested that Canadian National Railway provide locomotives to power a government building and warming center in the city. A Montreal Locomotive Works M420W was derailed and moved under its own power down the main street to serve as a portable generator for the town's civic buildings (Figure 1). Two other locomotives remained on the rails and provided power to the towns of Richelieu and Coteau. The locomotives provided power for 7 days until grid power was restored.

Figure 1. CN 3502 Moving On Street

In 2001, two SD45-2 Montana Rail Link locomotives (Figure 2) were converted by Peaker Services to operate as generators in parallel with the grid. Modification included changing the governor and modifying one dash 2 electronics card. The concept was successfully tested for one week before being discontinued.

Figure 2. Connected SD45-2's Providing Synched Grid Power

The Boucherville and Montana Rail Link cases are two of numerous instances in which locomotives have been used to provide emergency power.

Locomotive Candidates

Numerous locomotive types from all 3 legacy manufacturers have been used as backup generators in the past. A brief summary of locomotives that have been used to provide backup power and their available power output are listed in Table 1.

Locomotive Type	Output	RPM	Notch
EMD SD/GP-38, AR-10	750 kW	720	6
EMD SD/GP-40-2, 45-2, AR-10	1200 kW	720	6
GE with GTA9 TA	750 kW	600	4
GE Dash 7 with GTA11 TA	950 kW	720	4
EMD SD70MAC HEP (Alaska RR)	730 kW	NA	All
MLW M420W (Alco)	375 kW	Unknown	Unknown

Table 1. Locomotive Types and Power Output

One limitation of using traction alternator output to directly provide utility power is the diesel engine must be run at the RPM that provides 480VAC / 60 Hz output. Because this frequency occurs at less than full engine RPM, engine power output and therefore electrical output is roughly half of the total available locomotive horsepower.

Passenger locomotives have Head End Power (HEP) systems that provide 480V / 60 Hz power for passenger car heating, cooling, and lighting. Older passenger locomotives such as the EMD F40PH have separate HEP generators powered from the prime mover. Modern locomotives such as the Siemens ALC-42 Charger have a separate inverter powered by the main DC link. HEP systems can provide up to 1000 kW of power and offer a very suitable source of emergency power. However, the availability of passenger locomotives during power grid failure events could be very constrained.

Scope of Conversion

Conversion of the locomotives to emergency generator configuration can be accomplished by railroad shop personnel. Detailed instructions for modification and operation of legacy EMD and GE locomotives for emergency power operation have been identified. EMD service document "Locomotive Usage for Emergency AC Power Operation", reference 1, covers EMD SD/GP38-2, 40-2 and 45-2 series locomotives equipped with AR10 alternators. Equipment Engineering document EEI-145 "Conversion of GE & EMD Locomotives for Emergency Standby Power", Reference 2, covers GE Dash 7 locomotives equipped with GTA 9 and 11 alternators as well as AR10 equipped EMD locomotives.

An outline of the conversion process is as follows:

EMD AR10

1. AR10 Generator Phase Cabling Alteration. Thirty phase leads from the diode heat sink, Figure 3, are disconnected, and then each phase group is connected to external power cabling.
2. Locomotive Engine Governor Adjustment. The governor fulcrum nut is adjusted while in throttle notch 6 to obtain 60Hz at roughly 720 RPM.
3. Locomotive Control System Alteration. The generator voltage regulator module is recalibrated to obtain 480 VAC power output. Other connections are made to remove the load control system and provide external controls for the engine speed and AR10 field control.

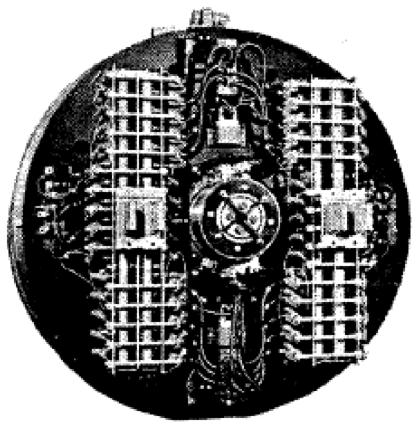

Figure 3. AR-10 Diode Assembly

GE GTA9/11

1. Load Connection. Connect 3external load cables through a current transformer to rectifier panel leads. Load should be protected by a 1000 amp, 3-phase circuit breaker or fusing.
2. Locomotive Modification. Modify control system for direct generator control using potentiometers. Adjustments are made to achieve 480V / 60 Hz output.

Facility Identification and Modification

In addition to the locomotive conversion, the building electrical service entrance needs to be modified to disconnect grid power and connect temporary emergency power. Ideally the building requiring backup emergency power would be identified and wired with a transfer switch, reducing connection time (Figure 4). NEC Article 702 and NFPA 110 govern emergency backup power connection requirements. Building loads should be evaluated to ensure locomotive generator output is not exceeded. Loads that are not necessary should be tagged out.

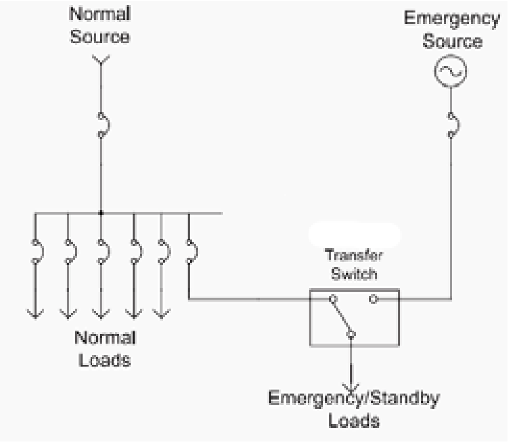

Figure 4. Building Transfer Switch

Future Developments

Locomotives used in the past for emergency backup power are all relatively old. Modern locomotives such as the GE Evolution and Progress Rail SD-70ACe are controlled by microprocessors and manually adjusting engine speed to achieve 480 VAC / 60 Hz traction alternator output might not be possible without software changes. OEMs could offer an upgrade package on existing locomotives or option on new locomotives to provide an emergency power feature. While these changes would allow 480 VAC / 60Hz output, they would still be limited to partial power operation.

Locomotive traction inverters can be modified to output 480 VAC / 60 Hz. This would increase power available because the engine could be run at full RPM. However, the power quality would not be suitable for commercial use without a large isolation transformer and output filters. This was done on the Alaska Railroad EMD SD70MAC HEP project, in which one traction inverter was modified to provide 480 VAC / 60 Hz output for passenger car requirements. The project was successful for this specific passenger/freight locomotive, but required extensive design work, locomotive space, and cost to develop and would not be practical for a standard freight locomotive.

Another potential emergency power solution would utilize the locomotive traction DC link to power a commercial inverter. Because engine speed would not be a limitation, power output would be limited only by size of the inverter

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selected. Inverters designed for large solar installations have DC voltage inputs that match locomotive traction DC link voltages (Table 2). The inverter could be installed trackside or on a flatbed railcar for increased flexibility. While this option would provide the highest output power, it would come at a high cost and a permanent emergency backup generator would likely be a better solution.

Inverter	Input	Output
DynaPower CP-1500	740-1500VDC	1200kW @ 480VAC
DynaPower CP-3000	740-1500VDC	2400kW @ 480VAC
Ingecon C450	650-1300VDC	2494kW @ 450VAC

Table 2. Industrial Inverters

Conclusions and Recommendations

The future is likely to bring an increased likelihood of power outages. Railroads should perform a risk assessment of the potential impact of electrical grid failure. Shops critical to operations should have a backup power plan. Depending on power requirements and locomotive availability, using company locomotives as an emergency backup power source may provide an efficient risk mitigation tool. However, the existing locomotive fleet that is capable of providing backup emergency power is rapidly shrinking. Engineering studies of modern locomotives should be conducted to determine the scope of hardware and software changes required to enable generation of 480 VAC, 60 Hz power.

Contributors

Stephen Alessandrini, Canadian National Railroad
Mark Duve, Higher Power Industries

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2. Equipment Engineering document, EEI-145, Conversion of GE & EMD Locomotives for Emergency Standby Power 480V 3 PH 60HZ
3. Energy Transmission in PJM: Resource Retirements, Replacements & Risks Feb 24, 2023
4. DOE Electricity Transmission System Research & Development: Grid Operations
5. NFPA 110, Standard for Emergency and Standby Power Systems
6. NEC Article 702, Optional Standby Systems

Locomotive LED Headlight Evolution

Author: John Madzar, Smart Light Source Co.
Co Author: Rodney Myers, Wheeling & Lake Erie Railway

LED – Light Emitting Diode
FRA – Federal Railroad Administration
AAR – American Association of Railroads
CCT – Correlated Color Temperature
CRI – Color Rendering Index
KWH – Kilowatt Hour
AMP – Ampere
SKU - Single Keeping Unit

Background

For the locomotive headlight and auxiliary lighting currently lamps such as Quartz Halogen PAR56 are being used. In addition, old incandescent lamps continue to be used by the railroad industry. These lamp designs are made of glass, and in many instances, they break and/or crack from roadside debris impact and by comparison lamp life is much shorter than what LED technology offers. The development of smaller and more powerful LEDs has enabled a more compact headlight design that can be used as a retrofit and can match the candelas output required by the railroad industry. However, minor changes and alterations to the locomotive electronics, due in part to the fluctuating voltage and lower current draw by LED headlights, is needed for proper operation. LED headlight controllers are now available that can replace conventional dimming resistors and flashing controllers used for conventional lamps. A need further exists for an assembly including removal of heat from the sensitive electronics and LEDs in the headlight so longer lamp life is realized.

Over the last few years, a significant amount of work has been done and coordinated between manufacturers, FRA, AAR, Class 1 railroads and others, to establish a standard for LED headlights. In 2019 AAR S-5516 standard was adopted to cover LED headlights and auxiliary lights. In addition, LED headlights and auxiliary lights must comply with 49 CFR 229.125 standard. One added requirement to the FRA standard is that LED headlights must be capable of melting snow and ice since the operating temperature of the LEDs in comparison to conventional lamps is much lower.

The higher cost of LED headlight can be overcome by the benefits it provides. The four major benefits provided are:

a) Lower maintenance costs due to longer lamp life
b) Reduction in fuel consumption due to lower power requirements
c) By reducing fuel consumption in essence LED headlights significantly reduce carbon emissions
d) Due to the current draw being lower, the strain on batteries is reduced and potentially battery life can be extended

FRA and AAR Mandates for LED Headlights

- Each headlight and auxiliary light shall output a minimum of 200,000 candela and a maximum of 250,000 candela when on bright.
- ·When on bright, the minimum luminance at an angle of 7.5° shall be 3,000 candela and at an angle of 20° shall be 400 candelas.
- The headlight shall be capable of illuminating a person 800 ft ahead of and in front of the locomotive when on the bright setting.
- The headlight shall be capable of illuminating a person 300 ft ahead of and in front of the locomotive when on the dim setting.
- The color temperature of the headlights and auxiliary lights, on either bright or dim, shall be 2800K to 3200K (similar to tungsten and halogen lamps).
- Additionally, considering that LEDs are of electronic components, the EMI emission must be filtered so that there are no interferences with communications.

LED Headlight / Auxiliary Lights Benefits

In comparison to conventional tungsten and Halogen lamps that offer 500 hours and about 4000 hours in field operation, LED PAR56 provides a lamp life of up to 50,000 hours. This in return provides lower maintenance costs for railroads as lamp change outs have been reduced. Considering that conventional lamps operate at 350-watts and by comparison LEDs operate between 40-60-watts, a significant reduction in fuel consumption is realized since less energy/diesel is required to operate LEDs. By burning less fuel, a decrease in carbon (CO_2) emissions is realized, thus an advantage can be taken in reducing the carbon footprint.

While conventional lamps draw about 5 amps, LEDs operate with one amp or less, and therefore provide less strain on batteries, thus extending their life. Figure 1 is an example that provides a detailed comparison of savings. This example is based on a fleet of 3000 locomotives and 4 lamps. LED headlights rated at 75V-40W draw 0.53amps compared to conventional lamp 75V-350W that draw 4.66amps. Headlights burn 0.274738 gallons of diesel fuel per Kilowatt hour, to operate. Based on this, LED headlights can reduce diesel fuel expenditure by 87%, on

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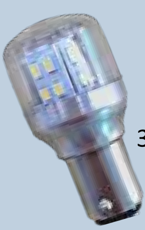

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75V DC LED Work Lights

60W LED Headlight and Ditch Light

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an annual basis, and lamp change outs are 8.5-to-1. By investing in this new technology ROI can be realized within one year. Lower maintenance costs and reduction of fuel consumption contribute further to sustainability and reduction of CO2 emissions and further improve operational efficiency goals.

Example - fuel-maintenace-carbon emmissions

LED 75V 40W Headlight / Auxiliary Light

Industry Standard 75V 350W Headlight / Ditch Light

Data for 3000 Locomotives and 4 lamps

Lamp Watts	Daily Hours	Weekly hours	Monthly hours	Yearly hours	Kilowatt Hours per lamp (KWH)	Fuel Consumption per KWH (Gal)	Fuel consumption Per Lamp (Gal)	*Fuel consumption x 4 lamps (Gal)	Fuel consumed by 3000 locomotives (Gal)	Fuel cost at $3.74 per gallon
350	16	112	480	5840	2044	0.274738	561.56	2246.26	6,738,773.66	$ 25,203,013.50
40	16	112	480	5840	233.6	0.274738	64.18	256.72	770,145.56	$ 2,880,344.40
								Total Annual Savings		$ 22,322,669.10

Maintenance

Halogen vs LED	Total # of lamps	Halogen Lamp Cost $	Halogen Lamp Life (hrs)	Total Lamp Cost	Lamp Life Cycle (yrs)	LED Life Cycle (yrs)	Annual Relamp Savings	**Relamp Labor cost $	Relamp Labor cost $ vs. LED Cycle	Total Current lamp maintenance cost vs.LED Cycle
350W vs 40W	12,000	$ 20.00	4,000	$ 240,000.00	0.685	8.562	$ 3,000,000.00	$ 93.75	$ 14,062,500.00	$ 17,062,500.00

Annual Fuel Savings	$ 22,322,669.10
Life Expectancy of LED Lamp (yrs)	$ 8.562
Total LED Energy Savings	$ 191,118,742.32
Bulb & Maintenace Savings	$ 17,062,500.00
Total Return on Investment	$ 208,181,242.32
***Total LED Lamp Cost	$ 4,800,000.00
Total Cost to Retrofit LED Technology	$ 1,125,000.00
Controller Cost	$ 6,000,000.00
Total Net Savings	$ 196,256,242.32
Lbs. Of Co2 Emmission Saved	937,722,720.00

ESTIMATE

**Labor hourly rate $125.00. For lamp changes $93.75 used (45min)

KWH = kilowatt hours

* four lamps is two headlights plus two ditch lights

Diesel Fuel cost $3.74 P/G based on US Energy Information Administration

*****Controllers used to Operate LED Headlight (3000x$2,000.00)

Data for 3,000 (4 Lamps) locomotives.

Lbs of Co2 is equal to 407,000 short tons US

Smart Light Source Co. confidential and proprietary

Figure 1.

Correlated Color Temperature (CCT) Explained

Correlated Color Temperature (CCT) is a measure of what tone of light the artificial source provides. It is expressed in Kelvin (K) and can also be referred to as Warm White (3000K) or Cool White (5000K). Warm white light sources provide less strain to the eye when in direct contact and this has been chosen as the right color temperature for LED headlights. Cool white light sources appear brighter and provide strain when in direct contact with the eye at night. Figure 2 provides an example of light output for various color temperatures.

Figure 2

Color Rendering Index (CRI) Explained

An important measure in artificial light sources is also the color rendering index (CRI). The CRI of a light source provides the ability to accurately reproduce the colors of the object it illuminates. CRI is rated on a scale of 1-100. A CRI of 80 and above is considered good at color rendering and accurately reproduces the colors of the object it illuminates. CRI below 80 is considered poor. This is important when it comes to track signals so that Red cannot be mistaken for Amber or vice versa. Figure 3 is representative of the same object under the same color temperature but different CRI.

Figure 3

LED Headlight Operating Temperature (snow and ice melting)

Is the Headlight able to generate enough heat to melt snow and ice? There are concerns with LED Headlight operating temperatures. Even though the LED chip might reach a junction temperature of 100°C or more, the heat sink is utilized to dissipate the heat and extend lamp life. The FRA standard requires that a lamp must be capable to get hot enough to melt snow and ice under negative 20°C operating conditions. The LED must get hot enough to melt snow and ice within 30 minutes of operation. Figure 4 provides temperature data measured every 5 minutes for 35 minutes while lamp continues to operate under negative -20°C. At 30 minutes the temperature measured on the lamp lens was recorded to be at approximately +16°C, temperature fully capable of melting snow and ice.

Time	12:45	12:50	12:55	13:00	13:05	13:10	13:15	13:20
Temp(°F) (°C)	4.36 °F -20.2 °C	5.18 °F -14.9 °C	21.02 °F -6.1 °C	33.8 °F +1 °C	44.78 °F +7.1 °C	52.88 °F +11.6 °C	60.62 °F +15.9 °C	66.56 °F +19.2 °C

Figure 4

Issues with Operating LED Headlights / Auxiliary Lights

Existing locomotive electronics are made exclusively to operate conventional lamps. For headlight operation, a set of resistor banks is utilized to provide dimming. This resistor bank varies from OEM to OEM and locomotive to locomotive. In particular, a fleet may consist of locomotives manufactured from 1969 as well as locomotives built in 2020's. How dimming resistors are set up and their values from old units and new units is different and have posed a major problem for users to be able to reach light output consistencies on their fleets comparable with conventional lamps. Similarly, for railroads that utilize flashing for auxiliary lights, existing controllers are made to operate conventional lamps and the inrush voltage to LED auxiliary lights from the controller is very high and over time appears to either burn the LED auxiliary light circuitry or provide inconsistent or no flashing.

Solutions for Operating LED Headlights and Auxiliary Flashing Lights

The railroad industry desires that one single LED light be capable of operating as a headlight and auxiliary light across the entire locomotive fleet. In order to make this possible and provide a Single Keeping Unit (SKU) of LED headlight an LED controller is essential to be utilized. LED controllers eliminate the use of resistor banks for LED headlight dimming as well as old outdated auxiliary flashing. These LED headlight controllers come with different options, in that they can operate both LED headlight and conventional lamps and some are made to operate exclusively LED headlight for dimming and auxiliary light flashing. In addition, they can operate 8 lamps (4 LED headlights and 4 LED auxiliary lights) or operator can choose to have one controller installed for headlights and one for auxiliary lights. Simple installation is available through external wire brackets. Figures 5 and 6 are examples of LED light controllers.

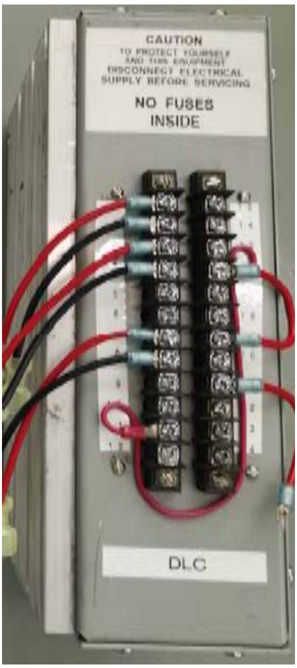

Figure 5; Supplier #1

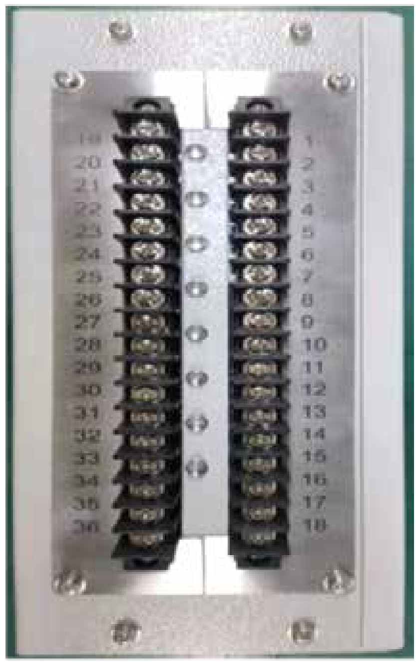

Figure 6; Supplier #2

LED Headlights on Locomotives

Figure 7; Supplier #1

Figure 8; Supplier #2

Figure 9; Supplier #3

Conclusion

LED headlights and auxiliary lights have become an industry trend and are growing in popularity. They are made to meet the AAR and FRA candela standards. LED headlights and auxiliary lights made for locomotive applications run much cooler than conventional lights thus reducing the risk of combustion or burnt fingers. Sturdier – LEDs are made with aluminum housings and epoxy lenses thus they will not break during installation or flying debris during operation compared to conventional lamps made from glass. In service lamp life of LEDs is rated for 50,000 hours in comparison to the conventional lamps rated for in service lamp life of 500 to 4000 hours. Longer lamp life provides lower maintenance costs for operators due to less lamp change outs. Because LEDs operate with lower wattages the battery life can potentially be extended. Lower operating wattage also allows for less diesel fuel consumption to operate, and this promotes the need for lowering the carbon foot print by the railroads. Locomotive LED headlights auxiliary lights could potentially help railroads become more profitable.

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DC to AC Diesel-Electric Locomotive Conversion

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Co Author: Mark Duve – Higher Power Industries

Table of Contents

Acronyms

The following acronyms used in this paper.

AC	Alternate Current
CapEx	Capital Expenditure
DC	Direct Current
MU	Multiple Units
OpEx	Operating Expenditure
ROI	Return On Investment
VVVF	Variable Voltage, Variable Frequency
USDOT	U.S. Department of Transportation

Note: for all footnotes specified in this document, the reference table is provided at the end of this document.

Abstract

- After a short drop in transporting volumes at the beginning of pandemic period, the Rail Freight Transportation Industry had a quick rebound and recovery to the pre-pandemic level. Today, the freight transportation is demonstrating strong trends of volume increase as a result of quick shift in consumer demand from services to products as a result of exploded e-commerce shopping activities.
- In 2019 the U.S. transportation system moved a daily average of about 55.2 million tons of freight valued at more than $54.0 billion.[9]
- The Freight Analysis Framework estimates tonnage will increase at about 1.4% / year between 2022 and 2050. About +30% increase over that time span.[9]
- The value of freight is forecast to increase faster than tonnage, rising from $996 per ton in 2022 to $1,256 per ton in 2050, when adjusting for inflation (in today's dollar value). This increase is due to high-value, low weight commodities growing at a faster rate than low-value, high-weight commodities.[9]

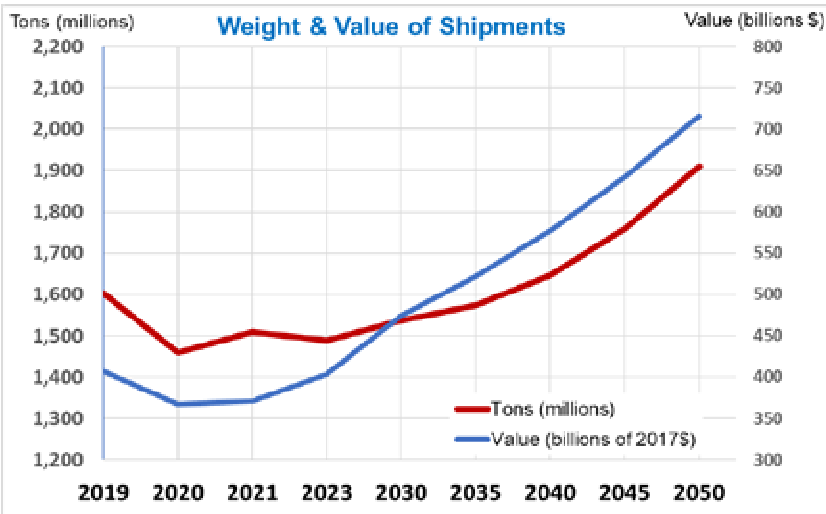

Figure 1 Weight and Value of Rail Freight Shipments for Class I railroads
Source: Department of Transportation, Bureau of Transportation Statistics and Federal Highway Administration, Freight Analysis Framework.8

Rail Freight Transportation Industry challenge

- Increasing annual freight volume, aging fleet, assets maintenance and fuel price increase puts more pressure on all major railroads.
- Rising freight volumes require more motive power that forces railroads to seek for new solutions.
- Today, Class I railroads provide freight transportation using over 23,000 locomotives and 1.66 million railcars [AAR report 2021].[10]
- North American railroads are still using nearly 1600 EMD SD70s and over 3500 GE Dash-9 DC locomotives [Wikipedia].[6,7]
- DC locomotives may provide an opportunity for railroads to increase motive power and to improve their locomotive fleet efficiency. Market for high horsepower locomotives will be increasing in US and Canada.

DC-to-AC conversion benefits and scenarios to consider

Converting diesel-electric locomotives from DC to AC can provide numerous benefits, including:

1. Improved efficiency: Modern AC motors are generally more efficient than DC brushed motors even though AC motor shall be less efficient as it has to introduce current into the stator to create a magnetic field. However, DC motor will also have some losses due to brush contact resistance, which tends to increase over time. Converting a locomotive's electrical system from DC to AC can improve its overall efficiency, which can result in cost savings over the long term.
2. Increased power output: AC motors have a better power-to-weight ratio compared to DC motors. Therefore, they can produce more power than DC motors of the same size, especially when higher voltage is selected for AC motor (DC motor has a limitation on the voltage levels it can be used on). This means that converting a locomotive from DC to AC can increase its hauling capacity, allowing it to pull more freight or passengers.
3. Increase starting effort – AC locomotive tends to be heavier than DC locomotives, so for freight locomotive results in the increased tractive effort. Tractive effort is directly proportional to the adhesion that represents the ability of the locomotive to convert the available friction (between the wheel and the rail) into the usable friction that moves the train. This parameter is much greater for AC traction (almost double) compared to the DC traction. Together with power increase railroads may experience the gain of 10-30% on traction effort.
4. Better reliability: AC motors are generally more reliable than DC motors, as they have fewer moving parts and require less maintenance. This is especially valuable when comparing to DC motors brushes intensive maintenance. All these considerations can reduce locomotive's downtime and increase their overall availability.
5. Improved control: AC motors offer better control over speed and torque than DC motors. This can make trains more responsive to changing conditions and enable smoother acceleration and deceleration. On the other hand, the AC motor torque will be reduced at higher speed, which may be seen as a disadvantage by some of the railroads transporting light-weight trains (DC motor may reach the higher speed faster if wheel slipping problem is properly addressed, which may be a challenging task).
6. Reduced emissions: Converting diesel-electric locomotives from DC to AC can reduce emissions, as AC motors are generally more efficient and will require less power from the prime mover engine. This in turn will produce less emissions compared to DC traction as the engine needs to burn less fuel to achieve the same the same output power. This can have environmental benefits and may also help railways comply with emissions regulations.

Based on GE (now Wabtec) comments in 2009, AC locomotives using AC current cuts fuel consumption by 17% and emissions by 70%. As an example, 600 AC locomotives can do the work of 800 DC models – saving 70 million gallons of fuel annually and cutting CO2 emissions by 1 million tons.[13]

7. Remanufacturing locomotives costs about 40-50% less than the new locomotive and provides great business opportunity for both railroads and industry suppliers.

Pros and Cons

High maintenance cost, parts availability and obsolescence can be a trigger point to consider an upgrade to newer technology. The following table will help to understand some advantages and disadvantages regarding DC and AC traction.

Parameter	DC Traction		AC Traction	
	Pros	Cons	Pros	Cons
Cost of ownership	Low initial cost	High maintenance cost.	Low maintenance cost.	High initial cost.
Performance	Can be cost effective when used on light-haul trains or short distances.	Less tractive effort (especially at low speed), risk of wheels slipping. Traction power varying with speed.	Good tractive effort, especially at low speed and including motor stall conditions.	Less horsepower at high speeds due to AC motor torque decrease.
Traction motor	Simple control, higher initial torque and power delivery capabilities	Can quickly overheat at low speed. High maintenance cost, lower reliability	Less parts, higher reliability. Can run with full current at low speed.	More complex controls – requires VVVF drive.
Train haul efficiency	Good for light-haul trains	Poor traction effort on heavy-haul trains	Good tractive effort. Easier to use in MU	Less cost-efficient on light-haul trains

Table 1 DC vs AC Traction


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DC to AC conversion major parts

- **New parts required.**
    - AC traction motor
    - Propulsion system
    - Traction converter

- **Major parts to be replaced / upgraded.**
    - Generator/Alternator (needs to be rebuilt for AC propulsion)
    - Truck assembly (has to accommodate new AC traction motor)
    - Possibly air-cooling duct
    - Operator Cab (integration of new AC propulsion)
    - Aux Cab
    - Control system and excitation controller
    - Optional: removal of DC motor sensors: voltage/current transducers, thermal sensors

- **Reused parts / assemblies.**
    - Radiator Cab
    - Engine Cab
    - Frame


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Traction Motors

Generator / Alternator

Rules/Regulations/Legislations

- EPA-driven emission control
- 40 CFR Part 1033.640 (in US) – Provisions for repowered and refurbished locomotives
- Railway Safety Act subsection 47.1 – Locomotive Emissions Regulations (in Canada).
- Percent of previously used parts as per 40 CFR 1033.640(c) – ratio of total dollar value of previously used parts relative to the total dollar value of unused parts and previously used parts.
- Remanufactured locomotive – locomotive originally built after 1972 that contains more than 25% previously used parts.
- Refurbished locomotive – a remanufactured locomotive with less than 50% of previously used parts.
- Line-haul remanufactured locomotives that are deemed to be refurbished must follow same Tier requirements as new locomotives.

Financial Impact

- **Main considerations**
  - Short-term: (initial investment / CAPEX vs maintenance and OPEX)
  - Long-term: savings and ROI (operating/maintenance cost savings)
  - Lifespan and residual value (locomotive residual value vs investment on conversion)
  - Impact of motive power increase on revenue and logistics

Railroads invested $2.31B in 2021 to improve their equipment (see the following table for the rail industry fiscal data).

Table 1-5 Rail Transportation System: Fiscal Years 2000, 2010, and 2018–2021

Item	2000	2010	2018	2019	2020	2021
Equipment and mileage operated by Class I						
Locomotives	20,028	23,893	26,086	24,597	23,544	23,264
Freight cars[a]	560,154	397,730	293,742	270,378	252,400	243,087
Average freight car capacity (tons)	92.7	101.7	104.6	103.3	105.1	104.9
System mileage	99,250	95,700	92,837	92,282	91,773	91,651
Revenue ton-miles (trillion)	1.47	1.69	1.73	1.61	1.44	1.53
Capital expenditures, $billion						
Roadway and structures	$4.55	$7.86	$9.33	$9.09	$8.35	$7.93
Equipment	$1.51	$1.91	$3.08	$3.88	$2.46	$2.31
Total	**$6.06**	**$9.77**	**$12.41**	**$12.97**	**$10.81**	**$10.24**

[a] Includes totals for Canada and Mexico.

Source: USDOT: Transportation Statistics Annual Report 2022.[8]

ROI comparison

When considering the conversion of diesel-electric locomotives from DC to AC versus purchasing new AC locomotives, the return on investment (ROI) is an important factor to consider.

The cost of converting an existing locomotive from DC to AC can vary depending on the age and condition of the locomotive, as well as the specific components that need to be replaced or upgraded. However, estimates suggest that the cost of conversion can range from $1.5 to $3 million (in 2020 USD dollars) per locomotive.

In comparison, the cost of purchasing a new AC locomotive can range from $4 to $6 million per locomotive, depending on the specific features and capabilities of the locomotive.

To determine the ROI of converting an existing locomotive from DC to AC, it is necessary to consider the cost savings that will be achieved through improved efficiency, increased power output, reduced emissions, reduced maintenance, and traction motors failures. These cost savings will vary depending on the specific operating conditions of the locomotive, such as the frequency and duration of use, the type of cargo being transported, and the terrain of the railway. As an example, Canadian Locomotive Fleet survey for the year 2000 1 was showing annual fuel consumption of 407 million of US gallons (1.92 billion liters) for the fleet of 1744 locomotives (mainly SD-40, SD75 and GE). This is almost 250,000 gallons per locomotive annually. If it would be DC locomotives, then the conversion potentially could provide about 10-15% of fuel savings, which is almost 38,000 gallons per year. For an average price of diesel fuel of 2.8USD/gal. the annual savings per locomotive would be about $100,000 (US funds) not counting the savings on the maintenance, reliability, and the gain of tractive effort; these fuel savings alone could pay off $1.5M investment in 15 year. There are other sources on the internet providing similar conclusion regarding fuel savings of modern locomotives.[12]

In general, it is estimated that the ROI for converting a locomotive from DC to AC can range from 5 to 7 years, which represents about 10.5% ROI rate. This means that after 5 to 7 years of operation, the cost savings from improved efficiency and other benefits will offset the initial cost of conversion (results may vary depends on railroad operation scenario).

However, the ROI for purchasing new AC locomotives can vary depending on the same factors as the ROI for conversion. In some cases, purchasing new AC locomotives may be more cost-effective than converting existing locomotives, especially if the existing locomotives are outdated or in poor condition (at the end of their lifespan).

Ultimately, the decision to convert an existing locomotive from DC to AC or purchase new AC locomotives will depend on a range of factors, including the specific operating conditions of the railway, the available budget for investment, and the long-term goals and priorities of the railway.

Historical data / Success stories

There were multiple DC to AC conversions done in the past on both EMD and GE locomotive.

Railroad	Project
Norfolk Southern	2017 - NS began converting fleet of over 1000 DC units (GE and EMD) with a rate of 100 DC units per year. 50 x SD70s already converted to SD70ACC. Wabtec announcement (2022) to convert NS 330 Dash-9 units (more than 20 years old) into AC44C6M by 2025 (NS will reach 950 upgraded units)
Union Pacific	Wabtec (Fort Worth, TX) will convert 75 Dash-9 DC units
CN	Wabtec (Fort Worth, TX) converting 50 Dash-9 DC units

Conclusion

In Brief

- Positive impact on reliability / availability of the locomotive fleet
- Reduced OPEX via better traction effort control and increased motive power with less involved assets => higher assets turn-around ratio

ROI estimations

Remanufactured locomotive may add up to 20 years to locomotive's life cycle. Locomotive can last 60 years or longer if properly maintained. Therefore, ROI can be estimated based on the age of the locomotive and expected life cycle of the asset.

Benefits

Converting locomotives from DC to AC can provide a range of benefits, from improved efficiency and reliability to increased power output and reduced emissions. While the conversion process can be expensive, it can be estimated as 40-50% of the cost of new AC locomotive. The long-term savings and benefits may make it a worthwhile investment for railways (ROI on conversion may provide better ratio comparing to new locomotive investment).

Recommendation

More research and testing are required to understand the full implications of this topic.

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EPA Locomotive Emissions Regulations: Are You Compliant?

By:
Mark Duve, Higher Power Industries

Wednesday, October 4, 2023 - 8:30 AM

Disclaimer

This paper summarizes the US EPA emissions regulations as codified by 40 CFR Part 1033 as it pertains to the owners and operators of locomotives. It does not cover every part of the regulation particularly the elements pertaining to the responsibility of locomotive builders and emissions kit providers. It is suggested that each railroad or locomotive operator thoroughly read the emissions regulations in 40CFR1033 and discuss with their legal counsel. It is the responsibility of the manufacturer, remanufacturer and/or the owner/operator to fully understand the rules and to ensure compliance with those rules. This paper does not represent an official interpretation of the rules or legal advice but is to be used to help provide a basic understanding of some of the general requirements to the mechanical staff.

Which Railroads Need to Comply with Emissions Regulations?

When 40 CFR Part 92 was released, it was clear that the Class I railroads had to comply with the emissions regulations; however, it wasn't very clear for the Class II and Class III railroads. The regulations exempted small railroads and most non-Class I railroads considered themselves to be small railroads.

In section 1033,1 the EPA regulations do not specifically call out railroads, but new "locomotives and all locomotives containing a new locomotive engine." (The EPA has a different definition for the term new that is discussed further in the paper.) Further regulations found in 1033.610 and 1033.901 clarify that Class II and Class III railroads must comply with the regulations, unless the Class III railroad is considered a small business per the criteria set by the Small Business Administration's regulations as found in 13 CFR Part 121. But there are a couple exceptions to the small business exemption. The first exception is if a Class III railroad is owned by a large corporation, the EPA does not consider the railroad itself as a small railroad. The second small business exemption is found in 1033.610 (a). It states that if a Class III railroad buys a used locomotive that has been brought into emissions compliance, then that railroad must maintain the emissions compliance on that locomotive. In addition, the EPA does not consider commuter or passenger railroads to be a small business either.


These reduce
CO_2 emissions.

It should also be noted that because the regulations do not specifically state that the law applies to railroads; therefore, lease locomotives and manufacturer owned locomotives must also comply with the regulations. A manufacturer can apply for an emissions exemption for a limited amount of time for developmental testing. In addition. 1033.815 states that anyone performing locomotive maintenance is subject to the regulations.

In summary Railroads that must comply with the emissions regulations are as follows:

- Class I
- Class II
- Class III, owned by a large corporation.
- Passenger and Commuter railroads.
- Locomotive Leasing companies
- Locomotive Manufacturers
- Locomotive Maintenance companies
- New locomotives
- Locomotives that have previously been emissions certified regardless of railroad Class.

Background and History

Early Regulations 40 CFR Part 92

Locomotive emission regulations came into effect with 40 CFR Part 92 in the year 2000. Prior to these regulations, locomotives in the United States did not have any emissions regulations. These emissions regulations established limits for the Oxides of Nitrogen (NOX), Carbon Monoxide (CO), Hydrocarbons (HC), Particulate Matter (PM) and smoke opacity. Part 92 had three Tiers of emissions limits which depended upon the time the locomotive was manufactured.

Locomotive Emissions Tiers

The idea of the emissions tiers was to provide the locomotive and emissions kit manufacturers time to develop, test, and manufacture lower emissions locomotives and retrofit kits. The first Tier, Tier 0 was established with minor changes to the engine or locomotive and could also be retrofitted to older locomotives that were built after 1972. Starting in 2002, with Tier 1, each emissions tier has a lower emissions limit than the previous tier. Thus, over time with each progressive emissions tier, less emissions are produced. In addition, the amount of smoke produced is also regulated by opacity measurements, and over time smoke reduction is regulated with the emissions tier. The early emissions regulations, 40 CFR Part 92, established Tiers 0, 1 and 2.

Emissions Duty Cycles

The actual tier limits are determined by the measured emissions for each throttle notch per hour times a weighting factor for each throttle position including idle and dynamic brake. These emissions are then divided by the brake horsepower for each throttle position multiplied by the weighting factor. The sum of the weighted emissions is divided by the weighted horsepower. This weighting factor is the percent of time in each throttle that the EPA determined through a study. These throttle weighting factors are known as a duty cycle.

There are two duty cycles listed in section 1033.350, one for switch locomotives and one for line haul. The EPA defines a switch locomotive that produces a maximum of 2300 or less brake horsepower at the full rated load. All other locomotives that are not considered a switch locomotive are considered line haul including passenger locomotives. The Line Haul and Switch EPA duty cycles are found in Table 1. Note, there are other variations based upon a single engine idle speed and no linehaul dynamic brake.

Throttle	EPA Line Haul	EPA Switch
8	0.162	0.008
7	0.030	0.002
6	0.039	0.015
5	0.038	0.036
4	0.044	0.036
3	0.052	0.058
2	0.065	0.123
1	0.065	0.124
Idle	0.019	0.299
Low Idle	0.19	0.299
DB	0.125	0
Total %	1.00	1.00

Table 1

Current Regulations 40 CFR Part 1033

In 2008, 40 CFR Part 1033 became effective which established Tiers 3 and 4, and established lower emissions levels for Tier 0, 1, and 2 that were previously established under Part 92. For those locomotives that were previously certified under Part 92, the new 1033 regulation would take effect at time of remanufacture for locomotives that were previously certified under the Part 92 regulations The new reduced emissions for Tiers 0, 1 and 2 were then referred to as Tier 0+. Tier 1+ and Tier 2+ The emissions tiers for both 40 CFR Parts 92 and 1033 are shown in Table 2. In addition to the reduction of the emissions limits, Part 1033.115(g) also requires that locomotive be equipped with idle reduction which is known in the railroad industry as Automated Engine Start Stop (AESS).

In recent editions of Part 1033, the "+" signs have been dropped, which leaves a Tier 0 Limit for locomotives covered under Part 1033 and a different Tier 0 emissions limit for those locomotives that were brought into compliance under Part 92.

The effective emissions tier for each locomotive depends upon the original manufacture date of the locomotive, the horsepower and whether locomotive was built with split cooling. In addition, if the locomotive is modified, upgraded, or refreshed, the required tier may change. Since there are many factors that can determine a locomotives emissions tier, this topic is discussed in detail further in the paper. All the emissions tiers are shown in Tables 2 and 3.

Family Emissions Limits

A Family Emissions Limit (FEL) is used by locomotive and kit manufacturers to garner emissions credits under Average Banking and Trading (ABT). To obtain the credits, the kit would have an FEL that would be below the regulated limit. When using the credits, the kit provided with the credits would have an FEL that shows emissions levels above the regulated limits.

Sometimes a railroad desires to have a locomotive that is lower than the legally required emissions kits. The reasons for this would be to get a government grant or to provide lower emissions per agreement with a local municipality. In this case, the locomotive certified would have a Family Emissions Limit (FEL) which states lower emissions than the regulated Tier. For instance, if a locomotive built before the year 2000 was brought to Tier 2 standards, the locomotive would be certified at Tier 0+, but with a Family Emissions limit that would be equivalent to Tier 2+.

Line-Haul Locomotive Emission Standards							
Year of Original manufacture	**Overhaul Year or Build Date Clarification**	**Tier Standards (g/bhp-hr)**					**Other Standards**
			NOx	PM	HC	CO	
1973-2001	Either built new between Jan 1, 2000 and Dec 31, 2001 and/or Overhauled between Jan 1, 2002 and Dec 31, 2009 with exception of 710 Engined Locomotives which the effective date was Jan. 1, 2000.	Tier 0	9.5	0.60	1.00	5.0	
1973-2001 with **NO** Split Cooling	Overhauled after Jan 1, 2010	Tier 0+	8.0	0.22	1.00	5.0	Must also meet T0+ Switch Standards
2002-2004	Built new between Jan 1, 2002 and Dec 31, 2004 and overhauled prior to Dec, 31, 2009.	Tier 1	7.4	0.45	0.55	2.2	
1993 to 2004 with Split Cooling	Overhauled after Jan 1, 2010	Tier 1+	7.4	0.22	0.55	2.2	Must also meet T1+ Switch Standards
2005-2011	Built new between Jan 1, 2005 and Dec. 31, 2011	Tier 2	5.5	0.20	0.30	1.5	
2005-2011	Locomotives ovehauled after Jan 1, 2013	Tier 2+	5.5	0.10	0.30	1.5	Must also meet T2+ Switch Standards
2012-2014	Built new after Jan 1, 2012	Tier 3	5.5	0.10	0.30	1.5	Tier 3 Line Haul Locomotives must also meet Tier 2+ Switch Standards
2015 or later	Built new after Jan. 1, 2015	Tier 4	1.3	0.03	0.14	1.5	

Table 2

Switch Locomotive Emission Standards							
Year of Original Manufacture	**Overhaul Year or Build Date Clarification**	**Tier Standards (g/bhp-hr)**					**Other Standards**
			NOx	PM	HC	CO	
1973-2001	Either built new between Jan 1, 2000 and Dec 31, 2001 and/or Overhauled between Jan 1, 2002 and Dec 31, 2009.	Tier 0	14.0	0.72	2.10	8.0	
1973-2001	Overhauled after Jan 1, 2010	Tier 0+	11.8	0.26	2.10	8.0	
2002-2004	Built new between Jan 1, 2002 and Dec 31, 2004 and overhauled prior to Dec, 31, 2009.	Tier 1	11.0	0.54	1.20	2.5	
2002-2004	Overhauled after Jan 1, 2010	Tier 1+	11.0	0.26	1.20	2.5	Tier 1+ Switch Locomotives must also meet the Tier 1+ Line Haul Standards
2005-2011	Built new between Jan 1, 2005 and Dec. 31, 2011	Tier 2	8.1	0.24	0.60	2.4	
2005-2011	Locomotives ovehauled after Jan 1, 2013	Tier 2+	8.1	0.13	0.60	2.4	Tier 2+ Switch Locomotives must also meet the Tier 2+ Line Haul Standards
2011-2014	Built new after Jan 1, 2011	Tier 3	5.0	0.10	0.60	2.4	
2015 or later	Built new after Jan. 1, 2015	Tier 4	1.3	0.03	0.14	2.4	

Table 3

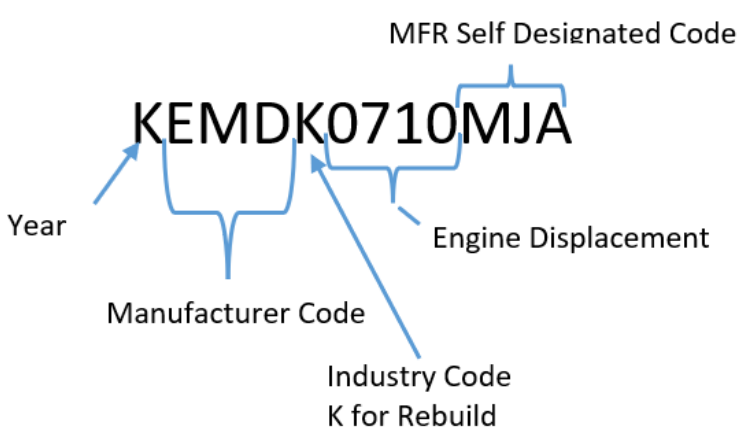
Smoke Standards for Locomotives (Percent Opacity)			
	Steady State	30-Second Peak	3-Second Peak
Tier 0	30	40	50
Tier 1	25	40	50
Tier 2 and Later	20	40	50

Table 4

Certified Locomotives and Emissions Kits

To comply with the emissions regulation, the locomotive owner or operator does not have to worry about the actual emission numbers, but that they have either purchased a new locomotive that complies with emissions per it's build date, or the owner of a locomotive can apply correct emissions kit that corresponds with the emissions regulations per the locomotive's original manufacture year.

Any locomotive manufacturer or emissions kit manufacturer must design, test, and certify with the EPA that their kit complies with the regulations. When the EPA accepts a manufacturer's engine family or emission kit application it grants the manufacturer a certificate of conformity. The engine family is a 12 digit name with the first digit reference a year letter code, followed by a manufacturer code, industry code, engine displacement and manufacturer designation code. The definitions for the code are found in the paper *Locomotive Emissions Labels* in the LMOA *Proceedings of the 81st Annual Meeting*, 2019. An example of an emissions family code is shown in the diagram below.



The manufacturer must provide maintenance instructions to the owners or operators. Those manufacturers that provide emission kits must provide installation instructions. Sometimes the emissions kit manufacturers do not provide all the components necessary in their kits, but the instructions must state what parts are required. An example of this is the EMD four pass aftercoolers for the 645 and 710 engines.

Idle Reduction

When offering emissions retrofit kit, a manufacturer may elect to get a partial certificate of conformity, by deferring the idle reduction requirement in 1022.115(b), (known as Auto Engine Start Stop in the railroad industry), to the buyer to purchase separately. When this occurs section 1033.20(i) states that two certificates of conformity are required.

Labeling

Section 1033.135 covers required labeling. There are two labels required, one for the locomotive and another for the engine. These labels are in addition to the serial numbers on the engine and locomotive, which per 1033.135(a) must be legible. The required information must match the locomotive label and the engine label plate.

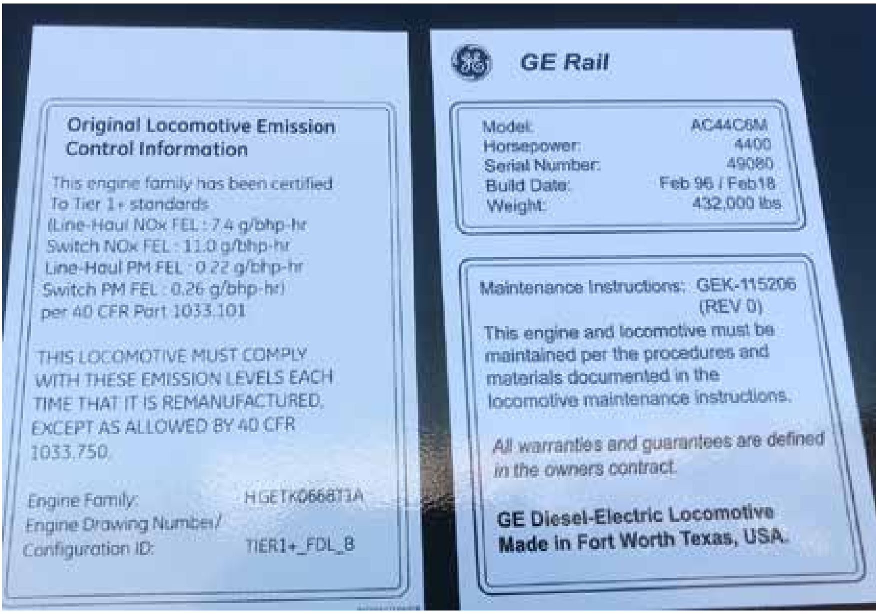
Locomotive Label

The locomotive label is provided at the time of manufacture if the locomotive built was emissions compliant. If the locomotive is being brought into compliance with an emissions kit, the manufacturer of the kit must supply the label. The verbiage on the label is stipulated in the regulations. Since it is provided by the manufacturer, and this paper is intended for locomotive owners and operators the specific details are not provided in this paper.

During an overhaul (or remanufacturing event, as will be explained in a later section in this paper) the locomotive label will remain. However, when bringing a locomotive that was built under 40 CFR part 92 in compliance with 40 CFR part 1033 the locomotive label will change that states the locomotive is certified under Part 1033. Wabtec (GE) typically provides a new label, Progress Rail (EMD) either provides a new label or a smaller label that goes over part of the original label.

The regulations do not state where the label is to be located. Generally, the kit manufacturer will state where the locomotive label is to be placed. On new EMD locomotives, the emissions label is found on the outside of the cab near the builder's label and is sometimes part of the builder label. On emissions retrofit kits, EMD instructs the kit installer to install the label inside the cab above windshields near the FRA noise emissions label. On GE locomotives, the emissions label is located on the outside of the cab near the builder label.

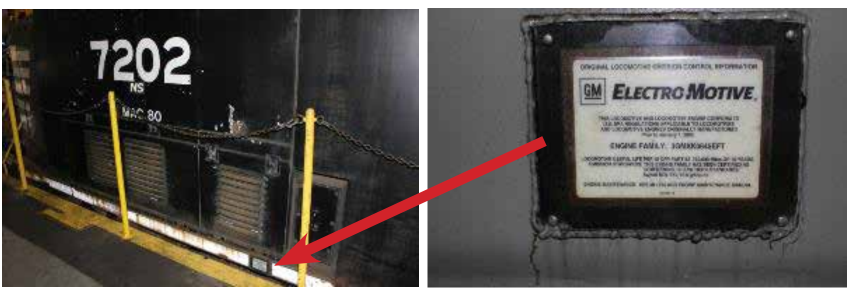
GE Locomotive Emissions Label



GE Locomotive Label Location
Engineer's Side of Operators Cab

New EMD Locomotive – Label Location
On the nose of the Operator's Cab

Rebuild EMD Locomotive Label
On the Under Frame Side Sill (either side)



<u>Engine Labels</u>

Each emissions certified engine must have a label per the 1033.135(c). The engine label should be changed every time the engine is overhauled (remanufactured). On EMD engines, the label is generally near the engine serial number. On GE locomotives, the label is part of the engine label on the engine/generator mount.

GE Dash 8 and Dash 9 Location Near Locomotive Engine Start StationEngine Blocks Alternator Mounting Face

GE EVO Engine Location Under Crankcase Door – Left Rear Side

Fuel Labels

Per 1033(b)(3), if the engine is certified with a specific fuel a label must be placed near the fuel fills stating the correct fuel. For example, most Tier IV locomotives are certified using Ultra Low Sulfur Diesel (ULSD) fuel. In that case, a label stating Ultra Low Sulfur Diesel must be placed near each fuel fill.

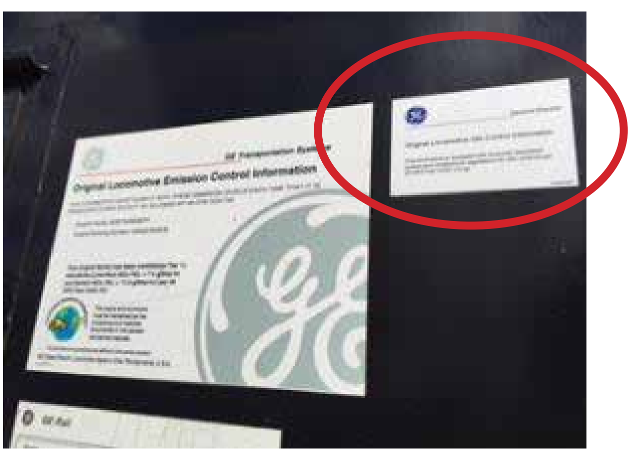
Ultra-Low Sulfur Diesel Fuel Label
Required for Tier 4 Locomotives (including Tier 4 Credit Locomotives)

EMD Rebuild Locomotive Label
Inside the Operator's Cab

AESS Labeling

If a manufacturer provides a partial emissions kit omitting the AESS, the locomotive must have a separate label for the AESS. Some railroads elect to have a separate AESS label on the locomotive regardless of whether the AESS system is provided as part of the kit or not. The regulations do not stipulate where the AESS label is to be placed, it is left up to the kit manufacturer to decide. Generally, it is placed by the locomotive label.

GE AESS Label next to Locomotive Label



What Tier is Applicable and When does a locomotive become compliant.

Newly built locomotives that are manufactured after the emissions regulations took effect, must comply with the Tiers that were established for the manufacture year when built by the manufacturer. This is straightforward. However, in the railroad industry it is not uncommon to see a 70+ year old diesel-electric locomotive built in the early 1950s still in service. In fact, most of the four axle locomotives in service today on Class I railroads are over 30 years old. When the EPA made the locomotive emission regulations, they made the regulations retroactive to locomotives built after January 1, 1973. The retroactive locomotives are assigned to the Tier 0 emissions level, which allows the highest emissions of all emissions tiers. This leads to the question of when does a locomotive that was built after January 1, 1973, and prior to the emissions regulations taking effect must comply to the regulations? This is addressed in the next section of the paper.

Effectivity of the Emissions Regulation for Uncontrolled Emissions Locomotive Built after January 1, 1973.

In the railroad industry it is not uncommon for a Class I railroad to overhaul a locomotive engine between six and sixteen years depending upon the amount of service, reliability, budget, engine failure etc. During this time a locomotive is typically overhauled. The EPA regulations consider an overhaul equivalent to making the engine "new" again, and that is where the emissions regulations take effect. The regulation does not specifically state the word "overhaul", but it defines an engine that has been "remanufactured" as being made new again. When this overhaul or remanufactured to "new" event occurs, the locomotive must conform to the latest emission tier as prescribed by its original manufactured date. For instance, if a Tier 2 locomotive manufactured in 2009 was overhauled in 2017, it must comply to the Tier 2+ regulations.

Other Definitions for the term "NEW

The EPA further defines the definition of new by replacing all the engine power assemblies within a five-year period. The power assembly replacement can be either with new, UTEX, or installing a running take out power assembly. The EPA considers a power assembly that has been taken out inspected and put back into a locomotive as good as a new power assembly.

If a locomotive engine does not have a power assembly, such as found in a high-speed diesel engine, the EPA considers replacing the all the engine components that are typically found in a power assembly as an overhaul.

Some locomotives go through programs during their life that significantly alter the locomotive. Examples of these programs include control system replacements, cab replacements, DC to AC conversion, or AC to AC conversion (GTO to IGBT inverters). When a significant amount of locomotive components are replaced with new, the regulations consider a locomotive to be either refurbished or remanufactured depending upon the number of new parts that were used in the program. If less than 25% of the parts on the locomotive are used, then the locomotive is freshly manufactured, and the emissions tier must correspond to the current new emissions tier which is Tier IV. If the number of used parts is between 25 and 50%, and the locomotive rating is greater than 3000 BHP, the locomotive must also meet the new emissions Tier standard of Tier IV. However, locomotives that are switch locomotives must meet the Tier III level.

Table 5 below shows the difference between newly built, remanufactured, and refurbished locomotives.

EPA Definitions for the word "NEW"			
	Newly Built	**Remanufacture**	**Reburbished**
Description	Freshly built by locomotive builder. Title transferred for the first time.	1) Engine Overhaul - replace all power assembies with either new, UTEX or running take out (RTO) at once or over a five year period. 2) Overhaul non power assembly locomotive (i.e. high speed diesel engine) 3) Install new, rebuilt or UTEX engine of the same type in a used locomotive 4) Upgrade a pre-1973 engine (see further definition) 5) Change the fuel from original fuel the locomotive was built to operate on	1) Repower with new engine (see further definitions) 2) Rebuild with more new parts than old/used parts (See further explanation)
Emissions Tier	Tier for the year manufactured	Tier for the original year the locomotive was manufactured	Tier depends upon the amount of new vs. used material (See Table 6)

Table 5

Percent of New Versus used Part in Determining Remanufacture and Refurbished.

One of the main questions asked in determining the amount used versus new part is what is the criteria, weight, quantity, or dollar amount? 40CFR1033.640(c) specifically states the relative amount of previously used parts may be determined according to the specifications of the Federal Railroad Administration

Remanufactured locomotive means a locomotive rebuilt or refurbished from a previously used or refurbished underframe ("deck"), containing fewer than 25% previously used components (measured by dollar value of the components). For calculation purposes, the percentage of previously used components is determined with equivalent value of new parts and is calculated using dollar values from the same year as the new parts used to remanufacture the locomotive. (49CFR229.5 Definitions)

Alternatively 1033.64(c) (1 through 3) reads as follows:

a. Identify new and used parts.
b. Weight new and used parts for dollar value. Calculate the used parts values by using the dollar values from the same year as the new parts.
c. Sum the values of the new and used parts; the fraction of the used parts is the total value of the used parts divided by the sum of the new and used parts.

Essentially the calculation of used parts are the same between the FRA regulations as stated in 49CFR229.5 and the EPA regulations as stated in 40CFR.640.(c). One of the major things to consider in this calculation is that the value of a used component can have the same value as a new component of the same type.

40 CFR 1033.640 PROVISION FOR REPOWERED AND REFURBISHED LOCOMOTIVES			
% Used Parts*	**<25%**	**>=25% AND <50%**	**>50%**
EPA Terminology	**Freshly Manufactured**	**Remanufactured "AND" Refurbished**	**Remanufactured**
Regulations	The manufacture date is changed to the day when the remanufacture is completed, which is the NEW manufacture date. All emissions regulations corresponding to **NEW** locomotives on the **NEW** manufacture date are applicable.	**Switch Locomotives:** •Before 1/1/15 Tier 0 locos must meet Tier 0 Switch and Line Haul Standards •After 1/1/15 Tier 3 and all other switch locos must meet Tier 3 Switch Standards **Line Haul:** •> 3000 HP must meet Freshly Manufactured (NEW) standards for date of completed refurbishment. •Before 1/1/15 <3000 HP, Tier 0 locos must meet Tier 0 Switch and Line Haul Standards. After 1/1/15 NEW loco emissions standards. Generation of emissions credits is prohibited.	The **original** date of locomotive is retained. All regulations that are applicable to the **original** date of locomotive manufacture are in effect. Typically, an engine overhaul is considered remanufactured.
Additional Labeling	Secondary locomotive label required stating the locomotive is refurbished and certified EPA tier	Secondary locomotive label required stating the locomotive is refurbished and certified EPA tier.	None

Table 6

<u>Exceptions to the Term "New"</u>

There are exceptions to the term new, which involve mainly locomotive built before 1973. The exceptions are as follows:

1. Locomotives and locomotive engines that were originally manufactured before January 1, 1973, unless they have been "upgraded" as defined by section 1033.901.

2. Locomotives that are owned by small railroads **that have never been certified.**
3. Switch locomotives that contain off road non locomotive engine(s) that is certified under 1033.150 do not become new when remanufactured except as specified in 1033.615.
4. Non-standard gauge locomotives if there is no certified kit available.

Upgrading Pre-1973 Locomotives

As the exceptions to the word "new" above state,

1. Repowering a locomotive that was originally manufactured prior to January 1, 1973. (The regulatory language on Repower means to install a freshly manufactured engine, which means a new engine that has not been overhauled or rebuilt.)
2. Refurbishing a locomotive that was originally manufactured prior to January 1, 1973, in a manner that is not freshly manufactured.
3. Modify a locomotive that was originally manufactured prior to January 1, 1973 (or a locomotive that was originally manufactured on or after January 1, 1973, and is not subject to emissions standards of this part [40CFR1033]), such that it is intended to apply to comply to Tier 0 standards.

Examples of Remanufacturing an Upgrading

Locomotive Remanufacturing

Currently there is a trend of remanufacturing DC locomotives to AC and converting old AC locomotives equipped with GTO inverters to IGBT inverters. These programs have been keeping the used content above 50% of the entire content and thus retain their emissions tiers corresponding to their original build date.

NS Dash 9 Conversion to AC44C6M

Reused Major Components
- Platform
- Engine
- Alternator
- Radiator Cab
- Engine Cab
- Air compressor

New Major Components
- Cab
- Aux Cab (Electrical – traction inverters)
- Trucks
- Traction Motors

NS SD90MAC conversion to SD70ACU

Reused Major Components
- Underframe
- Engine
- Alternator
- Equipment Rack and Radiators
- Trucks and Traction Motors
- Air Compressor

New Major Components
- Cab
- Electrical Locker – (traction inverters)

Locomotive Upgrade

Sometimes a railroad elects to upgrade a locomotive built before January 1, 1973 for fleet commonality rather than have some locomotives in a fleet comply with the emissions regulations and some do not. This way there is standardization of parts. Norfolk Southern upgraded a significant number of GP38-2 that were built prior to 1973 so that they would be identical with the rest of the GP38-2 rebuild fleet. If NS ever decides to sell the upgraded GP38-2 locomotives to a short line, that short line must maintain the locomotive to Tier 0 compliance, and if it is rebuilt the locomotive must meet Tier 0+ emissions.

NS 5054
Built in March 1972 as Southern Railroad 5054,
Rebuilt by NS in 2009 and upgraded to Tier 0

Useful Life

Since locomotives can operate for many years, the EPA has defined the time that an emissions certified locomotive must maintain emissions, this term is call "Useful Life" and it is defined below:

Useful Life: means the period during which the locomotive engine is designed to properly function in terms of reliability and fuel consumption, without being remanufactured, specified as work output or miles. It is the period during which a locomotive is required to comply with all applicable emission standards.

Section 1033.101(g) further clarifies that a locomotives useful life should be specified by the emissions certificate holder and should be specified in Megawatt-hours (MW-hrs.) and years, and the useful life ends when either of the values are exceeded or the engine is remanufactured (overhauled). The EPA also specifies that the minimum useful life in MW-hrs. should be the product of the horsepower multiplied by 7.5. For those locomotives that were manufactured before January 1, 2000, the minimum useful life shall be 750,000 or ten years, whichever comes first.

A manufacturer can petition for a longer useful life or a shorter (partial) life. This is done at the time of certification and the useful life is stated on the label that comes with the emissions kit. Per 1033.120 the manufacturer of the locomotive or emissions kit must provide an emissions warranty for at least one third of the useful life. Essentially useful life is the time period during which the OEM and or the certificate holder are responsible for emissions compliance. It does not mean that a locomotive owner or operator must overhaul the locomotive engine at the end of the useful life.

Regulations Specific for Locomotive Owners and Operators

Section 1033.815 details the regulations for locomotive owners and operators for maintenance, operation, and repair. The regulations state that the following must be done:

- Perform the emissions-related maintenance work per the instructions provided by the certificate holder.
- Perform unscheduled maintenance in a timely manner.
- Use good engineering judgement in the repair such that the locomotive will continue to meet the applicable emissions standards.
- Keep all emissions related maintenance records including emission related repairs for a period of eight years.
- If a locomotive needs an SCR reductant such as Diesel Emissions Fluid (DEF), it must be readily available, and if you run a locomotive without the reductant, it must be reported to the EPA.

The term “engineering judgement” is defined in 1068.30. It states, “Good engineering judgement mean judgements made consistent with generally accepted scientific and engineering principles, and available relevant information. See 1068.5.” Even though Section 1068.5 is for manufacturers who use engineering judgment in their certifications, it gives further clarifications on how the regulations define “engineering judgement.” Section 1068.5 states, “You must use good engineering judgment for decisions related to any requirement under this chapter. This includes your applications for certification, any testing you do to show that your certification, production-line, and in-use engines/equipment comply with requirements that apply to them, and how you select, categorize, determine, and apply these requirements.”.

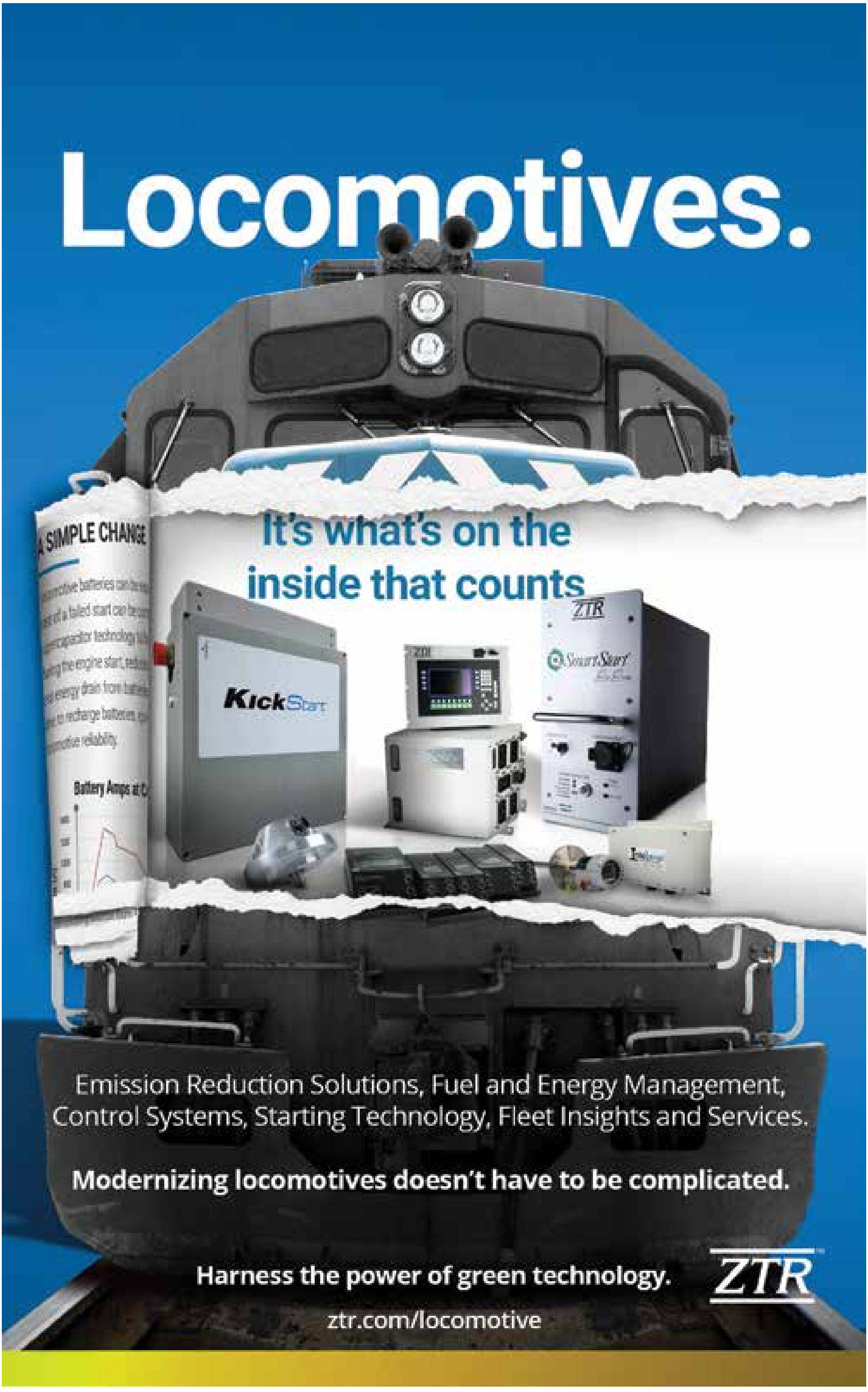
Suggestions for Locomotive Owners and Operators

Good Engineering Judgment

When the need arises to use “good engineering judgment” in maintaining or repairing a locomotive, it is suggested to document the reasoning why and retain that document in your emissions records. Generally, if there is an issue with the emissions maintenance instructions the emissions kit manufacturer should be contacted, and under the emissions warranty they should provide the solution. If a part is not available, then engineering judgement may be required.

Emissions Critical components

Although not required by regulations, to comply with the regulation in using good engineering judgement in repair, it is strongly recommended that each railroad keep a list of the Emissions Critical Components (ECC) for each locomotive or emission kit and provide the list along with the maintenance instructions to the mechanics who repair and maintain the locomotives. The best way to maintain a locomotive to stay within emissions compliance is to replace the emissions components with the correct part number. Keep in mind some there may be two different part numbers for the same part as EMD uses different part numbers for new and UTEX parts.


Locomotives.
It's what's on the inside that counts
KickStart
SmartStart
Emission Reduction Solutions, Fuel and Energy Management, Control Systems, Starting Technology, Fleet Insights and Services.
Modernizing locomotives doesn't have to be complicated.
Harness the power of green technology.
ZTR
ztr.com/locomotive

Record Keeping

At minimum it is suggested all owners and operators need to keep the following records on each locomotive:

- Model
- Original locomotive manufacture date
- Date locomotive was purchased or leased.
- Locomotive and engine serial numbers
- Dates of AESS installation (if equipped)
- Date of Auxiliary Power Unit installation (if equipped)
- Date emissions kit installed.
- The current emissions Tier limit and the certified engine family
- All repairs relating to emissions equipment (such as power assembly replacement)
- Dates of routine emissions maintenance, (such as fuel injector replacement)

Buying or Leasing Locomotives

When buying a locomotive, make sure to obtain the following information from the seller and do a visual inspection. The information needed is as follows:

- Locomotive Serial Number
- Engine Serial Number
- Locomotive Date of Manufacture
- Emissions Tier and Engine Family
- Current emissions kit application date (overhaul date)
- Emissions maintenance instructions
- Emissions maintenance records for the past 8 years (if the locomotive is not new)
- List of the emissions critical components

After obtaining the information listed above, make a visual inspection of the locomotive checking for the following components against the emissions maintenance instructions and ECCs.

- Emissions Label both on the locomotive and engine – the information should match.
- Locomotive and engine serial numbers
- Visible components
    - Check the fuel injector part number and date code.
    - Injector calibrations codes in the computer (EMD EUI engines only)
    - Turbocharger part number
    - Power Assembly part number
    - Correct Aftercooler or intercooler (for EMD it should have a four-pass aftercooler for emissions turbo locomotives.
    - Engine governor part number (non-electronic engines only)

It is not required to emissions test a locomotive prior to purchasing. However, it is advisable to run a load test and look at the exhaust stack. If you can see heavy smoke after 20 seconds, it is advisable to further investigate an emissions issue.

Contracting Maintenance on a Leased Locomotive

If a third party is performing maintenance work on an emissions regulated locomotive the following must be adhered to

- The maintainer must be aware what is and what is not EPA compliant in terms of replacing emissions critical components, making adjustments that effect emissions and maintaining the emissions compliance records.
- The locomotive owner must be supplied with the emissions records from the third-party maintainer.
- The operator must make sure the locomotive is in emissions compliance and that the emissions maintenance is being done.

Staff Training

It is highly recommended to have basic emissions training for the locomotive maintenance staff as well as shop management. The training should focus on the importance of following maintenance instructions, installing the proper emissions critical components and record keeping.

Self-Auditing

It is recommended that every year several locomotives are visually inspected to make sure the serial numbers for the locomotive and engine match the records along with the emission labels. In addition, the readily visible emissions critical components such as the turbo charger, fuel injectors, and aftercooler should be inspected to make sure the correct emissions critical components have been applied.

In Use Testing

Locomotives emissions testing must be in accordance with 1033 Subpart F (1033.501 - 1033.535) and 40 CFR 1065. The regulations describe the test procedure, equipment, and ambient conditions. Section 1033.810 requires only Class I railroads to submit locomotives for in-use testing, and exempts Class II and III railroads. Class I railroads may also have to provide locomotives to the certificate holders for in-use testing.

Due to the complexity of emissions testing, the Class I railroads hire third parties that specialize in emissions testing. Per an agreement with the EPA, the Association of American Railroads coordinates the emissions testing with the Class 1 railroad and emission testing providers and files the required emissions report with the EPA.

Frequently Asked Emissions Questions

What happens when a locomotive reaches the End of Useful Life for the certified emissions?

The owner or operator can still use the locomotive. The certificate holder must provide an emissions warranty for one third of the Useful Life per 1033.120(b) provided the locomotive is properly maintained. After the Useful Life, the owner or operator can still use the locomotive; however, if the locomotive is emissions tested and fails, the owner/operator must provide a remedy for the locomotive which is typically another overhaul with an emissions kit.

Beware, some kit holders expect the owner and operator to overhaul at the end of Useful Life. There is no legal obligation to overhaul at the end of the Useful Life.

What to do if there is no emissions kit available for your locomotive?

Section 1033.610(c) states that if a small railroad owns a locomotive where no emissions kit is available it may grant that small railroad an exception. For the non-Class 1 railroads that are not considered small railroad, section 1033.610(d) has a provision where the railroad can ask the EPA to exempt the locomotive where no emissions kit is available, but that railroad might have to retain a previous certified configuration, which means overhaul it as it was previously certified.

Can a non-OEM component be used in maintenance and repair?

Section 1033.645 allows after-market component manufacturers to certify their components to be used in locomotive remanufacturing (overhaul), maintenance, and repair. The manufacturer can obtain a certificate of conformity from the EPA. It is suggested when a railroad uses non-OEM components, the railroad obtains a copy of the certificate of conformity for the applicable parts and retains it in its emissions records. The allowed components are as follows:

- Cylinder Liners
- Pistons
- Piston rings
- Cylinder Heads
- Fuel Injectors
- Turbochargers
- Aftercoolers and Intercoolers.

What happens when the kit manufacturer goes out of business?

If the kit manufacturer no longer supplies a part or is no longer in business, it is advisable to contact the EPA and explain the situation. The EPA may grant an exception or allow the railroad to use engineering judgement to find a part substitute.

What Happens when a locomotive with a Family Emissions Limit comes due for Overhaul?

If a locomotive has a Family Emissions Limit, the EPA expects the locomotive to conform to that FEL throughout the locomotive's life. FELs are used mainly for the certificate holder to get credits, and the credit generation is calculated for the remaining life of the locomotive.

Conclusion

The locomotive emissions regulations are very complex with many details. The principal emissions regulations that apply to locomotive owners and operators are as follows:

- Locomotives are subject to emissions regulations. All railroads, locomotive leasing companies, manufacturers, and maintainers must follow the emissions regulations. There is an exception for small railroads that are not owned by a larger corporation.
- Any locomotive built after January 1, 1973, is subject to the emissions regulations.
- The amount of regulated emissions for a locomotive is determined by its manufacture date, refurbished or remanufacture (overhaul), date as set for by the emissions tier level.
- Emissions are in compliance with applicable emissions tier level for the original manufacture build date or refurbishment date.
- Emissions Regulated locomotives must be maintained per the emissions maintenance instructions provided by the locomotive or emissions kit manufacturer.
- All maintenance and repair related to emissions must be recorded, and the records kept for eight years.

The locomotive owner and operators' responsibility for following the regulations has many parts such as determining what emissions tier is applicable to a locomotive, maintaining and repairing the locomotive to ensure emissions compliance and maintain records. It is the responsibility of each locomotive operator to read and understand the regulations. If the EPA determines that a party has violated the Clean Air Act or implemented regulations (such as those under Part 1033), it may seek civil or criminal penalties against that party.

References:

A) Title 40 of the US Code of Regulations Part 1033
B) "Locomotive Emissions Kit", Timothy Standish, LMOA, 2017
C) "Locomotive Emissions Labeling", Mark Duve, LMOA, 2019

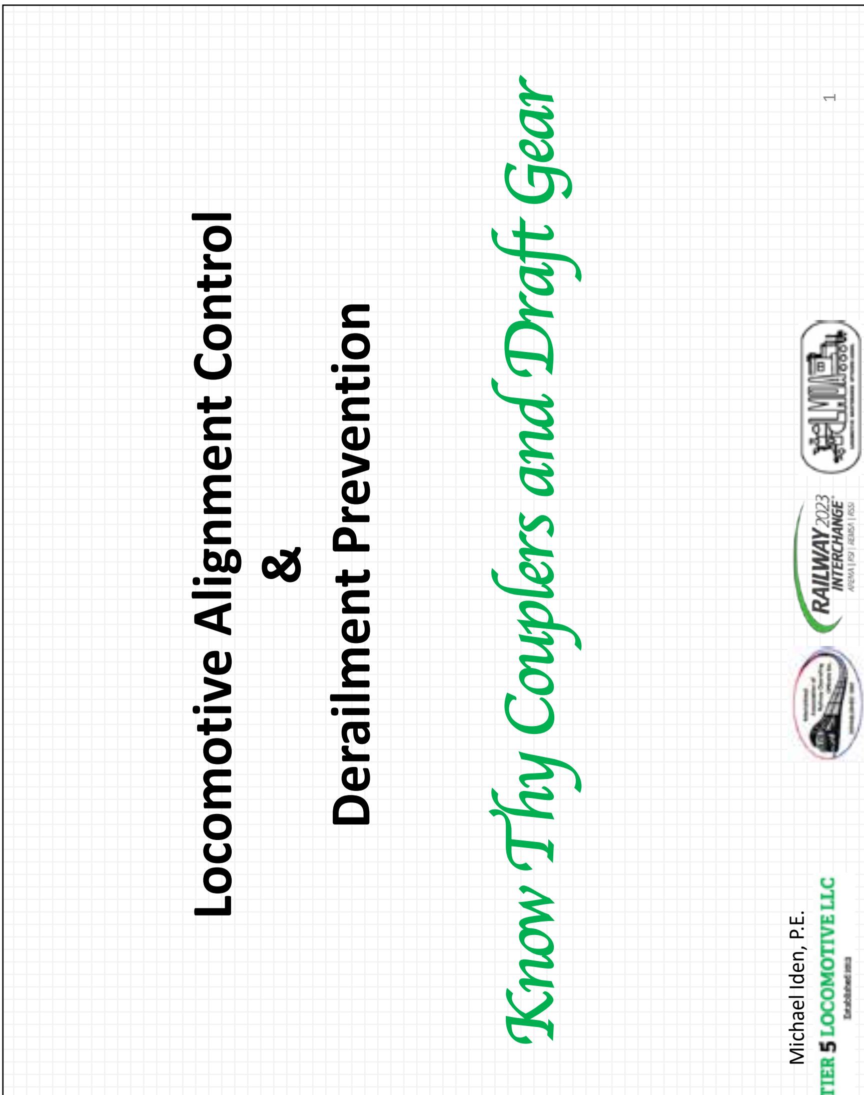
Acknowledgments:

Michael Iden, Tier 5 Consulting, Union Pacific, retired.
Jeff Cutright, L&J Consulting, Norfolk Southern, retired.
Steven Fritz, Southwest Research Institute

Know Thy Couplers and Draft Gears

By:
Mike Iden. Tier 5 Locomotive, LLC

Wednesday, October 4, 2023 – 9:30 AM



Importance of revisiting "alignment control"

- 6-axle high-HP DC-or-AC locomotives most common power for freight trains
- Very-high Dynamic Brake capabilities
- Longer & heavier trains, high buff forces can act on locomotives
- Especially descending grades, decelerating, moving through curves & crossovers
- Occasional movement of lighter 4-axle loco. (freight & passenger) w/o alignment control couplers & draft gear
- Under the "wrong circumstances" non-alignment control-coupler locos. can cause derailments due to wheel climb or rail rollover!
- Lack of industry standards; no definition of What is alignment control?
- Recommendations for AAR and industry actions

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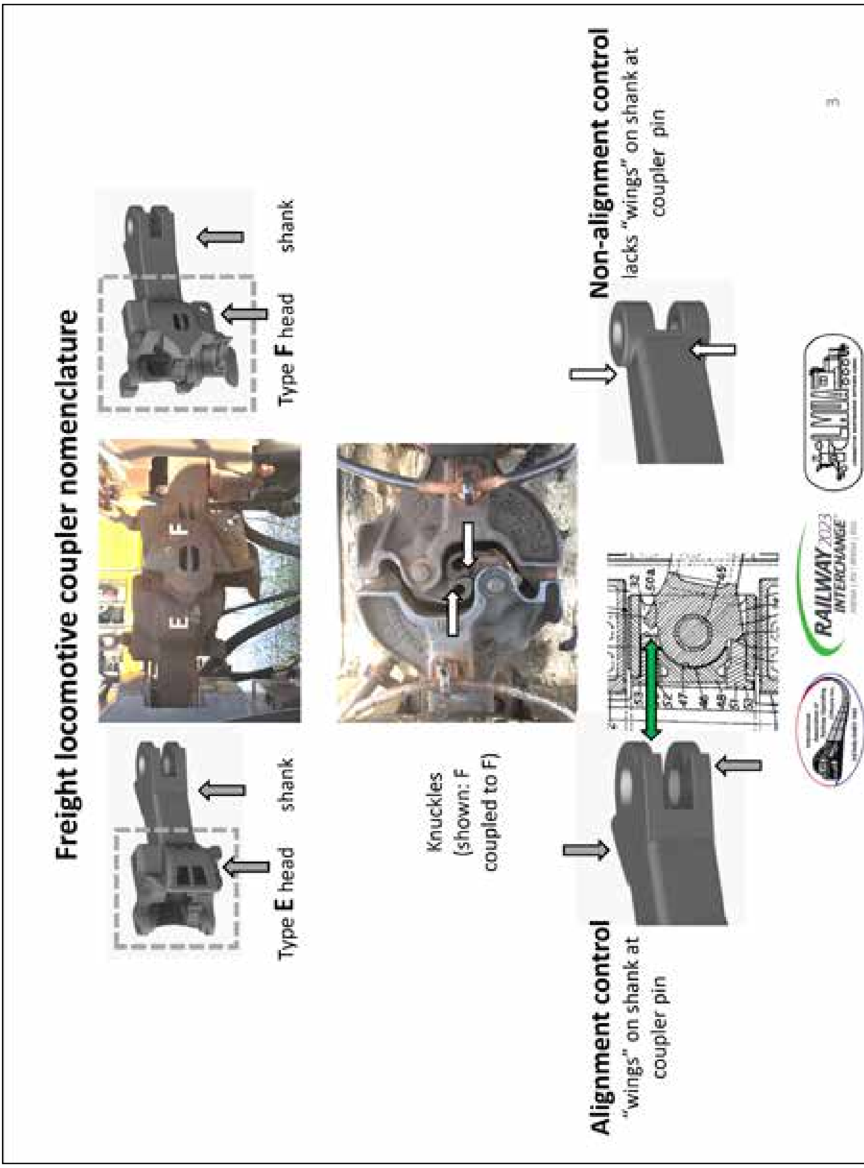
2


Freight locomotive coupler nomenclature
Type **E** head
shank
E
F
Type **F** head
shank
Knuckles (shown: F coupled to F)
Alignment control
"wings" on shank at coupler pin
Non-alignment control
lacks "wings" on shank at coupler pin
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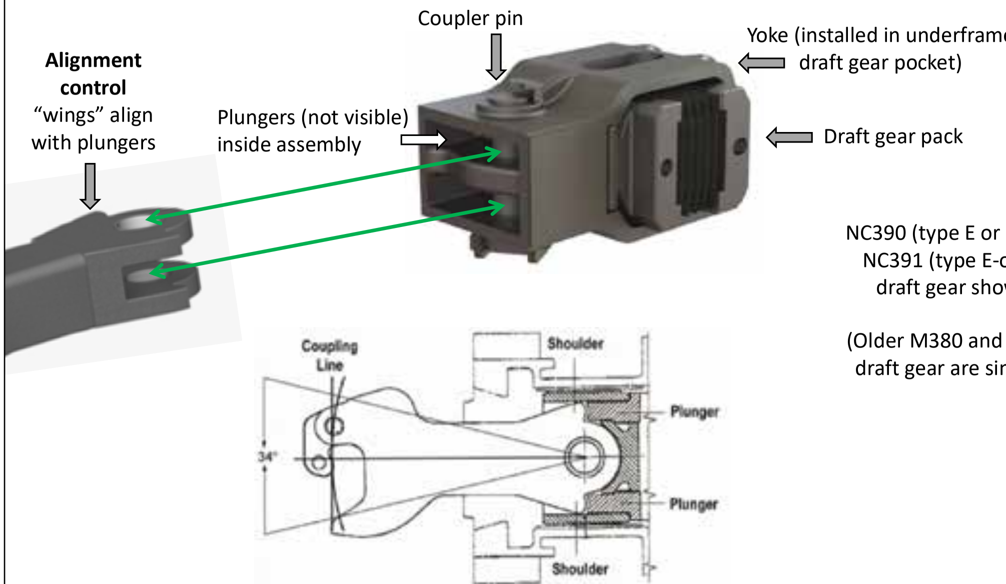
3

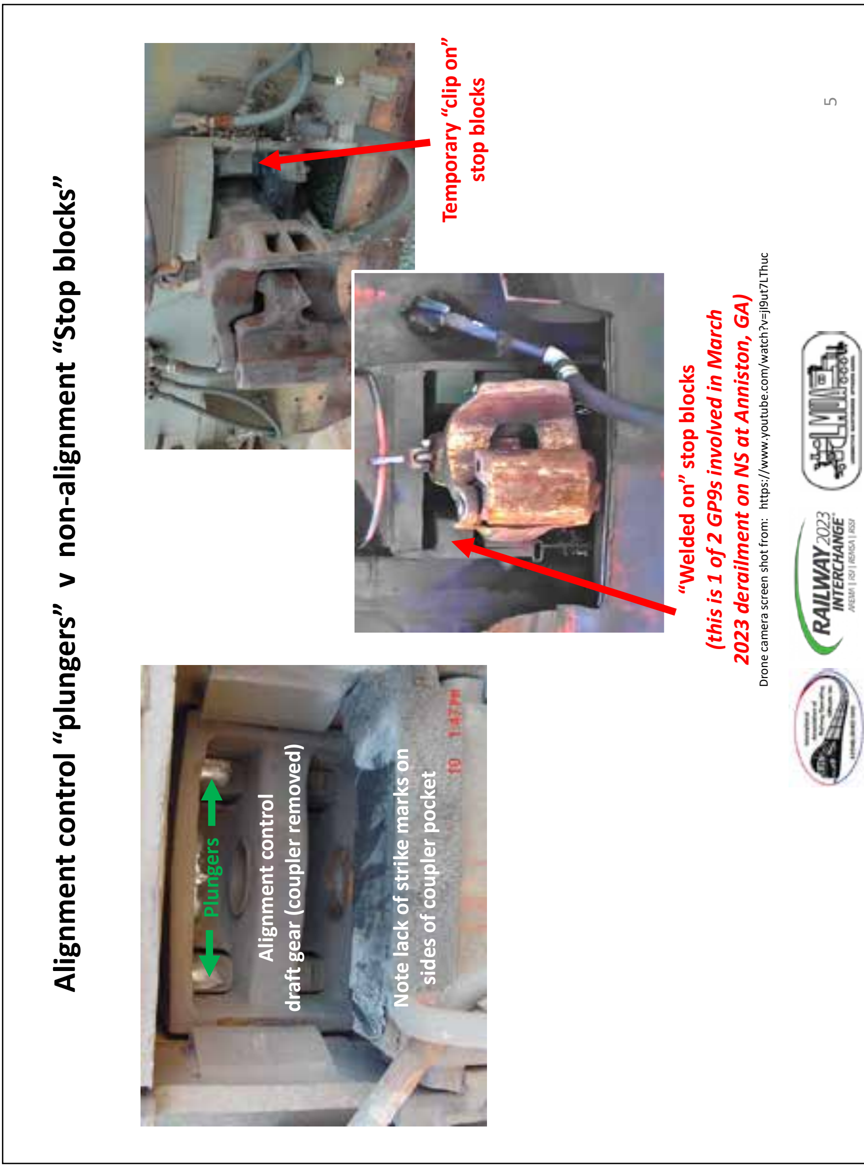
Locomotive alignment control draft gear nomenclature



NC390 (type E or F) and NC391 (type E-only) draft gear shown

(Older M380 and M381 draft gear are similar)

4


Alignment control "plungers" v non-alignment "Stop blocks"
Plungers
Alignment control draft gear (coupler removed)
Note lack of strike marks on sides of coupler pocket
Temporary "clip on" stop blocks
"Welded on" stop blocks
(this is 1 of 2 GP9s involved in March 2023 derailment on NS at Anniston, GA)
Drone camera screen shot from: https://www.youtube.com/watch?v=jl9ut7LThuc
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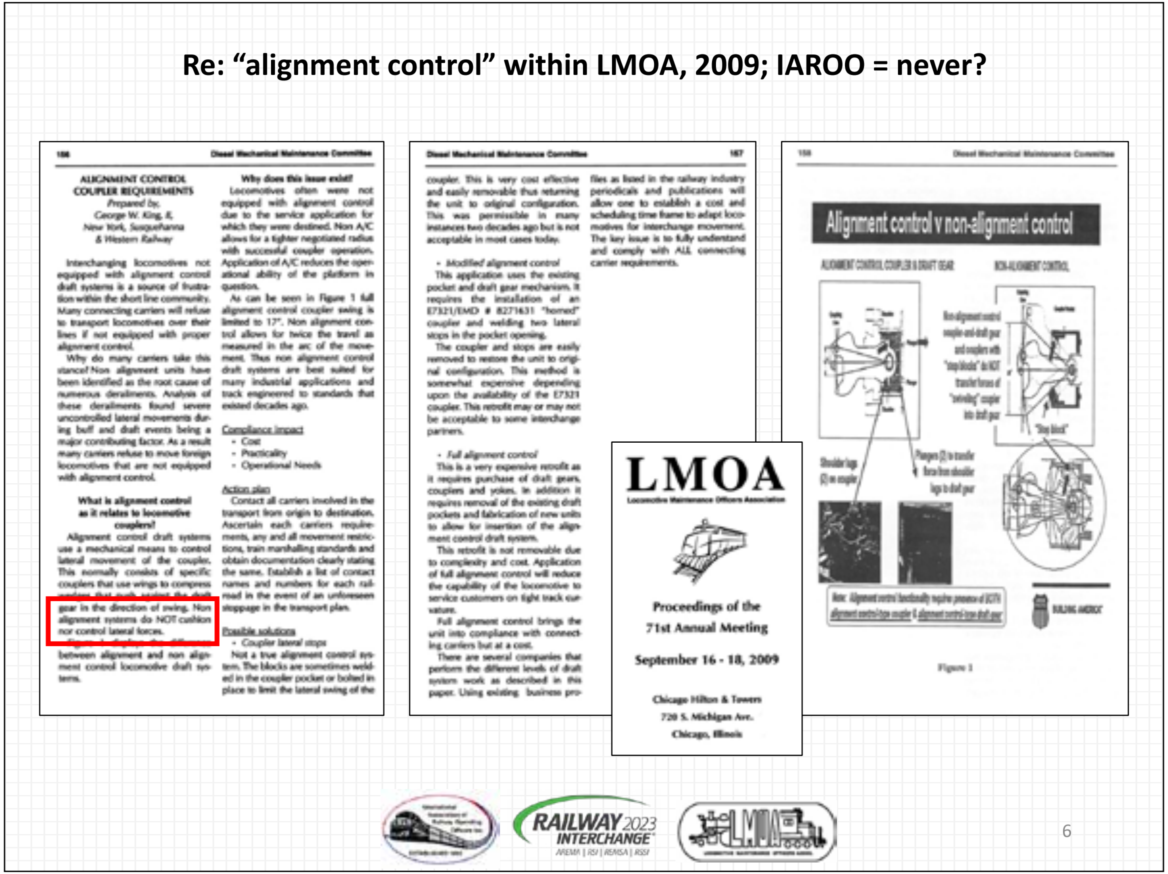
Re: “alignment control” within LMOA, 2009; IAROO = never?
156 Diesel Mechanical Maintenance Committee
ALIGNMENT CONTROL COUPLER REQUIREMENTS
Prepared by,
George W. King II,
New York, Susquehanna & Western Railway
Interchanging locomotives not equipped with alignment control draft systems is a source of frustration within the short line community. Many connecting carriers will refuse to transport locomotives over their lines if not equipped with proper alignment control.
Why do many carriers take this stance? Non alignment units have been identified as the root cause of numerous derailments. Analysis of these derailments found severe uncontrolled lateral movements during buff and draft events being a major contributing factor. As a result many carriers refuse to move foreign locomotives that are not equipped with alignment control.
What is alignment control as it relates to locomotive couplers?
Alignment control draft systems use a mechanical means to control lateral movement of the coupler. This normally consists of specific couplers that use wings to compress
gear in the direction of swing. Non alignment systems do NOT cushion nor control lateral forces.
between alignment and non alignment control locomotive draft systems.
Why does this issue exist?
Locomotives often were not equipped with alignment control due to the service application for which they were destined. Non A/C allows for a tighter negotiated radius with successful coupler operation. Application of A/C reduces the operational ability of the platform in question.
As can be seen in Figure 1 full alignment control coupler swing is limited to 17°. Non alignment control allows for twice the travel as measured in the arc of the movement. Thus non alignment control draft systems are best suited for many industrial applications and track engineered to standards that existed decades ago.
Compliance impact
- Cost
- Practicality
- Operational Needs
Action plan
Contact all carriers involved in the transport from origin to destination. Ascertain each carriers requirements, any and all movement restrictions, train marshalling standards and obtain documentation clearly stating the same. Establish a list of contact names and numbers for each railroad in the event of an unforeseen stoppage in the transport plan.
Possible solutions
- Coupler lateral stops
Not a true alignment control system. The blocks are sometimes welded in the coupler pocket or bolted in place to limit the lateral swing of the
Diesel Mechanical Maintenance Committee 157
coupler. This is very cost effective and easily removable thus returning the unit to original configuration. This was permissible in many instances two decades ago but is not acceptable in most cases today.
- Modified alignment control
This application uses the existing pocket and draft gear mechanism. It requires the installation of an E7321/EMD # 8271631 "horned" coupler and welding two lateral stops in the pocket opening. The coupler and stops are easily removed to restore the unit to original configuration. This method is somewhat expensive depending upon the availability of the E7321 coupler. This retrofit may or may not be acceptable to some interchange partners.
- Full alignment control
This is a very expensive retrofit as it requires purchase of draft gears, couplers and yokes. In addition it requires removal of the existing draft pockets and fabrication of new units to allow for insertion of the alignment control draft system. This retrofit is not removable due to complexity and cost. Application of full alignment control will reduce the capability of the locomotive to service customers on tight track curvature.
Full alignment control brings the unit into compliance with connecting carriers but at a cost.
There are several companies that perform the different levels of draft system work as described in this paper. Using existing business profiles as listed in the railway industry periodicals and publications will allow one to establish a cost and scheduling time frame to adapt locomotives for interchange movement. The key issue is to fully understand and comply with ALL connecting carrier requirements.
158 Diesel Mechanical Maintenance Committee
Alignment control v non-alignment control
ALIGNMENT CONTROL COUPLER & DRAFT GEAR
NON-ALIGNMENT CONTROL
Figure 1
LMOA
Locomotive Maintenance Officers Association
Proceedings of the
71st Annual Meeting
September 16 - 18, 2009
Chicago Hilton & Towers
720 S. Michigan Ave.
Chicago, Illinois
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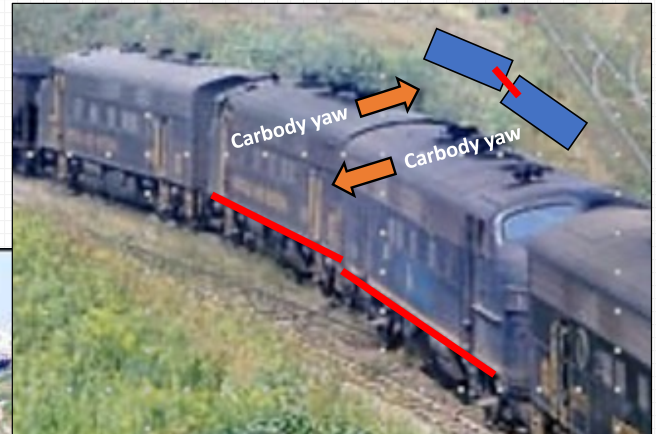
Early diesel derailments without "alignment control"

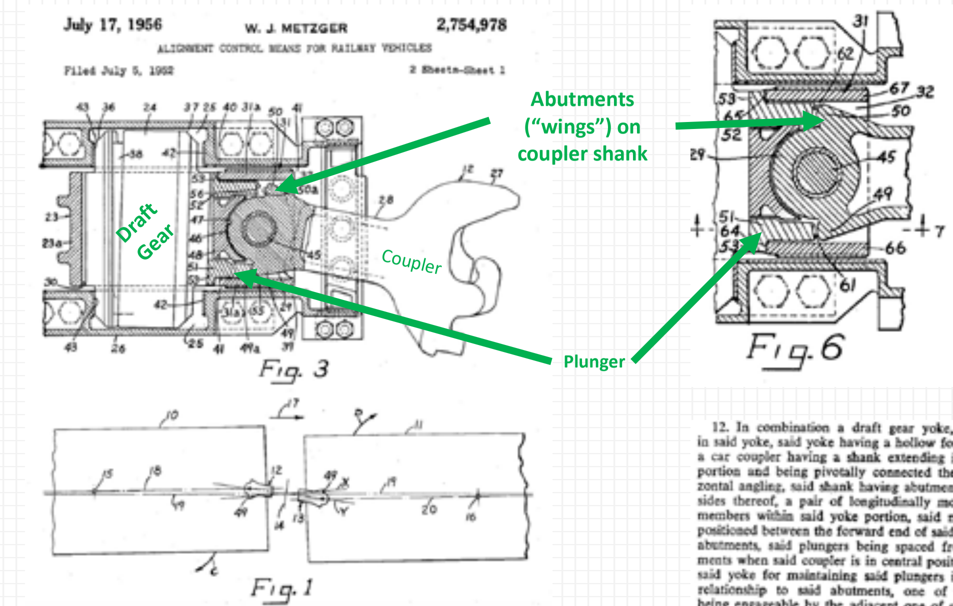
4 EMD F7 shoving coal train, 1971



Note lateral offset of the 2nd and 3rd units caused by carbody yaw, couplers swung to sides

7

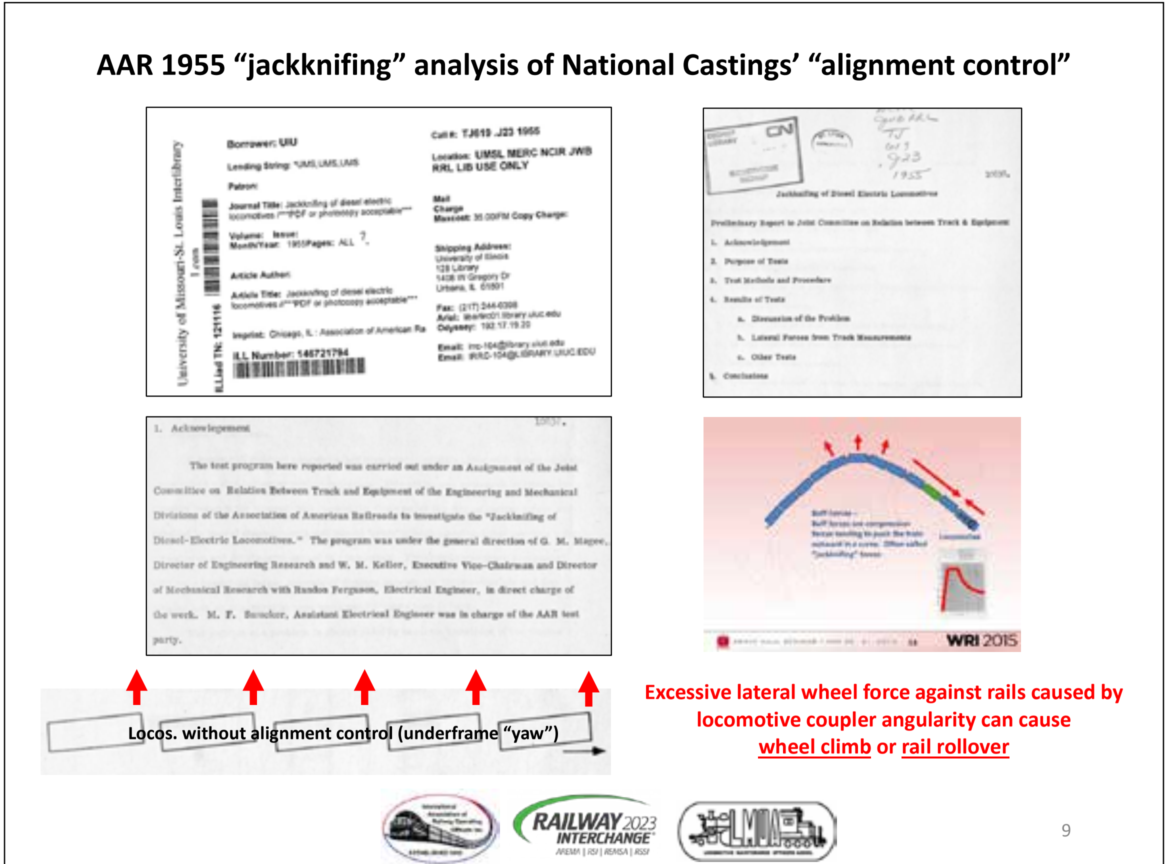
US Patent 2,754,988 (1956; *expired 1973*) "alignment control for railway vehicles"



12. In combination a draft gear yoke, a draft gear in said yoke, said yoke having a hollow forward portion, a car coupler having a shank extending into said yoke portion and being pivotally connected thereto for horizontal angling, said shank having abutments on opposite sides thereof, a pair of longitudinally movable plunger members within said yoke portion, said members being positioned between the forward end of said gear and said abutments, said plungers being spaced from said abutments when said coupler is in central position, means on said yoke for maintaining said plungers in said spaced relationship to said abutments, one of said plungers being engageable by the adjacent one of said abutments upon angling of said coupler laterally from central position a predetermined amount whereby buffing forces applied to the coupler are transmitted by said engaged plunger directly to said gear.

As loco. coupler rotates in buff, lateral forces are redirected back into the draft gear along the loco. centerline

8


AAR 1955 "jackknifing" analysis of National Castings' "alignment control"
Call #: TJ619 .J23 1955
Location: UMSL MERC NCIR JWB RRL LIB USE ONLY
Borrower: UIU
University of Missouri-St. Louis Interlibrary
Jackknifing of Diesel Electric Locomotives
Preliminary Report to Joint Committee on Relation between Track & Equipment
1. Acknowledgement
2. Purpose of Tests
3. Test Methods and Procedure
4. Results of Tests
a. Discussion of the Problem
b. Lateral Forces from Track Measurements
c. Other Tests
5. Conclusions
1. Acknowledgement
The test program here reported was carried out under an Assignment of the Joint Committee on Relation Between Track and Equipment of the Engineering and Mechanical Divisions of the Association of American Railroads to investigate the "Jackknifing of Diesel-Electric Locomotives." The program was under the general direction of G. M. Magee, Director of Engineering Research and W. M. Keller, Executive Vice-Chairman and Director of Mechanical Research with Randon Ferguson, Electrical Engineer, in direct charge of the work. M. F. Bencker, Assistant Electrical Engineer was in charge of the AAR test party.
WRI 2015
Locos. without alignment control (underframe "yaw")
Excessive lateral wheel force against rails caused by locomotive coupler angularity can cause wheel climb or rail rollover
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Alignment Control v Non-Alignment Control tests (AAR), 1954

Typical jackknifing pattern of unrestrained locomotives in heavy buff loading ("Z pattern")

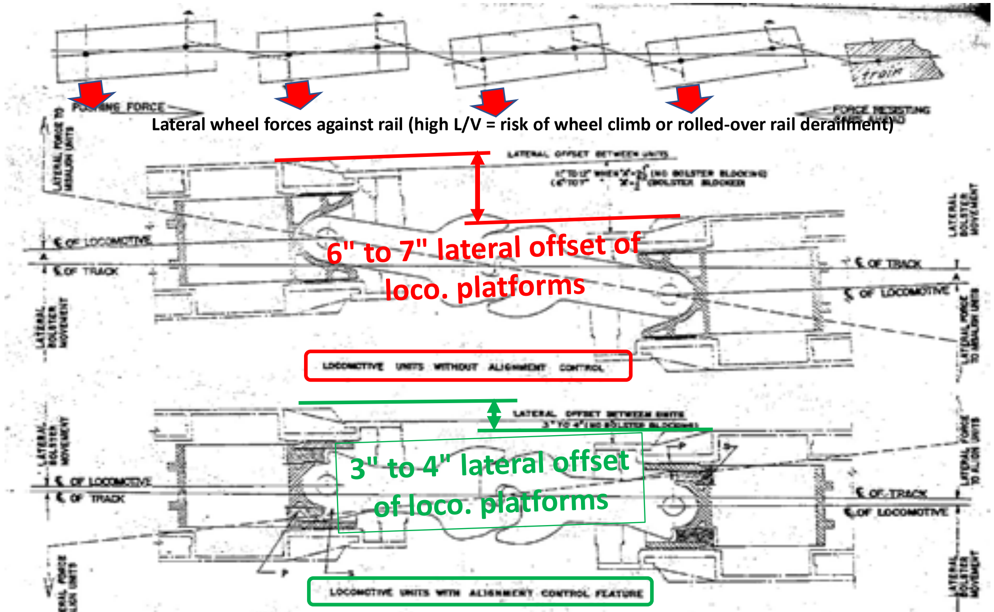

FIG. 11-DIAGRAMMATIC REPRESENTATION OF ACTION OF THE ALINEMENT CONTROL

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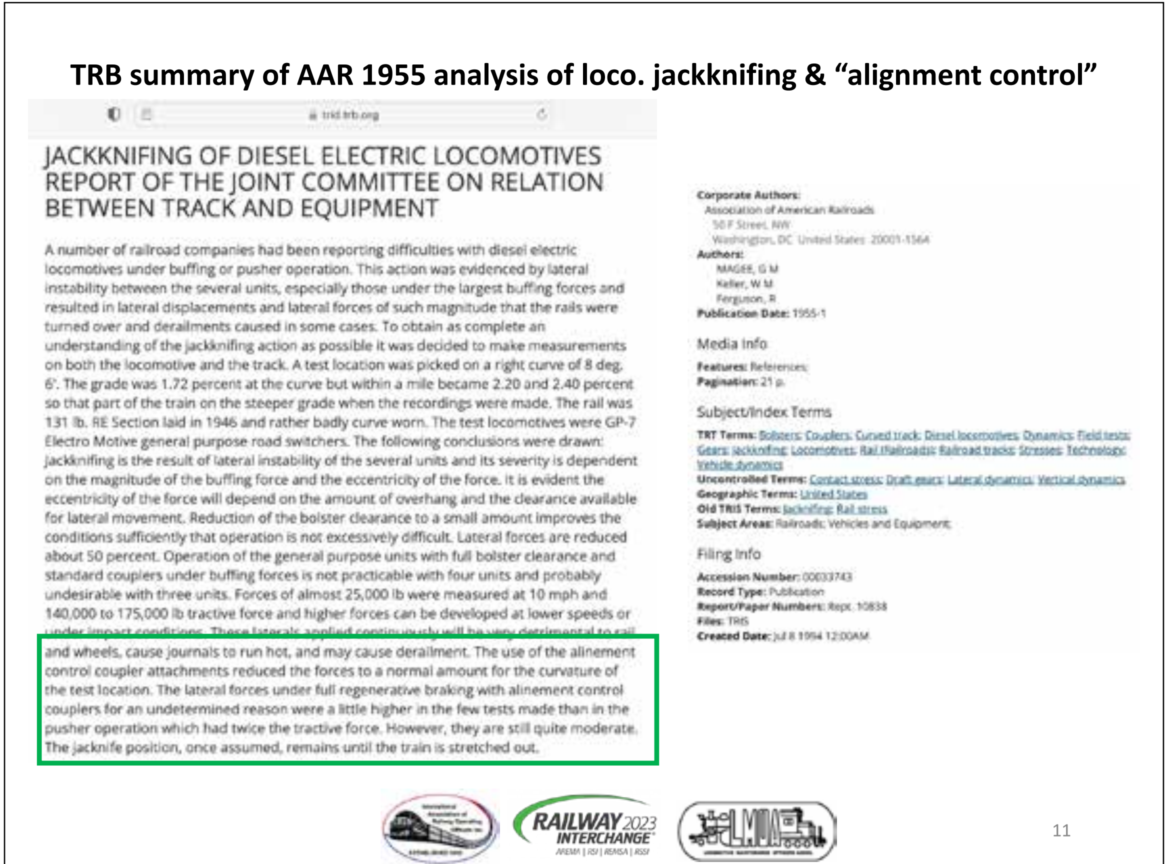
TRB summary of AAR 1955 analysis of loco. jackknifing & "alignment control"
trid.trb.org
JACKKNIFING OF DIESEL ELECTRIC LOCOMOTIVES REPORT OF THE JOINT COMMITTEE ON RELATION BETWEEN TRACK AND EQUIPMENT
A number of railroad companies had been reporting difficulties with diesel electric locomotives under buffing or pusher operation. This action was evidenced by lateral instability between the several units, especially those under the largest buffing forces and resulted in lateral displacements and lateral forces of such magnitude that the rails were turned over and derailments caused in some cases. To obtain as complete an understanding of the jackknifing action as possible it was decided to make measurements on both the locomotive and the track. A test location was picked on a right curve of 8 deg. 6'. The grade was 1.72 percent at the curve but within a mile became 2.20 and 2.40 percent so that part of the train on the steeper grade when the recordings were made. The rail was 131 lb. RE Section laid in 1946 and rather badly curve worn. The test locomotives were GP-7 Electro Motive general purpose road switchers. The following conclusions were drawn: Jackknifing is the result of lateral instability of the several units and its severity is dependent on the magnitude of the buffing force and the eccentricity of the force. It is evident the eccentricity of the force will depend on the amount of overhang and the clearance available for lateral movement. Reduction of the bolster clearance to a small amount improves the conditions sufficiently that operation is not excessively difficult. Lateral forces are reduced about 50 percent. Operation of the general purpose units with full bolster clearance and standard couplers under buffing forces is not practicable with four units and probably undesirable with three units. Forces of almost 25,000 lb were measured at 10 mph and 140,000 to 175,000 lb tractive force and higher forces can be developed at lower speeds or under impact conditions. These laterals applied continuously will be very detrimental to rail and wheels, cause journals to run hot, and may cause derailment. The use of the alinement control coupler attachments reduced the forces to a normal amount for the curvature of the test location. The lateral forces under full regenerative braking with alinement control couplers for an undetermined reason were a little higher in the few tests made than in the pusher operation which had twice the tractive force. However, they are still quite moderate. The jacknife position, once assumed, remains until the train is stretched out.
Corporate Authors:
Association of American Railroads
50 F Street, NW
Washington, DC United States 20001-1564
Authors:
MAGEE, G M
Keller, W M
Ferguson, R
Publication Date: 1955-1
Media Info
Features: References;
Pagination: 21 p.
Subject/Index Terms
TRT Terms: Bolsters; Couplers; Curved track; Diesel locomotives; Dynamics; Field tests; Gears; Jackknifing; Locomotives; Rail (Railroads); Railroad tracks; Stresses; Technology; Vehicle dynamics
Uncontrolled Terms: Contact stress; Draft gears; Lateral dynamics; Vertical dynamics
Geographic Terms: United States
Old TRIS Terms: Jackknifing; Rail stress
Subject Areas: Railroads; Vehicles and Equipment;
Filing Info
Accession Number: 00033743
Record Type: Publication
Report/Paper Numbers: Rept. 10838
Files: TRIS
Created Date: Jul 8 1994 12:00AM
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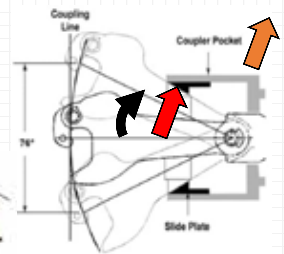
How "alignment control" manages lateral coupler forces

Non-alignment control coupler has 76º of "swing" (38º to each side = 8" to each side)

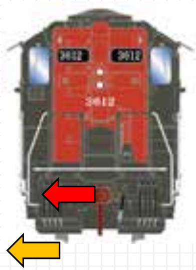


Non-alignment control coupler can swing until it strikes the side of the coupler pocket creating a lateral (sideways) force that will "push" the underframe in that direction, forcing wheel flanges against the rail.

If lateral force is great enough, a wheel climb or rail rollover derailment can occur.

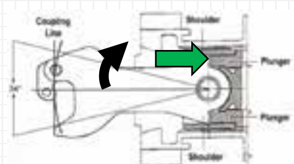
"Stop blocks" do <u>NOT</u> prevent lateral forces, they only limit coupler swing.

Non-alignment control high coupler lateral force *results in high lateral wheel force against rail (risk of wheel climb or rail rollover)*



Non-alignment control coupler has 34º of "swing" (17º to each side = 4" to each side)

Lateral coupler forces are minimized reducing risk of wheel climb or rail rollover



Alignment control coupler has ~half the allowable swing and can never strike side of coupler pocket.

This prevents most lateral force by redirecting the force into the alignment control draft gear (and the locomotive underframe).

Drawings reproduced from TSB Canada accident report R05C0082 (2005)

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Non-alignment control loco. derailments

NS
Anniston, AL
March 9, 2023

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"Jackknife" derailments, non-alignment control locomotives: 1992-2010

July 26, 1992 — FRA acc. report — UP — Evanston, WY — **3 SD60** w/ **5 waybill F59PH DIC** & 92 cars
Train in DB descending grade 25mph thru a $3^o40'$ curve
Non-equipped 3rd, 4th & 5th F59's derailed + 17 freight cars derailed

Oct. 31, 1999 — FRA acc. Report — ARR — Canyon, AK — **3 GP40-2** w/ **2 DIC MP15** & 46 cars (5,477 tons)
Train in DB
Non-equipped 2 MP15s derailed + 10 cars (HZM, jet fuel spill)

July 8, 2002 — TSB Canada report — CN — Camrose, AB — **3 SD60-70-75** w/ **2 DIC GP9** & 150 cars (17,201 tons)
Train in DB descending 0.7% grade to a 6^o curve
Non-equipped 2nd of 2 GP9s derailed + 26 cars derailed

May 27, 2005 — TSB Canada report — CP — Bowden, AB — **2 AC4400** w/ **2 DIC GP9** & 77 cars (4,512 tons)
Train in full DB at work zone, then into power and accelerated
Non-equipped 2 GP9s derailed + 24 cars derailed

February 2010 — FRA acc. report — CSX — LaGrange, GA — **2 AC4400** & **5 waybill SW1500** + unknown train
Unknown train handling
Non-equipped 5 SW1500 derailed + unknown cars derailed

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"Jackknife" derailments, non-alignment control locomotives: 2010-2023

March 30, 2010 TSB Canada report	CN	Pickering, ON	**3 SD70** w/ **4 waybill F59PH** & 149 cars (12,166 tons) **Med-to-full DB decelerating and approaching a crossover** **Non-equipped 4 F59PHs derailed** + 11 cars derailed
2015-16 Personal inspection	UP	Nelson, IL (?)	**2 SD9043AC** w/ **1 DIC MP15DC** & train **Train in DB through mainline crossover** **Non-equipped MP15DC derailed** + unknown number cars derailed
March 7, 2018 FRA acc. report	CSX	Sherwood, TN	**2 AC** w/ **2 DIC F40PHM** & 177 cars (14,837 tons) **Train in DB descending mountain grade** **Non-equipped 2 F40PHM** & 13 cars derailed (**1 F40PHM destroyed**)
March 9, 2023 NTSB report CNN video	NS	Anniston, AL	**2 AC + 2 DC** w/ **2 waybill GP9** & 106 cars **Train in DB descending grade exiting a curve** **Non-equipped both GP9s derailed** & 29 cars (+8 cars @ rear) derailed

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Non-equipped waybilled SW1500s derailed, LaGrange, GA, 2010
5 waybilled SW1500s moving E. St. Louis to Patterson, GA behind a pair of AC locomotives … jackknifed in curve
Note damage
1511
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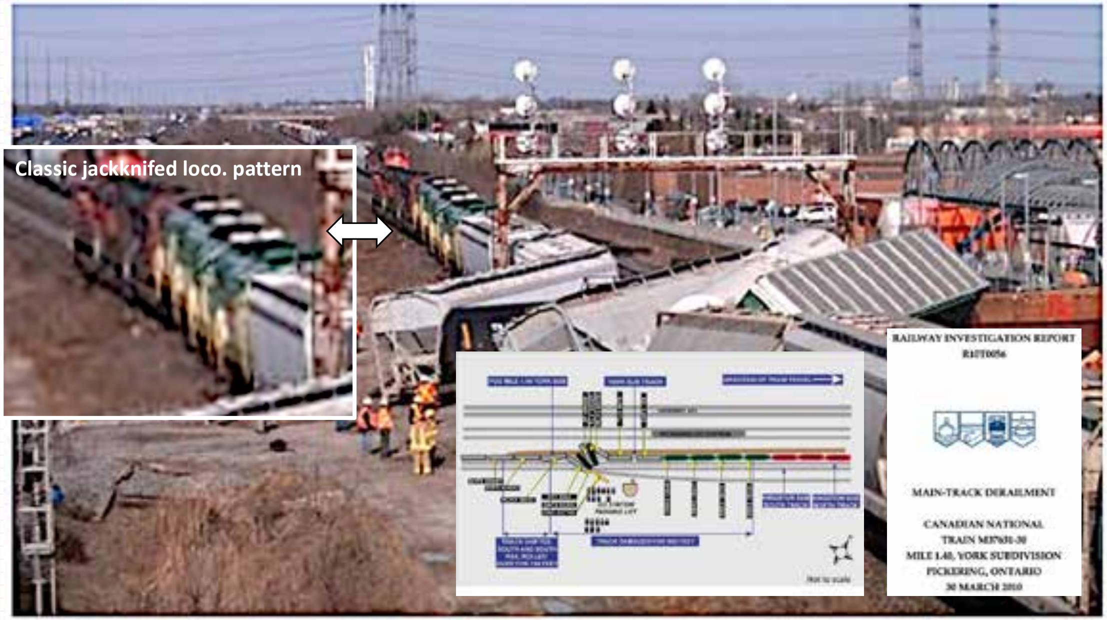
Non-equipped F59PHs, CN, Pickering, ON, March 30, 2010



The derailment on CN's rail line near the Pickering GO station on Tuesday, March 30, 2010 left a jumbled mess of cars. (Rob McDonell / MyNews.CTV.ca)

Non-alignment control F40PHM destroyed, Sherwood, TN 3-07-2018

Non-equipped GP9s, NS, Anniston, AL, March 9, 2023

Images copied from:
https://www.youtube.com/watch?v=jl9ut7LThuc

One or both GP9 had previously been incorrectly coded in Umler File as being "alignment control equipped"

UP AC	UP AC	NS SD60M	NS SD60M	***GP9 DIC***	***GP9 DIC***	108 car train

Dynamic Brakes operative & applied (UP AC, UP AC, NS SD60M)

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Special issues w/ Passenger & Commuter locos.

- Passenger and commuter locos. typically operate “outside” freight operations
- But they occasionally are transported (waybilled), relocated by freight RRs
- New PRIIA-spec. passenger locos. have Crash Energy Management pushback couplers with no alignment control cpability


Passenger & Commuter locos. w/o alignment control
PRIIA psgr. "pushback" coupler w/o alignment control
Visual clue: Coupler is "swung" >4" to extreme side of pocket.
Commuter loco. Type F coupler w/o alignment control
Visual clue: Coupler is "swung" >4" to extreme side of pocket.
Pin-connected shank with NO alignment control functionality
F coupler head
"Shear tube" w/ 9" crush length
https://www.dellner.com/products/automatic-couplers/automatic-coupler-type-aar-pushback
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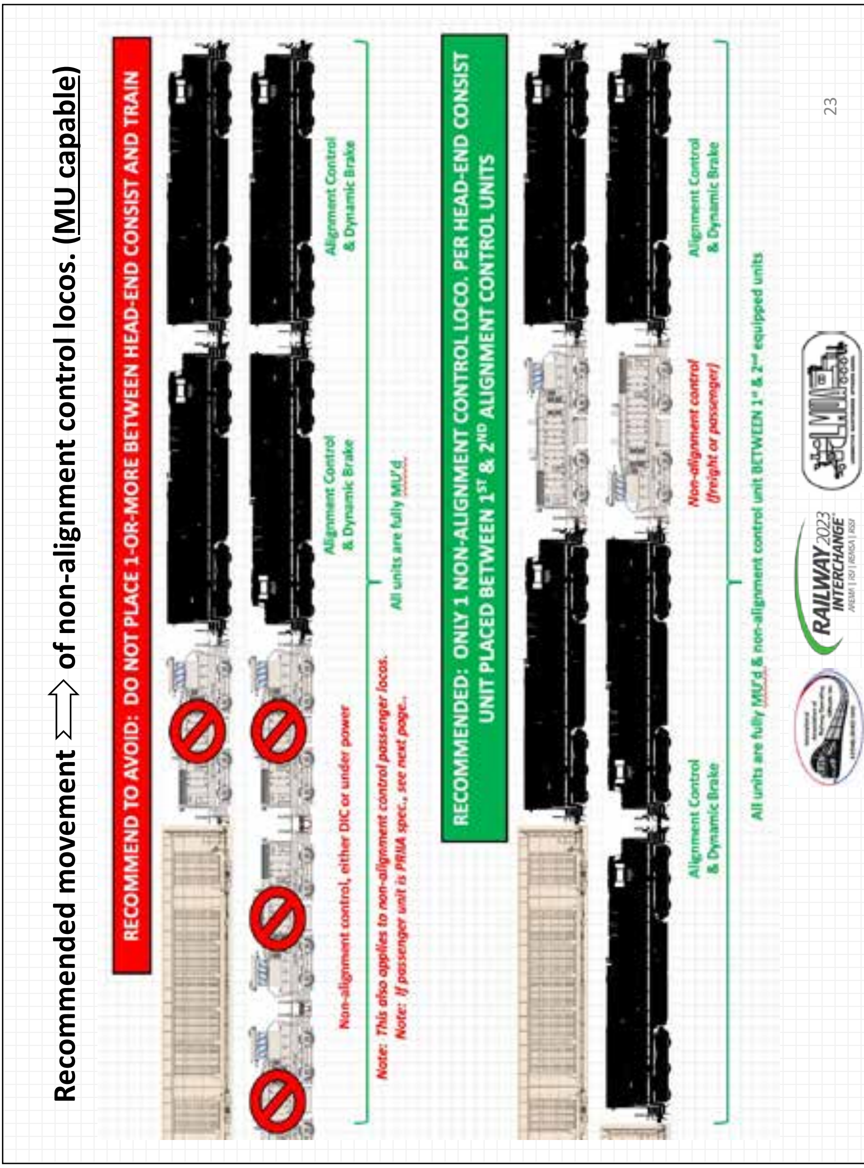
Shipment of a commuter locomotive with (temporary) alignment control coupler

Placard decal above coupler (both ends) reading "SELF ALIGNING COUPLER-MPEX"

… providing advise to any RR personnel handling the waybilled locomotive that it has alignment control

If customer did not want alignment control, MPI-Boise would replace on arrival at customer


Recommended movement ⟹ of non-alignment control locos. (MU capable)
RECOMMEND TO AVOID: DO NOT PLACE 1-OR-MORE BETWEEN HEAD-END CONSIST AND TRAIN
Non-alignment control, either DIC or under power
Alignment Control & Dynamic Brake
Alignment Control & Dynamic Brake
Note: This also applies to non-alignment control passenger locos.
Note: If passenger unit is PRIIA spec., see next page..
All units are fully MU'd
RECOMMENDED: ONLY 1 NON-ALIGNMENT CONTROL LOCO. PER HEAD-END CONSIST UNIT PLACED BETWEEN 1ST & 2ND ALIGNMENT CONTROL UNITS
Alignment Control & Dynamic Brake
Non-alignment control (freight or passenger)
Alignment Control & Dynamic Brake
All units are fully MU'd & non-alignment control unit BETWEEN 1st & 2nd equipped units
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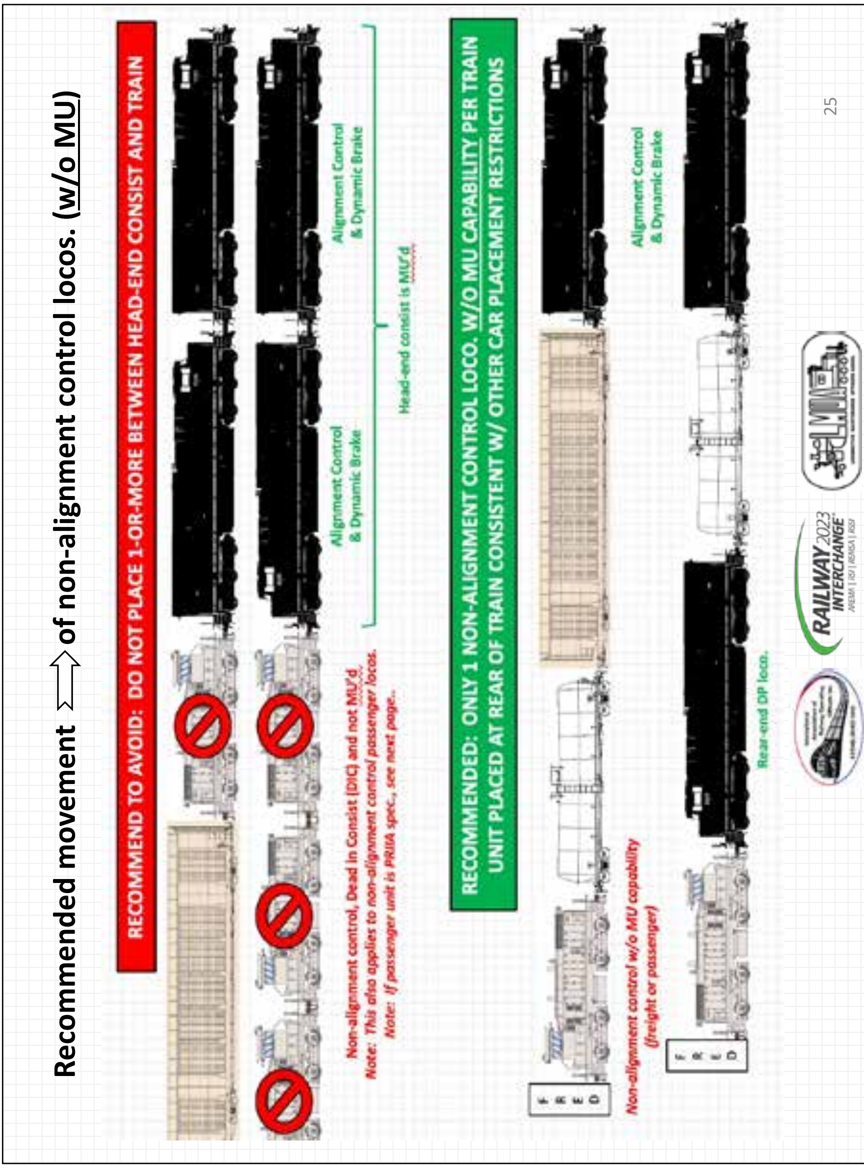
Handling non-alignment control switchers on UP, 2002 (“by the Rule”)



Recommended movement ⟹ of non-alignment control locos. (w/o MU)
RECOMMEND TO AVOID: DO NOT PLACE 1-OR-MORE BETWEEN HEAD-END CONSIST AND TRAIN
Alignment Control & Dynamic Brake
Alignment Control & Dynamic Brake
Head-end consist is MU'd
Non-alignment control, Dead in Consist (DIC) and not MU'd
Note: This also applies to non-alignment control passenger locos.
Note: If passenger unit is PRIIA spec., see next page..
RECOMMENDED: ONLY 1 NON-ALIGNMENT CONTROL LOCO. W/O MU CAPABILITY PER TRAIN
UNIT PLACED AT REAR OF TRAIN CONSISTENT W/ OTHER CAR PLACEMENT RESTRICTIONS
Alignment Control & Dynamic Brake
Rear-end DP loco.
Non-alignment control w/o MU capability (freight or passenger)
FRED
FRED
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Recommended movement ⟹ of PRIIA pushback coupler locos.
RECOMMEND TO AVOID: DO NOT PLACE 1-OR-MORE BEHIND HEAD-END CONSIST AND TRAIN
PRIIA passenger loco. w/ Pushback Couplers
Alignment Control & Dynamic Brake
Alignment Control & Dynamic Brake
1-OR-MORE PRIIA PUSHBACK COUPLER PASSENGER LOCOS. MOVED AS A SPECIAL TRAIN WITH NO TRAILING FREIGHT TONNAGE
F R E D
NO trailing freight tonnage
1-or-more PRIIA passenger loco(s). w/ Pushback Couplers
Alignment Control & Dynamic Brake
All units are fully MU'd
CAUTION: If PRIIA locos. are set-up DIC, brakes will not bail off on long descending grades!
Risk of braking discs overheating causing wheels to loosen, shift inward on axle
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What can be done to eliminate derailment of nonalignment control locos?

- Future new freight locomotives should all have alignment control as defined below
- Existing "legacy" locomotives w/o alignment control will likely continue to exist
  - *Occasional movement (waybill or other) of legacy locomotives will happen*
  - *RRs moving legacy locomotives must have proper instructions*
- Suggest AAR Locomotive Committee create a Standard(s):
  - *Defining alignment control: 380/381/390/391 draft gear w/ "winged" couplers*
  - *Create & require application of "non-alignment equipped" placard as needed*
- Suggest AAR Op. Practices Committee develop consensus requirements for how legacy locomotives w/o alignment control are transported
  - *Have all Class 1 RRs move/transport non-alignment control locos. Consistently*
- *AAR Railinc Umler Equipment File needs new definition of "alignment control" and must be be checked for how locomotives are coded in field B008*
- Jointly discussed with AAR Loco. and Op. Practices Committees on June 20, 2023 (update by October?)

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Future Fuels Review

Prepared by:
Michael Cleveland, Progress Rail
Eric Dillen, Wabtec
Jerainne Heywood, Wabtec
Steve Fritz, Southwest Research Institute
John Hedrick, Southwest Research Institute
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Abstract

Investigation into low or zero carbon fuels is driven strongly by the railroad's commitments to carbon reduction (SBTI), regulations, and funding incentives. Five candidate fuels were summarized and reviewed for their applicability to locomotive service in reaching carbon reduction goals. These alternative fuels and technologies include battery electric, hydrogen, methanol, ammonia, and natural gas. Several key properties such as energy density and combustion properties were compared and discussed for each fuel type and alternative technology. Additionally, operational impacts such as infrastructure, storage, and refueling were also considered. Our comparative analysis revealed that the different use cases and considerations will drive the adoption of different low carbon fuels; there are no clear cut fuel or technology winners to assist the rail industry in attaining zero emissions; the transitions to adapt to the use of different fuel types will be slow and varied, predominantly driven by regulations and incentives; the rail industry is currently focused on demonstrations to understand and optimize these future technologies.

Introduction

All North American Class I railroads have adopted the Science Based Targets Initiative (SBTi) [1] [see definition below] target standards to address climate change within the next decade (Table 1). The target averages are above 30% Greenhouse Gas (GHG) reduction for all Class I Railroads to support a well-below 2ºC near term target. Additionally, the Federal Railroad Administration (FRA) has instituted a goal of net-zero GHG emission by 2050 [2]. Meeting these goals may require complete independence from fossil fuels. This paper aims to investigate some of the most promising technologies that can be utilized to achieve these sustainable goals.

Railroad	Target
Canadian National	43% cut in GHG emissions intensity by 2030
CSX	37% GHG intensity reduction by 2030
Norfolk Southern	42% GHG intensity reduction by 2034
BNSF	30% GHG absolute reduction by 2030
CPKC	37% GHG intensity reduction by 2030
UP	26% GHG absolute reduction by 2030

Table 1. Class 1 Railroads current GHG emissions goals for the next decade

There are many paths forward and each has its own strengths and weaknesses. The two most prevalent technologies are biofuels and electrification. The use of biofuels in the rail industry has increased markedly in the past 10 years. Predictions are that biofuels will increasingly be used, that research and development will continue. and that for the near future, they will be an important part of decarbonizing the rail industry. The LMOA has investigated biofuels extensively and has reported its findings in other papers [1]. Therefore, biofuels will not be addressed here.

Another path forward is electrification. The US's rail electrification effort is miniscule in comparison to Europe, India, and China. A major hurdle for electrification is the amount of capital needed for infrastructure. Cost estimates range between $1 million to $3.5 million per mile to install a catenary system. Additional costs include replacing the fleet with new electric locomotives. The AAR has published a fact sheet entitled: "*Oppose Rail Electrification & Support Sensible Climate Policy*", which provides reasoning as to why nation-wide electrification is not the most feasible path forward to achieve sustainability goals. At this point electrification appears to be an unpopular and expensive option for North American Railroads.

The following technologies will be explored as possible solutions for carbon reduction in the railroad industry: Battery Electric, Hydrogen, Methanol, Ammonia and Natural Gas. Although natural gas is a fossil fuel technology, utilizing this fuel has been included in this assessment because of its lower GHG emissions vs. diesel. Natural gas locomotives are proven, currently in commercial use, and can be a viable strategy for railroads to meet their short term GHG reduction goals.

Battery Electric, Hydrogen, Methanol, and Ammonia are considered net- or near net-zero technologies. They have been proven to significantly reduce carbon-based emissions in light duty applications but will require further research and development to be used in line-haul rail applications.

Transition to the use of these alternative fuel solutions will require a mixed strategy. Using existing technologies such as biofuels and natural gas, can contribute to meeting the near-term goals as stated in Table 1. Further development of the other technologies being investigated will be required to meet the zero emission goals, and the FRA and DOE are currently funding trials to develop them.

Future Fuels Review

Battery Electric

Battery technology has rapidly improved over the last two decades – largely around energy density, cycle life, and cost. This has presented new technologies across consumer and industrial technologies from cell phones to electrical grid scale energy systems and electric vehicles. While somewhat new in the modern rail industry, batteries for heavy haul freight and passenger locomotives show considerable promise.

Unlike other fuels considered in this paper, batteries are not quite a "fuel". Instead, they are best known as a chemical storage mechanism for electricity, which is the actual "fuel" in the system. Batteries are available in a wide variety of primary (non-rechargeable) and secondary (rechargeable) chemistries. This paper focuses on the recent revolution driven by Lithium-ion batteries that has allowed batteries to be a viable prime mover technology. Lithium-ion batteries represent a broad category of chemistries with varying properties and suitability and is a topic of academic discussions. For this purpose, the following diagram is sufficient.

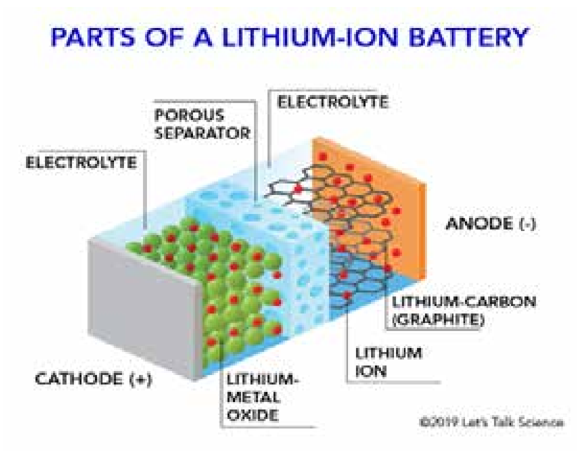


Figure 1: Components of a Lithium-ion battery

By applying a voltage to the battery, lithium ions are driven toward the anode, which stores energy in the form of chemical potential energy. When energy is required, a load can be applied, and the flow of lithium ions to the cathode induces a current. Thus, lithium-ion batteries are rechargeable and can be used for dynamic brake recapture, enabling regenerative braking. Lithium-ion batteries provide a high-power output with higher energy density compared to other battery varieties. However, this energy density is significantly less than many other fuels and therefore either limit their applicability or require hybrid architecture to match the performance of diesel-powered locomotives.

Batteries may be used in a variety of architectures on locomotives. The diagram below shows some of the existing or proposed concepts and drivers for the architecture choice.

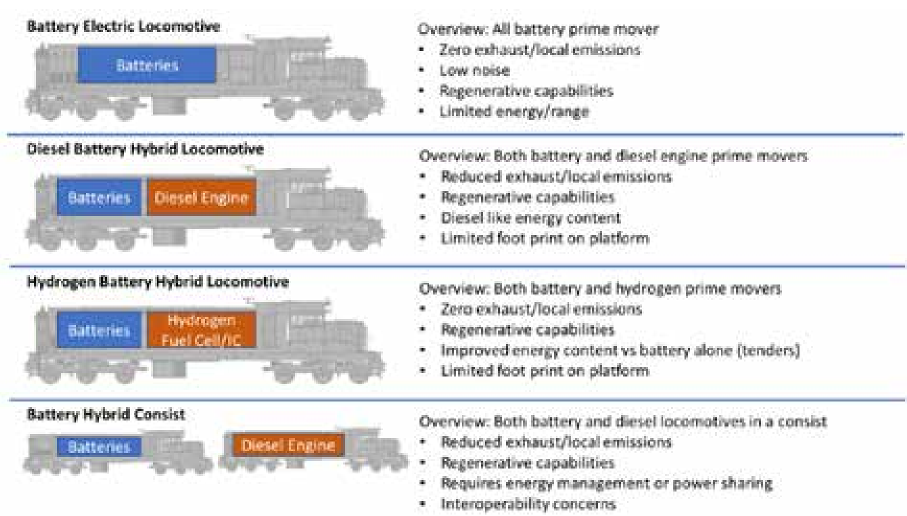


Figure 2: Locomotive architecture choices for existing and proposed battery concepts

Battery electric and hybrid locomotives have several advantages over diesel locomotives. The emissions for a battery electric or hybrid locomotive are reduced or eliminated locally. As with all alternative fuels, a "wells to wheels" analysis can show the true benefits of an alternative fueled vehicle. The national average carbon reductions by switching to all electrics can be as high as 80% versus traditional vehicles. Noise is also significantly reduced, which positively impacts the working/living environment of employees and surrounding communities. The ability of batteries to be recharged allows dynamic braking energy to be recaptured, therefore offsetting the total amount of energy required or displacing diesel fuel. The reduction of moving parts and shift toward high reliability battery systems can greatly reduce maintenance time, effort, and costs while improving availability. If the charging infrastructure is appropriately designed and integrated to the operation, downtime for fueling and regular service can be greatly reduced.

Battery electric locomotives (100% battery prime movers) provide local exhaust emissions elimination, low noise, lower fuel, and maintenance costs when compared to a diesel only locomotive. However, they are not without fault. Since batteries hold significantly less energy than diesel on a volumetric basis, care needs to be taken to ensure the battery on the locomotive is sized correctly for the intended application. To determine suitability for a particular application, a thorough energy analysis of the intended service should be completed. This can be done by analyzing the current locomotives in the operation and/or by simulating the operation to determine required battery size. Additionally, this analysis will inform the opportunities and requirements for recharging the locomotive.

Charging infrastructure likely represents the most significant challenge for battery electric locomotives. Due to the size of the batteries (up to 14.5MWh) for locomotive applications, the charging power can be quite significant, requiring electrical distribution upgrades. There is currently no consensus or standard around battery electric locomotives, with each OEM providing their own solutions. An AAR Locomotive Charging Interface Standard Task Force recently sunset without generating a standard due to a lack of consensus and limited need in the market (April 2023). While this makes interoperable deployments challenging, captured service locomotives, such as switchers and regional units, make an appealing use case.

Hybrid consists and locomotives resolve many of the infrastructure and energy limitations of pure battery electric locomotives by using a diesel engine to bridge the energy gap. While not a zero-exhaust emissions technology, through using recaptured energy in the batteries and external charging, diesel fuel displaced can be as high as 50%, depending on the route or application. When coupled with other technologies, such as bio/renewable diesel or hydrogen fuel cells, this approach has the potential for large carbon reductions.

Battery electric and hybrid locomotives can fill a variety of locomotive applications from switching to heavy haul mainline freight applications. Due to their limited energy storage capabilities, battery electric locomotives are particularly well suited for applications where charging is readily available, such as yard, switching, hump and commuter services. When combined with other diesel locomotives in a hybrid consist, they can extend their services into regional applications. Hybrid locomotives have fewer limitations and are ideally suited for mainline applications with high dynamic brake usage and services where recharging infrastructure is infeasible.

While at the turn of the 20th century, railroads were dotted with low power battery electric locomotives, battery electric and hybrid locomotives are new in the modern era. The most notable examples were the RailPower GG20Bs, with

55 total 2000HP units produced starting in 2004. In 2007, NS produced the NS 999, a 100% battery electric locomotive using lead acid batteries and producing 1.1MW of power; the unit was used in switching tests [3]. The unit was purchased by Rail Propulsion systems in 2019 and moved to Los Angeles, CA [4]. In 2021, Wabtec demonstrated the first FLXDrive locomotive with BNSF in California. This 2.4MWHh battery electric locomotive operated with two Tier 4 locomotives in a hybrid consist mode between Barstow and Stockton, California, and reduced fuel consumption by at least 10% [5]. In 2020, Progress Rail produced their first battery electric locomotive, the EMD® Joule GT38JC, for Vale in Brazil. This 2.1MW & 1.9MWh (later upgraded to 2.4MWh for hybrid consist demonstration) locomotive is used in iron ore unloading operations at Vale's Vitória port. _[6] Progress Rail released their next Joule locomotive, the SD40JR, for the Pacific Harbor Line in 2023 [7]. This 2.1MW locomotive with 2.4MWh of energy storage uses a rebuilt SD40-2 frame and is being used at the Ports of LA and Long Beach in Los Angeles in switching service. Additionally in 2023, Progress Rail has supplied two GT38H hybrid diesel and battery locomotives to Rumo in Brazil. [8] Clayton in Britain has built class 18 hybrid+ CBD90 shunting locomotives for a trial with GB Rail Freight [9]. CRRC has also produced battery electric shunting locomotives for Hungary [10]. At the time of writing, several other battery and hybrid locomotives have been announced but not yet demonstrated.

Hydrogen

<u>Fuel Cell vs. IC Engine</u>

At the time of this report, no detailed information could be found in the public domain discussing H2 fueled IC engine technology designed for rail application (IC engine >1,500 HP). However, all the engine OEM's that work closely with the rail industry appear to be working on H2 projects (Figure 3).

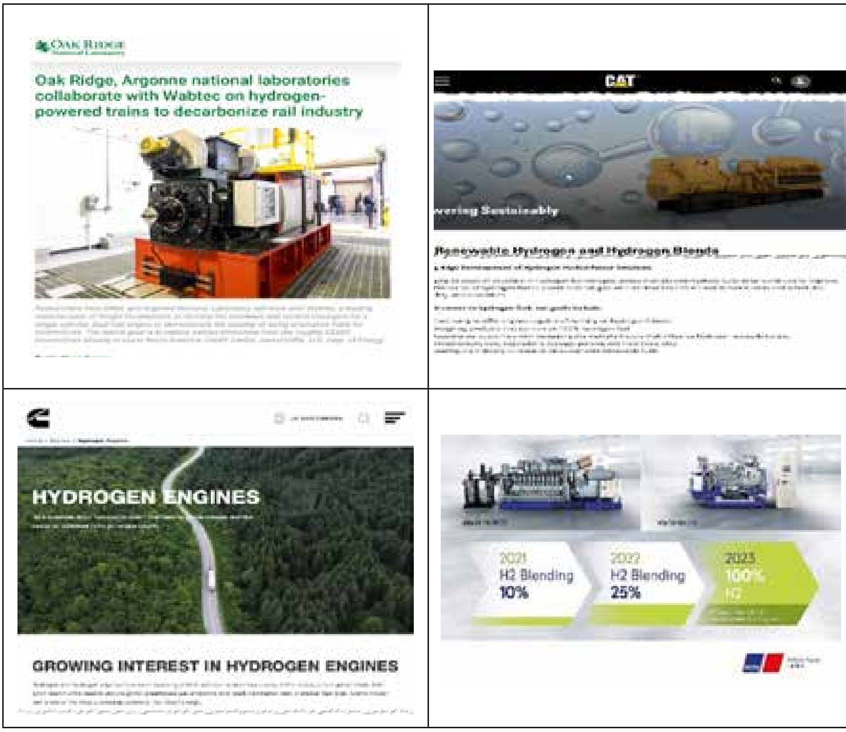
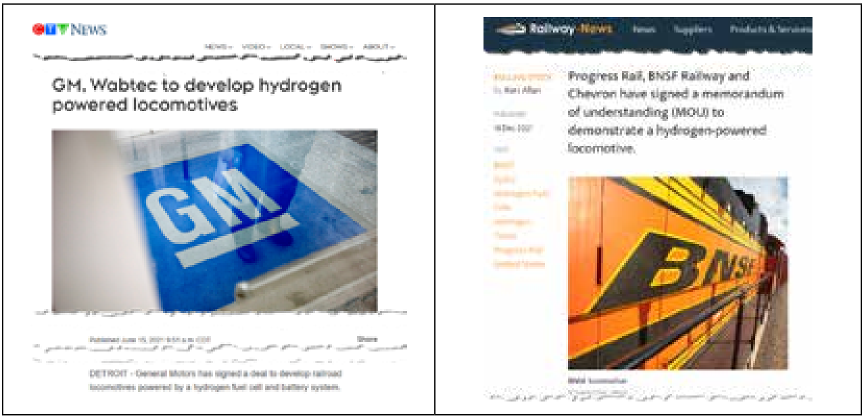


Figure 3: Engine OEM's showing interest in H2 fueled IC engine [11], [12], [13], [14]

There are published news reports stating that both US freight locomotive OEMs are working on H_2 Fuel Cell (FC) powered locomotive projects. However, Figure 4 suggests these FC locomotive designs are early in the development process.


GM, Wabtec to develop hydrogen powered locomotives

DETROIT - General Motors has signed a deal to develop railroad locomotives powered by a hydrogen fuel cell and battery system.

Railway-News

Progress Rail, BNSF Railway and Chevron have signed a memorandum of understanding (MOU) to demonstrate a hydrogen-powered locomotive.

Figure 4: Locomotive OEM's Working on H2 FC Powered Locomotives

Supporting Infrastructure Needed for H2

Figure 5 shows a LH2 system that was installed in late 2022. This system has a 17,500-gallon cryogenic tank with a LH2 capacity of ~4,650 Kg or ~4,170 Diesel Gallon Equivalents (DGE) of energy. This installation represents >$3,000,000 USD investment and provides CH_2 to various test cells supporting IC engine and fuel cell development. Because this system provides CH_2, a LH_2 fueling system for a locomotive would not require the high-pressure cryogenic pumps or vaporizers but would require a high volume / low pressure pump(s) or pressure differential system to transfer LH2 to an on-board cryogenic fuel tank.

Figure 5: LH2 Fueling System

Justification for this investment was based on the difference in the price between CH_2 and LH_2, expected H_2 consumption rate, and the cost of potential for project delays if CH_2 was not delivered daily. In late 2021, CH_2 delivered to San Antonio Texas cost ~$36/Kg or over $40 DGE. This cost does not include the cost of managing delivery of tube trailers with <250 DGE of energy (daily - out of Houston). At this same time, LH_2 cost was ~$10/Kg or just over $11 DGE) delivered to San Antonio, Texas.

Ideal Use - A Case Study

Sandia National Lab produced a report in H_2@RailSM Workshop (SAND2019-10191 R) in August 2019 that analyzed the use of H_2 in freight, passenger, and switcher locomotives. A high-level overview of their report reveals the following:

Freight locomotives:

The initial capital cost of a H_2 FC powered locomotive will be over 30% higher than a conventional diesel fueled locomotive (plus infrastructure) and will require a LH_2 tender to carry enough LH_2 to make a H_2 fueled freight locomotive viable. A FC powered freight locomotive should have ~30% higher efficiency on an EPA freight duty cycle, but the break-even cost of delivered LH_2 would need to be less than $2.20/kg (August 2019 $'s). This study likely does not include loss of revenue rail car in the train due to the addition of a tender or added cost of the infrastructure at the fueling facilities [15].

Regional commuter / passenger locomotives:

For this application, LH_2 is desirable in hopes that enough LH_2 can be stored on locomotives eliminating the need for a tender to carry the H_2 fuel. For this application, the FCs are projected to have ~37% higher efficiency on representative regional duty cycle, and the break-even LH_2 cost would be under $3.50/kg (August 2019 $'s). However, this break-even calculation does not appear to include the cost of the fueling infrastructure and the report offered no discussion on the increased cost of the locomotive [15].

Switchers & Industry locomotives:

FCs could be an attractive option for a switcher application. This application could use CH_2, preferably pressurized to ~5,150 PSI (350 bar), and the CH_2 could be stored on a CH_2 tender that could also be used as a traction slug. If the slug is not an attractive option, it is possible that LH_2 could be used with on-board cryogenic fuel tanks. These decisions will be dependent on the range of the switcher, actual duty cycle, and the desired refill interval. The report suggests that the FC powered switcher would have ~77% higher efficiency over EPA Switcher duty cycle. This is the most attractive application for H_2 fueled locomotives, but it is also likely an excellent application for BEL. This application would also need expensive infrastructure to fuel the H_2 fueled switcher, or truck delivery to fuel the locomotive [15].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Examples of H_2 Fueled Locomotives

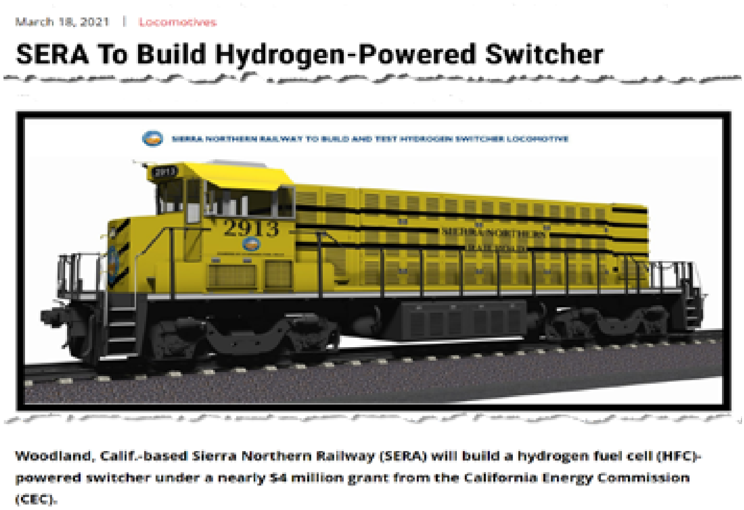
BNSF1205 was the first FC powered switcher in the United States and was used in a demonstration in ~2009. This unit was originally a Railpower GG20B "Green Goat" and was last seen at BNSF's Galveston TX Yard waiting to be scrapped, shown in Figure 6 with the car body essentially gutted of any FCl-related systems.

Figure 6: BNSF1205 in Galveston Texas

Stadler was contracted by San Bernardino County Transportation Authority (SBCTA) to build FC passenger locomotives and a conceptual drawing of the unit is shown in Figure 7. These demonstration units will be used for SBCTA's passenger service.

Figure 7: Conceptual Drawing of Stadler's Passenger locomotive for Service in SBCTA's System

Sierra Northern Railway (SERA) won a ~$4,000,000 grant from California Energy Commission to build a H_2 FC powered switcher and is shown in Figure 8.


March 18, 2021 | Locomotives

SERA To Build Hydrogen-Powered Switcher

Woodland, Calif.-based Sierra Northern Railway (SERA) will build a hydrogen fuel cell (HFC)-powered switcher under a nearly $4 million grant from the California Energy Commission (CEC).

Figure 8: Article on SERA H_2 powered Switcher

China has a Switcher that operates on H2 FC's shown in Figure 9.

Figure 9: GLOBALink I China's first hydrogen fuel cell hybrid locomotive starts trial run

South Korea has been working on a FC powered passenger locomotive that is designed to operate at ~70 MPH (110 km/Hr) and will be powered by a 1.2 MW FC system as shown in Figure 10. Initial projections suggest that it will have less than a 100-mile range (600 km) and will use batteries used to capture braking energy. The rest of Europe has several H2 passenger locomotive projects in progress.

Figure 10: Korean Hydrogen Fuel Cell Powered Train Project

Methanol and Ammonia

In addition to hydrogen, there are two low or no carbon fuels that are capable of being utilized in the existing diesel engine fleet, ammonia (NH_3) and methanol (CH_3-OH). Both fuels are considered the most promising "clean" fuels of the future for the shipping industry and will be looked at closely for locomotive applications as well. The intent of this comparison is to look at the two fuels and their potential utilization in locomotive applications.

The quickest way to introduce a new fuel for rail usage is by adapting the existing diesel engines to run on a combination of diesel fuel and a secondary alternate fuel, a dual fuel application. Dual fuel engines can be designed to run on 100% diesel fuel as well as varying percentages of diesel and the alternate fuel. This will allow the railroads the flexibility to transition to alternate fuels as the infrastructure for the alternate fuel is put in place.

The diesel fuel is used as the ignition source during dual fuel operation while the alternative fuel can be injected either in the cylinder intake or directly into the cylinder. This dual fuel architecture can have a wide range of the substitution rate of the alternative fuel depending on the fuel itself, engine architecture, alternative fuel injection method, and engine operating conditions.

Fuel Properties:

Both ammonia and methanol have significantly less energy per unit volume than diesel fuel (Figure 11) but can be transported as a liquid without the need for thermal containers that liquid hydrogen and liquid natural gas require. Ammonia needs to be at a pressure of at least 140 PSI to remain in a liquid state at normal ambient temperatures where methanol is a liquid at typical ambient temperatures and pressures.

Ammonia has a high autoignition temperature and requires a significant amount of energy to ignite which may limit the amount of ammonia that can be substituted for diesel. Ammonia is already transported by rail but additional handling and safety considerations (i.e.: material selection in the fuel supply and storage system will be required when it is used as a fuel due to its toxicity. The toxicity of ammonia may also lead to a need for exhaust aftertreatment to clean up any ammonia slip out the exhaust stack.

Methanol has a lower autoignition temperature and requires significantly less energy to ignite than ammonia. Methanol does burn hotter than diesel and that will require special engine design considerations. Methanol is easier to transport and can be stored in standard fuel tanks but requires attention to detail when selecting materials for the fuel system plumbing and fuel storage tank.

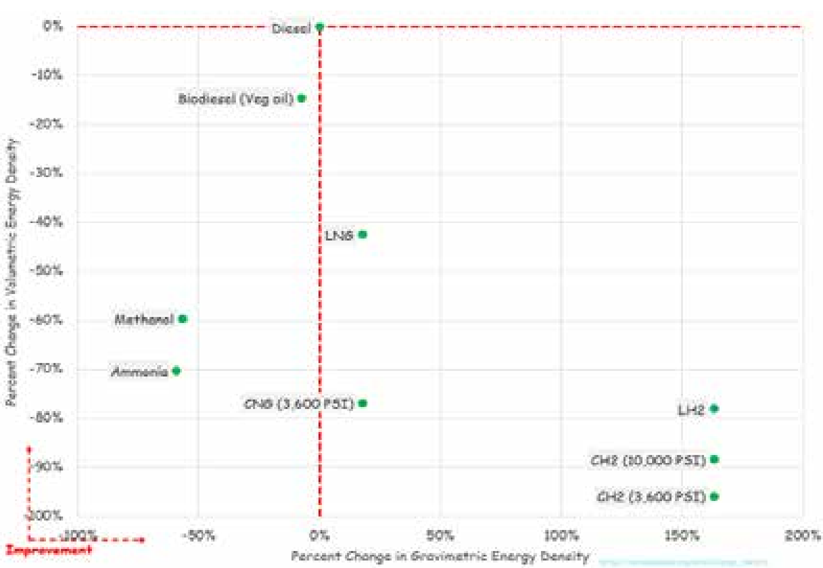


Figure 11: Plot of Energy Density of Different Fuel Types

Fuel Injection:

There are three types of injection technologies that can be used for the alternate fuels in dual fuel applications.

Port Fuel Injection (PFI) – Fuel is injected in the intake port during the intake stroke. The fuel can be at a relatively low pressure of around 120 psig. The standard diesel injector is used, and 100% diesel capability is maintained.

Low Pressure Direct Injection (LPDI) – Typical arrangement has a second injector mounted in the cylinder head and injects fuel directly into the combustion chamber. Fuel can be injected during the intake stroke and during the early stages of the compression stroke. As the name implies, the fuel will be at relatively low pressure, 120 to 200 psig. The standard diesel injector is used, and 100% diesel capability is maintained.

High Pressure Direct Injection (HPDI) – This arrangement also mounts a second injector in the head and injects fuel directly into the combustion chamber. Fuel is injected at the end of the compression stroke and during the expansion stroke (during combustion) and thus needs to be at a much higher pressure to overcome cylinder pressures of over 3000 psig. The fuel will be injected at 5000 – 7000 psig. The size of the diesel injector may be reduced, and full diesel capability will not be possible.

	Ammonia	Methanol
Ignitability	Difficult	Moderate
EHS	Toxic, corrosive	Similar to diesel fuel
Storage/Transport	-34 C or 10 bar	Ambient temp/press
GHG emissions	None	Yes, low vs. diesel
Injection Technology	PFI, LPDI, HPDI	LPDI, HPDI
Storage/Transport	Ambient temp./150 psig	Ambient temp./press.
Aftertreatment	Needed for ammonia slip	NA

Table 2: Comparison of Ammonia and Methanol

Natural Gas

Natural gas is a flammable gaseous fuel common around the world. It is primarily made up of methane with other constituents like ethane, propane, butane, etc. It has a long history of use in transportation applications with buses, trucks, ships, and even passenger vehicles using it as a primary fuel. While applications in rail have been limited, it has seen some success and limited adoption. When used as a transportation fuel, it is either compressed or liquified by cooling it below its vaporization point of -260F. When compressed natural gas (CNG) is used, it is stored in steel or fiber wrapped high pressure tanks typically at ~3,600 psi. When liquified natural gas (LNG) is used, it is stored in double walled vacuum insulated tanks at low pressures (<<150psi). While the different forms of natural gas storage have different energy densities, the storage tank design differences and overall impact on the whole storage package should be considered, as total system differences may erase any advantage the energy density differences between the options.

Natural gas distribution infrastructure is robust in much of the world, particularly North America, with the fuel readily available in significant quantities at many industrial sites, including rail yards. However, to be used in transportation applications, specialized and potentially costly compression, liquification, and dispensing equipment must be added. In the case of CNG, compressors are required to boost the pressures from ~200-1500psi [16] to the required ~3,600psi. For LNG, the gas must be cooled to cryogenic temperatures through a series of turbo expanders and heat exchangers.

Given its flexibility and availability as a transportation fuel, natural gas has been tested in all major locomotive applications in North America (excluding passenger service, though not for any known technical limitations) on trial basis and limited deployments. In the late 1980s through mid-1990s, several railroads including Union Pacific and Burlington Northern tested LNG in a variety of applications. From 2013 to 2017, natural gas experienced a renaissance of interest and development in North American freight service with several Class 1s conducting revenue service linehaul demonstrations [16], [17], and [18]. These programs largely wrapped up in 2017 when the price of diesel fell, making the cost of conversion not economically favorable. However, Florida East Coast Railway and Ferromex (both Grupo Mexico companies) operate approximately 50 Wabtec NextFuel converted ES44AC locomotives with LNG tenders from Chart Industries [19]. Additionally, Indiana Harbor Belt Railroad operates four SW1500 locomotives converted to CNG by Optifuel Systems [20].

A summary of the generalized advantages and disadvantages of natural gas are highlighted below.

Advantages

- Lower fuel costs compared to diesel
- Availability
- Engine suitability
- Reduced carbon footprint (~30% reduction) - while methane engine slip or leakage can erase this advantage

Disadvantages/Concerns

- Flammable gas concerns and hazards
- Compression/liquefaction equipment costs and energy requirement
- Energy density requires use of tenders (CNG or LNG) for long haul locomotive operations

Fuels Comparison

Table 3 presented below is an attempt at a "50,000 ft aerial view" of the existing and alternate fuel landscape. The table is designed to give an overall view of various fuels and areas of interest. This will help identify areas of opportunity and various "pain" points where additional development would be beneficial. The table is not meant to specifically, and categorically, rate each individual fuel precisely in each individual category. Indeed, various parties are likely to have different responses to the table. For example, it is not likely that railroads, OEM engine manufacturers and environmentalists would all rate each factor of each fuel equivalently. Further, it is likely, or even certain that rankings will change over time and may have changed between composing this paper and the time it is actually published. The goal of the table is to provide a framework for fostering discussion and an overall 'map' of points, which need consideration for future development. As the table is curated on a spreadsheet, it also provides a 'living' document which can be updated periodically and recalculated easily.

Some key notes regarding the table are as follows:

- Categories are generally compared to "Current Diesel" (Petroleum) as a 'standard'.
- The 1-5 scale is generally rated as 5 = desirable/good, 1 = undesirable/poor/bad
- Oftentimes, caveats have to be made, but may not always be obvious. For example – in the "Fuel, Cost" category, "Traditional Electrification" scores a 5, Very good. This is a reflection of the actual electric cost per Diesel Gallon Equivalent (DGE) and not a reflection of the cost of building the electrification infrastructure.
- When hydrogen fuel is considered, it is assumed to be 'Green' hydrogen.
- "Weighting" has not been considered at this point in development, though the category is left open should later users wish to explore this option.

Analysis:

In summing and averaging the various columns and rows, several factors become clear:

In ranking the fuels, the 'Total Score' (right hand column) of the table shows current (petroleum) diesel as the highest / most desirable fuel. Indeed, it does have the largest infrastructure, widest availability highest energy density, highest interchangeability, and many other desirable factors. Unless heavily weighted,

Group	Technology	Safety: Flammability	Safety: Derailment	Safety: Maintenance	Costs: Fuel	Costs: Equipment Purchase	Costs: Maintenance	Costs: Infrastructure	Equipment Specs: Transmission Efficiency	Equipment Specs: Range/Endurance	Equipment Specs: Energy Density	Implementation: Integration Barriers	Implementation: Train Length	Implementation: Operating Improvements	Implementation: Refueling	Efficiency: Production	Efficiency: Compression/Liquification	Efficiency: Energy Mgmt & Fuel Savings	Efficiency: Vehicle
	Weight	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Engine Based Tech	Renewable/Bio Blends	5	5	4	4	5	4	3	5	4	4	4	5	4	5	3	3	1	5
	Nat Gas - CNG/LNG	2	3	2	3	3	3	2	4	3	3	3	4	2	3	2	2	1	3
Battery Based Tech	Battery Locos (standalone)	5	3	3	5	4	4	1	3	2	1	4	3	2	2	1	3	5	5
	BEL/Diesel Hybrid Consists	5	3	3	5	4	4	2	3	4	1	4	5	4	4	1	3	5	5
	Hybrid Locos	5	5	3	5	4	3	2	4	5	4	4	5	3	5	1	3	1	5
	Discontinuous Electrification	5	4	3	5	3	2	1	4	5	5	2	5	2	5	1	3	5	4
Fuel of the Future	H2 Fuel Cells	1	2	2	1	2	1	1	3	2	1	1	2	1	2	1	1	3	3
	H2 IC Recipricating Engine	1	2	2	1	2	1	1	3	2	1	1	2	1	2	1	1	1	3
	Methanol	2	2	2	2	1	2	1	5	3	2	1	3	1	4	1	3	1	3
	Ammonia	5	2	2	2	1	2	1	4	3	2	1	3	1	3	1	2	1	3
Other Tech/Hybrid Approaches	Traditional Electrification	5	4	3	5	2	3	1	4	5	5	1	5	3	5	3	3	5	4
	Nat Gas/H2 Blends	1	2	2	3	2	1	2	3	4	3	2	3	3	3	2	2	1	3
	Current Diesel	5	5	5	3	5	5	5	5	5	5	5	5	5	5	5	3	1	5
	Sum	47	42	36	44	38	35	23	50	47	37	33	50	32	48	23	32	31	51
	Average	3.6	3.2	2.8	3.4	2.9	2.7	1.8	3.8	3.6	2.8	2.5	3.8	2.5	3.7	1.8	2.5	2.4	3.9
	Weighted Sum	47	42	36	44	38	35	23	50	47	37	33	50	32	48	23	32	31	51
	Weighted Average	3.6	3.2	2.8	3.4	2.9	2.7	1.8	3.8	3.6	2.8	2.5	3.8	2.5	3.7	1.8	2.5	2.4	3.9

Group	Technology	Markets: Design cross-compatibility	Markets: Equipment Flexibility	Markets: Peer Industry Adoption	Development: Initial Engineering	Development: Supporting Systems	Development: Software Needs	Development: Service Support	Product Viability: Initial Sale	Product Viability: Current Development	Product Viability: Modularity	Product Viability: Financing/Leasing	Product Viability: Partnerships	Environmental: CO_2 Potential	Environmental: Other Emissions (NOx, HC)	Environmental: EOL	Regulatory/Incentive: Safety Challenges	Regulatory/Incentive: Emissions Regs	Regulatory/Incentive: Credit Ability	Regulatory/Incentive: Grant Applicability	Results: Total Score	Results: Rank
	Weight	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		
Engine Based Tech	Renewable/Bio Blends	5	5	4	4	4	4	5	5	5	5	5	3	3	1	5	5	2	2	2	147	2
	Nat Gas - CNG/LNG	3	4	2	3	3	4	4	4	4	3	3	4	2	2	4	3	3	2	2	107	8
Battery Based Tech	Battery Locos (standalone)	3	2	3	3	2	3	4	4	4	4	4	4	5	5	3	4	5	2	2	122	5
	BEL/Diesel Hybrid Consists	4	5	3	3	2	3	4	4	4	4	4	4	2	2	3	4	3	2	2	127	4
	Hybrid Locos	5	5	3	3	2	4	4	4	4	5	4	4	2	2	4	4	2	2	2	132	3
	Discontinuous Electrification	4	5	2	2	1	3	3	2	4	4	1	3	2	3	4	4	3	1	1	116	7
Fuel of the Future	H2 Fuel Cells	3	2	1	1	1	2	2	1	2	3	2	2	5	4	3	2	4	3	3	76	10
	H2 IC Recipricating Engine	3	2	1	1	1	2	1	1	1	2	1	2	5	4	3	2	4	3	3	70	13
	Methanol	3	2	1	1	1	1	1	1	1	2	1	1	2	3	2	2	3	2	2	71	12
	Ammonia	3	2	1	1	1	1	1	1	1	2	1	1	3	4	2	3	3	2	2	74	11
Other Tech/Hybrid Approaches	Traditional Electrification	1	5	1	3	1	3	3	1	4	3	2	3	5	5	4	3	5	1	1	120	6
	Nat Gas/H2 Blends	2	3	1	1	2	2	3	2	3	3	1	2	2	3	3	2	3	2	2	84	9
	Current Diesel	5	5	5	5	5	5	5	5	5	5	5	1	1	1	5	5	1	1	1	153	1
	Sum	44	47	28	31	26	37	40	35	42	45	34	34	39	39	45	43	41	25	25		
	Average	3.4	3.6	2.2	2.4	2.0	2.8	3.1	2.7	3.2	3.5	2.6	2.6	3.0	3.0	3.5	3.3	3.2	1.9	1.9		
	Weighted Sum	44	47	28	31	26	37	40	35	42	45	34	34	39	39	45	43	41	25	25		
	Weighted Average	3.4	3.6	2.2	2.4	2.0	2.8	3.1	2.7	3.2	3.5	2.6	2.6	3.0	3.0	3.5	3.3	3.2	1.9	1.9		

Notes:

- Categories are generally compared to "Current Diesel" (Petroleum) as a 'standard'
- The 1-5 scale is generally rated as 5 = desirable/good, 1 = undesirable/poor/bad
- Cells can be changed / updated as new developments arise or opinion shifts
- Hydrogen entries are based / assumed to be 'green' hydrogen

Table 3: Fuel comparison table of key fuel properties and other considerations that will impact fuel technology choices.

the environmental concerns do not outweigh the many other desirable properties, though 'weighting' may be a consideration for future development. Biodiesel and renewable fuel blends rank closely behind current petroleum diesel – having slightly less availability, but slightly better environmental scores. The next highest ranking includes hybrid, battery and electric locomotives mainly bolstered by their relatively good environmental scores and ability to recapture braking energy generating high scores in the 'Energy Management / Fuel Savings' category. Finally, many of the hydrogen options fill in the lowest rankings, mainly due to cost and availability. 'Green' hydrogen is only a fraction of total hydrogen available and total hydrogen is only a fraction of diesel fuel availability. Further concerns with flammability and infrastructure dominate the overall score.

In considering the categories which need the most attention, each column is averaged and displayed in the bottom row of the table. The lowest scores indicate potential "pain points" across the industry.

Some of the lowest scoring categories include "Production", "Infrastructure" and "Support Systems" and "Compression / Liquification". Indeed, the production volume of various alternate fuels and the infrastructure to deliver them often limit the consideration of various alternate fuels. Compression and liquification also represent considerable challenges for natural gas and hydrogen fuels. "Energy Density" is also a relatively low scoring category reflecting the challenges in storing considerable amounts of energy in natural gas, hydrogen, or battery components.

In summary, the fuels table above is an attempt to give an overall view of various fuels and areas of interest. Higher scores generally indicate areas of opportunity while lower scores suggest various "pain points" where additional development would be beneficial. The table is curated as a spreadsheet to provide a 'living' document which can be updated periodically and recalculated easily as technology and the fuel landscape develop.

Please feel free to contact the authors of this paper to obtain a blank spreadsheet if you wish to derive your own rankings.

Conclusions

As a frame of reference, it took the US rail industry approximately 15 years to switch from steam to diesel electric. It was a more straightforward decision with only two real options. We are now faced with a massive change and a variety of options. All the options we have discussed are workable. Because of logistics, infrastructure, energy density, and capital requirements, the solution chosen by each railroad may include a combination of these options. Examples include, railroads using battery powered locomotives for switching, and battery locomotives paired with diesel/biofuel locomotives for line haul applications.

Battery powered locomotives have low energy density compared to the other options. This can be a limiting factor for implementation. They have the distinct advantage of using the existing electrical grid (although the grid will need to be improved). Future development in batteries should provide units that are lighter, have a high energy density, and last longer.

The other solutions listed will require an entirely new infrastructure to produce the fuel and deliver it to the railroads and this may be important to determining a path forward. For example, if methanol is adopted, then the railroad will have to source enough methanol to power a fleet of locomotives. If methanol is not adopted by any other transportation industry, then the railroad may have to work with suppliers to develop manufacturing capacity. They will not be able to leverage mass production on the scale we have with diesel.

Safety will be a major concern for all these technology options. Battery locomotives have high voltage and the potential for battery related fires. Hydrogen and natural gas are both highly flammable gasses. The particle sizes for these gasses (especially for hydrogen), make them challenging to contain. Both hydrogen and natural gas will require special equipment to prevent leaks, protect employees and contain potential fires. Ammonia is dangerous to handle and exposure to high levels can lead to respiratory issues. Methanol is extremely flammable.

We can confidently say that locomotives can be built with each of these power sources. The sources that have the most competitive advantage in being adopted are the ones that have locomotives already being tested (Hydrogen and Battery). Government funding may also affect the decision, essentially putting the finger on the scales to favor one technology over another.

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Definitions:

Science Based Target Initiative: The Science Based Targets initiative (SBTi) is a collaboration between the CDP (was Carbon Disclosure Project), the United Nations Global Compact, World Resources Institute (WRI) and the World Wide Fund for Nature (WWF).[1] Since 2015 more than 1,000 companies have joined the initiative to set a science-based climate target.[2]

https://en.wikipedia.org/wiki/Science_Based_Targets_initiative

Diesel Gas Equivalents (DGE)

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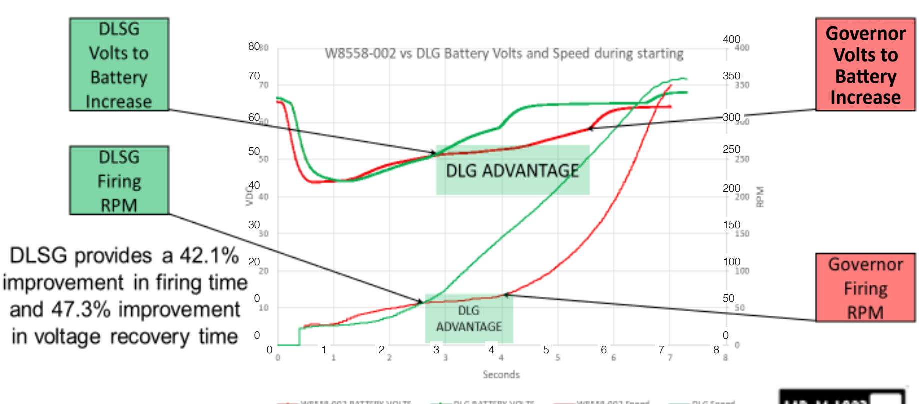

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