

LMOA

Locomotive Maintenance Officers Association

Proceedings of the 87th Annual Meeting

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2024 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 2024.

NAME	COMMITTEE	COMPANY
Eric Dillen	Mechanical Maintenance	Wabtec Corporation
Suzanne Golisz	Fuel, Lubricants and Environmental	Innospec
Jeremy Jovenall	Electrical Maintenance	Cattron
Andrew Walz	Facilities, Material and Support	Mid America Car

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

LMOA EXECUTIVE COMMITTEE

**LMOA JOINT TECHNICAL COMMITTEE MEETING
CHEVRON – RICHMOND TECHNOLOGY CENTER
RICHMOND, CA, USA – JANUARY 21, 22 and 23, 2025**

The Executive Committee of LMOA would like to express their sincere appreciation to Tom Gallagher and Chevron Oronite Company, LLC. for hosting the event and providing financial and logistical support.



Oronite

LMOA also wishes to thank the multiple planners, assistants coordinators and guides throughout the meeting, including:

**Lorraine Reyes – VP Global Technology
Justin Pajer – Global Product Line Manager
Bob Connel – Global Marketing Manager
Maura Matthews – Global Creative & Content Specialist**

PAST PRESIDENTS

- 1939 & 1949** F.B. DOWLEY (Deceased) Shop Supt., C. & O. Ry.
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1942-1946, Inc. J.E. GOODWINN (Deceased) Exec. Vice President, C. & N.W. Ry.
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1962 R.E. HARRISON (Deceased) Manager-Maintenance Planning & Control, Southern Pacific Co.
1963 C.A. LOVE (Deceased) Chief Mechanical Officer, Louisville & Nashville R.R.
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1968 G.F. BACHMAN (Deceased) Chief Mechanical Officer, Elgin Joliet & Eastern Ry.
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1970 G.R. WEAVER (Deceased) Director Equipment Engineering, Penn Central Co.
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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
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1983 F.D. BRUNER (Deceased), Asst. Chief Mechanical Officer, R&D, Union Pacific RR

- 1984 R.R.HOLMES (Deceased), Director Chemical Labs & Environment, 600 Brookstone 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-Gen'l 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
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- 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
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- 2015 BOB HARVILLA, Outside Sales Support, PowerRail, Exeter, 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
- 2023 TIM STANDISH, Quality Manager – Progress Rail-a Caterpillar Company, Winston-Salem, NC
- 2024 KEITH MELLIN, Sales Manager, Peaker Services Inc, Brighton, MI

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Union Pacific RR
Omaha, NE



BRANDON TEAL
Director-Railway Machine Systems
NSH USA Corporation
Albany, NY

2024 State of the Union Address

Keith Mellin

October 10, 2024

Chicago, IL

Ladies and gentlemen, members of the Executive Committee, Mr. Secretary, all committee members and fellow LMOA members. Thank you for the privilege and honor of serving as President of this association for the 2023-2024 term. It has been humbling to follow in the footsteps of so many Presidents before me and to serve this industry.

Welcome to the 2024 LMOA technical sessions here in Chicago

Thank you all for attending. We think you will find all the technical presentations interesting and most of all useful to you in your career as a railroader or supplier. This organization started in 1939. We currently have four committees presenting papers for this meeting

- Mechanical Maintenance Committee
- Facilities, Material and Support Committee
- Fuel, Lubricants and Environmental Committee
- Electrical Maintenance Committee

Please remember to thank the sponsors and suppliers who attend the conference, have displays and especially those who advertise in our book. Their sponsorship defrays some of the cost of printing the annual

proceedings book. These books are also available online to members of the LMOA. We have been scanning the books even back into the 1950s as they become available to us. We also thank the Railroads for their active participation in these busy times while they continue to drive our economy.

I will now take a few minutes to give you my perspective on the current state of LMOA

We have a total of 288 members in the organization. We have a total of 130 who registered for the conference which includes 42 Railroad personnel.

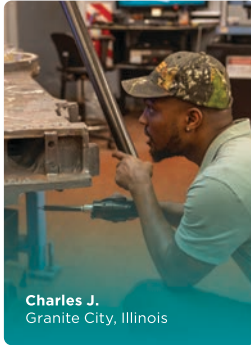
When accepting the office of President last year, I also felt the need to remind all of us of the stated objectives of the LMOA”

“The purpose of the association shall be to improve the interest of its members through education, to supply locomotive maintenance information to employers, to exchange knowledge and information with members of the association, and to make constructive recommendations on the locomotive maintenance procedures through the technical committee reports for the benefit of the railroad industry.”

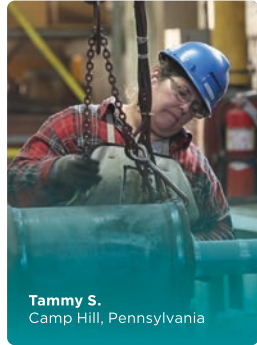
The LMOA is also about developing relationships. I would like



Matt L.
Kansas City, Kansas



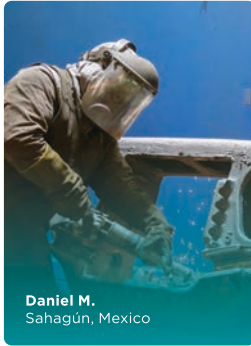
Charles J.
Granite City, Illinois



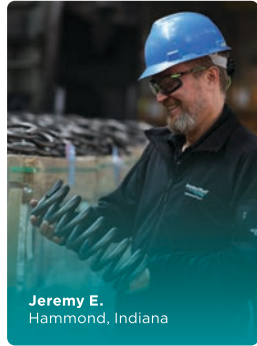
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to encourage you to continue your relationships with the professionals that are here. There is a lot to learn from the experience in the room. I have learned a lot from my participation in the LMOA. I encourage others to learn and participate in a great association.

We have been working with the AAR Locomotive Committee and the various technical advisory groups that support them with their current and future papers. We intend to make sure we maintain a constant communication stream with the AAR locomotive group and support their efforts.

To summarize, our association is healthy; overall we have good member

activity; we are sensitive to the needs of our constituents; we are responding to the challenges that we know about, and we are ready to make changes that support our stated objectives and meet the needs of our industry.

Thank you for the support of our association. As the gavel passes on to our newly elected President Corey Ruch of BNSF I want to wish him the best. This is a fantastic and committed group that continues to support and provide knowledge and assistance to the Railroad industry. It has been an honor to serve. Thank you for making the LMOA a successful and valuable organization. The State of the Union is strong.

2024 Acceptance speech

Corey Ruch

October 10, 2024

Chicago, IL

Good afternoon.

I am honored and humbled to accept the position of President.

As my first official duty, I want to take a moment, foremost, to thank Keith Mellin of Peaker Services for his leadership over the past year.

I know Keith has been a driving force at Peaker throughout his career, as well as over the past year with the LMOA. So please join me as I sincerely thank him for his guidance.

I would also like to take a moment to recognize Ron Pondel, our unsung wizard behind the curtain, so to speak. Through his tireless work, the LMOA remains on track – with all I’s dotted and T’s crossed. And I mean that literally! If anyone has ever had the pleasure of submitting a paper – spending countless hours reviewing, reading it forward, reading it backward, having others read and edit. You think you have perfection. Send it to Ron and his keen eye will find half a dozen errors!

Ron, I am sure I speak for the entire organization when I say, “You have my and our deepest gratitude for the work you do!”

If anyone in the room knows me in depth – I’m not one for long winded public speeches or verbose orations. I do not intend to change that today. So, I will keep this short.

In thanking Keith, I realize it was barely a year ago that he stood behind the podium and thanked his predecessor—Tim Standish from Progress Rail for his leadership of the LMOA.

A year before that, Mr. Standish was here thanking Tom Gallagher of Chevron Oronite for his service. A year before that Tom was up here... and on it goes...

Perhaps you remember or are friends with some of the recent past presidents...Kennedy, Bradbury, Beebe, Cutright, Olson, Harvilla—a variety of names from all segments of the rail industry. Each came to the podium, thanked their predecessor for helping move the organization forward, then added their own experience and direction.

In fact, we must go back to 1940 when the first President of the LMOA, Mr. F.B. Dowley, most likely stood behind his podium to turn the presidential gavel over—but had no preceding president to thank.

Think of that for a minute - for over 85 years now, the LMOA has been a central force in the Railroad Industry. The Association has worked in promotion of continual improvement from the time steam engines rose to the pinnacle of technology and locomotion, through the introduction of diesel

engines and their development, to their refinement and I'm sure some OEM's in the audience would argue, 'to their perfection'.

Now we stand at the edge of the next revolutions in alternate fuels, computer command/control, massive amounts of data acquisition and prediction, artificial intelligence – and more.

Through it all, the LMOA has been there – issuing papers and guiding principles across the various disciplines... Mechanical, Electrical, Facilities Material and Support, and Fuel Lubricants and Environmental aspects.

Each committee, changing with the times, issuing technical papers and knowledge needed to keep locomotives and their supporting shops operating at peak efficiency and safety.

Looking at our past presidents, I have to confess that I'm a relative newbie in the field, it's barely been over 31 years since that early May morning when I walked into the old Frisco Railroad Testing and Research

Laboratory in Springfield Missouri and started my railroad career.

My first task.... Clean out the chips which had accumulated in the band saw and sweep the floor!

A lot has changed since then!

But, as the old saying goes, "The only thing constant IS change."

So, with that, I hope everyone is as excited as I am to meet the coming year of change. Certainly, some change we already know about or have good ideas about – and likely have some papers coming in 2025 – so stay tuned! But it is likely that other changes we can scarcely imagine right now.

Overall, I am confident that the broad spectrum of members in the Association will leverage our diverse and collaborative nature to keep the LMOA on track for continual improvement – not only of the Association, but all the railroads and industries we serve.

Thank you once again for allowing me to be a small part of this amazing organization!





LMOA Executive Board meeting following the conclusion of the rail conference in Chicago, IL in October 2024



Picture of Newly elected President Corey Ruch and Past President Tim Standish

Report on the Committee on Fuel, Lubricants and Environmental

WEDNESDAY, MAY 21, 2025

10:45 AM



Chair

Chris Miller

Senior Director of Services Product Management
Wabtec Corporation, Chicago, IL

Vice Chair

Michael Cleveland

Director of Market Strategy
Peaker Services, Inc, Brighton, MI

Committee Members

D. Abeywickrama	Loco Fleet Leader-Mech Reliability	Canadian National Railway	Montreal, Quebec
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
			<i>Past President</i>
M. Blumenfeld	OEM Technical Advisor	Exxon Mobil	Annandale, NJ
M. Brinkman	Sales Manager-Engineering	Boll Filter	Novi, MI
T. Degerness	Manager Fuels	CPKC	Calgary, Alberta
R. Denton	Corp Chemical Technology Manager	Cummins, Inc	Columbus, IN
C. Fedoris	Senior Manager-Fuel Sourcing	Union Pacific RR	Omaha, NE
S. Fenwick	Technical Director	Clean Fuels Alliance America	Jefferson City, MO
R. Flott	Senior Engineer	BNSF Railway	Topeka, KS
P. Fontecchio	Engrg Mgr-Engine Cooling & Lube	Wabtec Corporation	Erie, PA
S. Fritz	Senior Manager-R&D	Southwest Research Institute	San Antonio, TX
T. Gallagher	OEM Technical Liaison	Chevron Oronite	Allendale, MI
			<i>Past President</i>
R. Garver	Business Development Director	Innospec Fuel Specialties	Englewood, Co
N. Gawin	Technical Sales Manager	Shell Whitmore Reliability & Sol.	Strathmore, Alberta
S. Golisz	Technical Director	Innospec	Newark, DE
D. Gray	Industry Liaison Advisor	Infineum	Brick, NJ
D. Hasagic	VP-Strategy & Growth	Veridapt	Chatswood, Australia
D. Hays	Manager Mechanical Maintenance	Terminal RR Assn of St. Louis	Venice, IL
R. Hays	Director-Sales	Red Gian Oils/HF Sinclair	Council Bluffs, IA
A. Hesse	Senior Mechanical Engr	Amtrak	Lincoln University, PA

Committee Members Continued

J. Heywood	Senior Fuels and Lubricants Engineer	Wabtec Corporation	Fort Worth, TX <i>Regional Executive</i>
J. Homer	President	Optimizing Consulting, LLC	Naperville, IL
S. Jaworski	Application Advisor	Exxon Mobil	Williamstown, Ontario
W. Kennedy	Consultant	Kennedy Rail Consulting	Omaha, NE
C. Koglin	OEM Relations Specialist	Afton Chemical Corporation	Southfield, MI
S. Koshy	Senior Mechanical Engr	Amtrak	Bear, DE
M. Lutz	General Director-Fuel & Environmental	Union Pacific RR	Council Bluffs, IA
T. Mack	President/Founder	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
G. Natarajan	Specialist-Research & Business	The Viswa Group	Houston, TX
S. Nevin	Managing Director-Supplies & Material	CPKC	Calgary, Alberta
J. Pettingill	Product Specialist (R&D)	Petro-Canada (HF Sinclair)	Mississauga, Ontario
L. Rasmussen	Project Engineer-Engine Systems	Progress Rail-Electro Motive Diesel	LaGrange, IL
L. Rawding	RR Product Manager	American Refining Group	Bradford, PA
C. Ruch	Asst. Director-Technical Research & Development	BNSF Railway	Topeka, KS <i>President</i>
G. Smith	Project Manager	Argus Consulting, Inc	Overland Park, KS
J. Soles	Director	Selkirk Consulting	Calgary, Alberta

PERSONAL HISTORY

Chris Miller

Senior Director of Services Product Management
Wabtec
Chicago, IL

Chris Miller is the Senior Director of Services Product Management at Wabtec 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. Much of that push is around understanding the impact of biodiesel and renewable diesel when used in Wabtec locomotives, but also includes alternative fuels such as hydrogen.

Chris started his railroad career with Norfolk Southern as a Mechanical Supervisor supporting operations in Atlanta, GA, Chattanooga, TN, and Macon, GA. He then spent eight years with Union Pacific in the Locomotive Engineering and Quality group managing the reliability of UP's fleet of ~7,000 locomotives. His last railroad stop was at Canadian National Railway as the Senior Manager of Mechanical Engineering where he functioned as an internal consultant guiding CN's locomotive decarbonization and other locomotive projects.

This railroad experience combined with his time as the General Manager of a Steak 'n' Shake restaurant makes Chris a versatile professional with experience in product management, employee development, problem solving, strategic planning, carbon reduction, sustainability, and customer service. He also enjoys learning about new concepts and technologies, 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 has three children aged 12, 10, and 6 with his wife, Liz. They moved to Chicago in 2021 and love the city and suburbs. He enjoys running when there's free time from all the kid's fun activities (soccer, dance, swimming, and basketball).

Gaseous Fuel – Fungibility, Carbon, and End Users

Prepared by :

Tom Mack – Zero-Emission Locomotive Technologies

Rajani Modiyani – Chevron

Fuel Fungibility – What is it?

Fuel fungibility is the ability to buy fuel without having to purchase the actual molecules you use.

“Fungibility is the ability to exchange one asset or good for another of the same type because they have the same value. Fungible items can be substituted for each other and the exchange process is simplified.” – Google definition

In other words, if I’m using enough natural gas (NG), I can buy it direct from a natural gas supplier and said natural gas could be produced from wells in New York state. But if I am located in California, my NG comes out of a pipeline in California. The natural gas that I “actually” bought, that enters the pipeline in New York, does not have to physically travel to California to be pulled from the pipeline. That’s because NG is fungible.

Going a step further, I can buy Renewable Natural Gas (RNG – mostly methane CH₄) produced by a landfill in New York and pull non-renewable natural gas (mostly methane CH₄) from a pipeline in California (said natural gas having come from, say, a gas well in Texas), and I don’t need to transport the actual molecules of RNG to California. But because I paid extra for RNG, I get to keep the carbon reduction credit associated with the RNG from New York. (More on this later.)

While fungibility becomes more important with low-carbon fuels, fungibility has been common for decades. When a buyer acquires barrels of oil on the market, the actual “physical” oil they bought from a supplier may not be the actual molecules they receive. The concept of fungibility for this paper is especially important for carbon reduction purposes since the production points and terminals for low-carbon renewable fuels are spread geographically across the country, and supplies may be limited in certain areas. For example, if I want to buy RNG, but I am located right in the middle of the gas fields of Texas, there may not be any local sources for RNG, but there is plenty of non-renewable NG all around me and coming out of the pipelines in my area.

Fungibility of natural gas is possible because we live in an electronic society where the credits for carbon reduction can be tracked and traded, and because there is a purchasing and tracking infrastructure already in place. This tracking and trading is done through the use of Renewable Identification Numbers (RINs), which will be discussed in detail in this paper. But first, a little background on how fungibility got started.

Money – our most “fungible” product

Let’s consider our current monetary system to better understand fungibility

In the beginning, there was product and bartering. Real tangible products were traded for other real tangible products:

“I have potatoes, and you have a plow. How many potatoes do you want for a plow?”

This is a great system as long as both trading partners have what the other person needs. But it fell apart when trading partners didn’t need what the other person has to offer:

“I have a plow, and you have potatoes, but I don’t need potatoes!”

This conundrum required traders to potentially find a third party that “needs what I have” and “has what you need”!

“I have potatoes, and Joe has coal, and Joe needs potatoes. You need coal, and you have a plow, and I need a plow! So, I give my potatoes to Joe, he gives me the coal, I give you the coal, and you give me the plow.”

There has to be a better way!! If only there was a material which is rare enough to convey wealth and power if you have it, but common enough that you can get more, has enduring appeal, historical significance, technological usefulness, exceptional physical and chemical properties and even divine symbolism.... in one word...gold! So, gold becomes what we all want, and all can trade for and suddenly we have currency.

But gold is awfully heavy. It sure would be nice to have something lighter to carry around.

Paper is lighter, so some government somewhere says we’ll take and hold your gold and give you a piece of paper with a unique serial number on it, and that will be proof to anyone in our country that you *own* gold that is in the government’s possession, and therefore you have something of value you can give to someone else just by transferring the paper record – a serialized note.

But paper can get lost, so why even carry the paper around with you? Now that we have computers, just make an electronic record of your money, and let

a computer keep all the “serial numbers,” and now you can go anywhere in the world. Just make sure that they accept the “electronic” currency.

That’s where we are today. There are now clearly backed currencies (historically backed by a government) that people trade all the time for goods and services.

The Importance of Fungibility in a Low Carbon Fuel Environment

The concept of fungibility becomes especially important in a low carbon fuel environment. To get the full impact, low carbon fuel purchases actually involve not one, but two purchases:

1. The purchase of the actual fuel that is used in the locomotive (e.g. natural gas)
2. The purchase of any associated carbon credits (e.g. purchasing RNG vs NG, or Petro-Diesel vs. Biodiesel)

What gets confusing is that the chemical makeup of biodiesel and renewable diesel is actually different than that of natural gas (CH_4) or even a liquid fuel such as ethanol ($\text{C}_2\text{H}_5\text{OH}$). But the concept is still the same. It’s just that in the case of biodiesel or renewable diesel the molecules themselves are the basis for the associated carbon credit. With NG and ethanol, the source feedstock is what really creates the carbon credit. With ethanol, the source feedstock can also affect the amount of carbon credit that you get when you buy the fuel (e.g. corn ethanol vs. cellulosic ethanol).

Is it complex? Yes

Is it trackable? Yes

Is it the tracking that matters? Yes

Introducing the Renewable Identification Number (RIN)

As with any form of currency, there has to be something of value behind it. In our earlier example, gold was used as a currency, and it was physically exchanged. To move to a fungible currency, there has to be some governmental power behind the issuing of paper and/or serial numbers that have some value and can be traded between partners in exchange for goods. In the case of fuels such as NG, the U.S. government in 2005 created the Renewable Fuel Standard. The Renewable Fuel Standard program is under the Clean Air Act (CAA), which was created under the Energy Policy Act of 2005 and further expanded by the Energy Independence and Security Act of 2007.

So almost 20 years ago the U.S. government created a national policy requiring that certain volumes of renewable fuel be used to reduce the quantity of fossil fuel in transportation fuel, home heating oil, or jet fuel. There are only four specific categories of renewable fuel under the Renewable Fuel Standard (RFS):

- Biomass-based diesel
- Cellulosic biofuel
- Advanced biofuel
- Total renewable fuel

While the original Energy Independence and Security Act of 2007 (EISA) only set out yearly volume requirements to 2022, the CAA provides EPA with the authority to establish or “set” the applicable renewable fuel volume targets for calendar years after 2022 via rulemaking. Per the EPA website, “EPA must determine the applicable volumes of each biofuel category based on a review of implementation of the program and an analysis of multiple factors. Those factors include, for example, the impact of the use of renewable fuels on the cost to consumers of transportation, and the impact of the use of renewable fuel on other factors, including job creation, the price and supply of agricultural commodities, rural economic development, and food prices.”

So very clearly the carbon value of renewable fuels is dependent on government policy and regulation. Thus, the value of renewable fuels can in theory be changed at any time, and it is also dependent on cost and economic factors. While this may make it seem that renewable fuels are on very shaky ground, the value proposition of renewable fuels is not much different than that of any other commodity whose value can at any time be affected by market conditions and even government decrees. As an example, think of the government that suddenly revalues its currency. What today is a \$100 bill, by a single government decree could be valued at \$10. Historically this has happened to currency of many countries in the past, but it is extremely rare. The same holds true for the value of RINs. While there has been some fluidity as to the volume of renewable fuels that are required to be used or blended, for all practical purposes it does appear that renewable fuels such as biodiesel, renewable diesel, ethanol, and RNG are here to stay. As such, they will always have some level of value and necessity as transportation fuel.

At this point, we might want to step back and consider why renewable fuels have value. First, and perhaps the most basic value, is that these are fuels and can be used to power a vehicle (in our case, a locomotive). Assuming I could produce a renewable fuel that is a 100% drop in for a non-renewable fuel, the renewable fuel has a minimum value of the non-renewable fuel it replaces. RNG is a good example of this. RNG is primarily methane (CH₄), and as such the methane component of the RNG is no different molecularly than methane that



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comes out of any gas well. (While there are differences in the gas mix of “natural gas”, for the sake of this example, we are just highlighting the primary component of natural gas, namely methane.) The two big differences are:

1. Supply – in theory the RNG will last forever, as long as the feedstock is available year-after-year, whereas the gas well has a finite supply of gas in the ground.
2. Cost – classically it is more expensive to convert feedstock such as landfill waste or cow manure into RNG than it is to simply drill a hole and pull the natural gas from the ground.

Assuming, however, that I have a source of feedstock that is not going away for the foreseeable future (e.g. a herd of dairy cows that will keep being replaced with younger cows as the older cows die off), and that the cost of converting all that cow manure to RNG is no more than drilling a well and pulling the gas from the ground, I do not require any offsets to the cost of my RNG. I can make as much money on every cubic foot of RNG that I produce as my competitor does with the non-renewable gas well. Based on supply and cost, both the renewable and non-renewable fuels are equal and can compete in the market, or even share the market if it is big enough for both players.

However, renewable fuels have an added value over non-renewable fuels, and this has to do with their carbon footprint. While the carbon content is no different between methane in RNG and methane in non-renewable NG, the carbon footprint is different. The carbon released by a cubic foot of cow manure based RNG will theoretically be used by plants which are once again eaten by cows to produce the manure used to make the next cubic foot of RNG, and hence the carbon footprint of RNG is lower.

Another way to think about it is that if I use four cubic feet of RNG, in theory, since the carbon is recycled through the plants, then back to the cows and manure, the same amount of carbon is released from four cubic feet of RNG as is released from one cubic foot of RNG. But from a non-renewable natural gas well, I pull four cubic feet of NG with no offset of carbon. If we don't care about this higher carbon emission, there is no additional value in our RNG. As such, unless RNG is the same cost as non-renewable NG there would be no reason to buy it. But remember that the value of RNG is in its lower carbon footprint. But how do I track that value?

So again, we come back to the RIN. Based on government calculations and regulations, a certain amount of renewable fuel must be blended each year into the fuel supply. But how do you track whether enough renewable fuel is even made? That is where the RIN comes in. For each gallon of renewable liquid fuel made, or for each cubic foot of renewable natural gas produced, there is an assigned Renewable

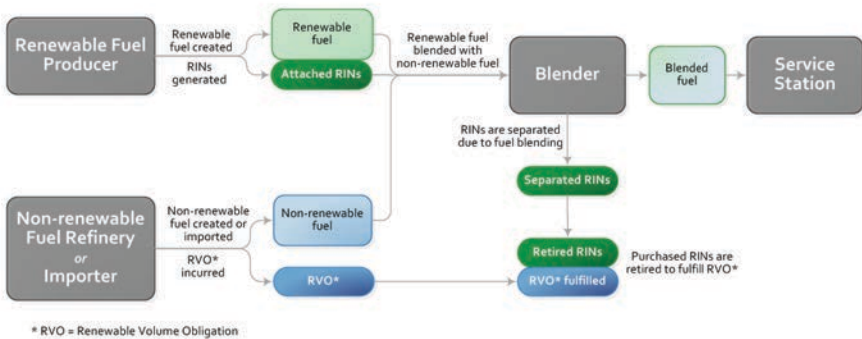
Identification Number. RINs can be traded between parties, bought as attached RINs to fuel purchased (in other words, purchased by the actual user of the fuel), and/or bought unattached on the open market (similar to trading currency on a currency exchange market where the money is bought as an investment and not actually used by the purchaser to buy something). Unlike normal currency, however, another important aspect of RINs issued by the government is that they expire. So, at some point in time, they have to be “exercised” by the buyer to show that the buyer has blended a certain amount of biofuel into their product or used a certain amount of biofuel in their vehicle and has thus offset a certain amount of carbon emissions.

Entire papers have been written and published on RINs, but for the sake of this paper, the key takeaway is that RINs provide a government accepted “proof” that a company has cut down on its carbon footprint. It should be noted that cutting down on carbon emissions is not necessarily linked to a government mandate. It may be based on an internal corporate policy. This is important to locomotive fuels and the cost associated with a given amount of carbon reduction.

To start with, because of the RFS, all users of diesel fuel today are actually reducing their carbon footprint. Under the RFS there is a Renewable Volume Obligation stating the amount of carbon offsetting renewable fuel that must be blended with non-renewable fuel. Hence every gallon of diesel put in a locomotive will have some renewable fuel, such as biodiesel, blended with it. The railroad, however, as the end user does not really get to count the carbon reduction associated with the fuel used since the blender is required under the RFS to use a certain amount of renewable fuel. So, when the blender buys biodiesel from a producer, they get the RIN that shows they actually bought the biodiesel and its associated carbon reduction. Every time the blender buys a gallon of non-renewable diesel (petroleum diesel), they must use their RIN’s to show that they have offset the RVO associated with the non-renewable fuel they are selling. The government not only issues the RINs but also retires them. So, by the time the blended diesel fuel gets to our locomotives, the RINs have already been retired by the blender, and there is no additional carbon reduction.

What if a railroad has decided they want to reduce their carbon emissions even beyond what the RFS requires of each gallon of diesel fuel used? In this case, the railroad can utilize a higher blend of renewable fuel, and the RINs associated with the level of fuel beyond the RVO can become the property of the railroad, who in turn retires the RIN and takes credit for the additional carbon reduction. In essence, the railroad purchases biofuel, but the RIN associated with the biofuel is the currency used to “buy” additional carbon reduction credits. Since everything is tracked via valid “serial numbers,” there is an audit trail all the way back to the creation of renewable fuel and the associated amount of carbon reduction.

Example lifecycle of a Renewable Identification Number (RIN)



The RIN Lifecycle

<https://www.epa.gov/renewable-fuel-standard-program/renewable-identification-numbers-rins-under-renewable-fuel-standard>

This is also important since not every renewable fuel carries the same amount of carbon credits. Each gallon of biodiesel produced, for example, does not have the same level of carbon reduction, hence the value of a RIN may be higher or lower depending on the feedstock and manufacturing process. A biodiesel made from palm oil may have a lower carbon reduction value than a gallon of biodiesel made from waste vegetable oil. All of these nuances are calculated and tracked by the government who issues the RIN so that there is a clearly established and accepted basis for the value of the RINs and the amount of carbon emissions that are removed by using renewable fuels.

Carbon Neutral and Carbon Negative Renewable Fuels

This brings up another very important point in regard to renewable fuels, especially RNG. Because of the various ways in which biofuels are manufactured, and the source of the bio-material feedstock, renewable fuels can actually be carbon negative! Carbon negative means removing more carbon dioxide (CO₂) from the atmosphere than is emitted. According to the SoCalGas website:

“When RNG is used to fuel vehicles, it can provide major reductions in greenhouse gas emissions - in addition to clean air benefits. According to the California Air Resources Board, RNG sourced from landfill-diverted food and green waste can provide a 125 percent reduction in greenhouse gas emissions, and RNG from dairy manure can result in a 400 percent reduction in greenhouse gas emissions when replacing traditional vehicle fuels.

More than half of all natural gas dispensed in California for transportation utilize RNG, powering buses, refuse trucks and heavy-duty trucks.”

What this means is that for every Diesel Gallon Equivalent (DGE) of landfill RNG we use to replace a gallon of petroleum diesel, we get an extra 25% carbon reduction credit for the diesel we still use. All of this is controlled through the issuance of RINs and their associated carbon value.

Even using 125% (landfill) reduction RNG we won't get to zero carbon emissions if we use a dual fuel diesel/RNG system until we get to a high ratio of RNG to diesel. The calculations below show that it's still a good reduction even at a 50% replacement.

1000 gallons of diesel = 11.192 tons CO₂

-500 DGE RNG (50% diesel replacement) = 5.596 tons of CO₂
removed by replacement

5.596 tons of CO₂ remaining gets a 25% reduction credit leftover from
the RNG = 1.399 tons additional CO₂ removed

5.596 + 1.399 = 6.995 tons of CO₂ removed by using 50% landfill RNG
= 6.995 / 11.192 = 62.5% GHG reduction

By using 400% (dairy manure) reduction RNG we can be carbon neutral with just 25% diesel reduction!

1000 gallons of diesel = 11.192 tons CO₂

-250 DGE RNG (25% diesel replacement) = 2.798 tons of CO₂
removed by replacement

8.394 tons of CO₂ remaining gets a 300% reduction credit leftover from
the dairy RNG:

2.798 tons of CO₂ removed by RNG x 300% = 8.394 tons of CO₂
removed

2.798 + 8.394 = 11.192 tons of CO₂ removed by using 25% dairy RNG
= 11.192 / 11.192 = 100% GHG reduction

This math supports the carbon reduction in theory, but none of this is possible without an existing official way to buy and sell the carbon reduction credit. Additionally, as long as we have the RIN, it doesn't matter if we actually have the NG molecules that produced the RIN. It doesn't matter what molecules we get, as long as molecules that reduced the GHG were put into the system somewhere and were used by someone in the system. The RIN is simply tracking who made it possible, by their monetary input, for the producer to make and sell the RNG, which by nature of the processes needed to produce RNG, will usually be more expensive than non-renewable NG.

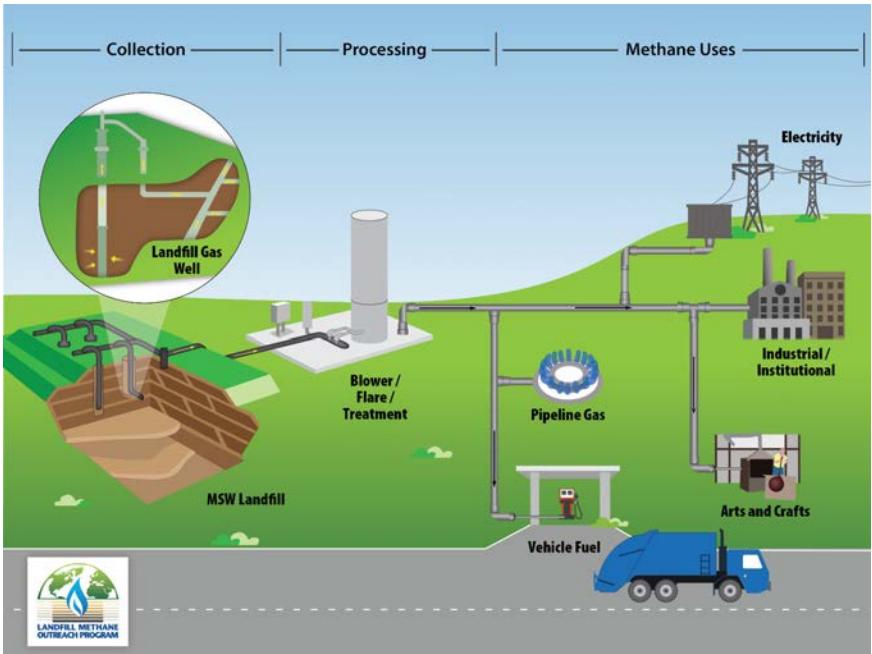
Why does this work for GHG emissions and not NOx or PM emissions?

It's because GHG is a global problem, and it is the overall worldwide increase of GHG that is trying to be tackled by government regulations such as the RFS. There is no inherent benefit or detriment to a slight local change in CO₂. NOx and PM tend to stay localized. They are the local smog and soot around an EPA "nonattainment area" that is being tackled by criteria emissions reduction (i.e. locomotive Tier levels). Reduction of NOx in Cincinnati will not reduce smog in Los Angeles, but reduction of GHG anywhere in the world benefits the rest of the world. The problem is not "Local" Climate Change but "Global" Climate Change (once called Global Warming).

Interestingly, however, we do see local emissions credits given for criteria pollutants such as NOx and PM. These come in the form of federal and local grants to offset these emissions, such as DERA, CMAQ, and other funding (e.g. California Carl Moyer funds). The concept is the same. If a railroad can show that they are using a lower criteria emissions locomotive (e.g. Tier 4 diesel or zero-emission battery) there is value in the emissions reduction. Through complex government formulas an area can lower their constituent emissions and the value of this emissions reduction can be traded between partners through the use of emissions credits and even grant dollars.

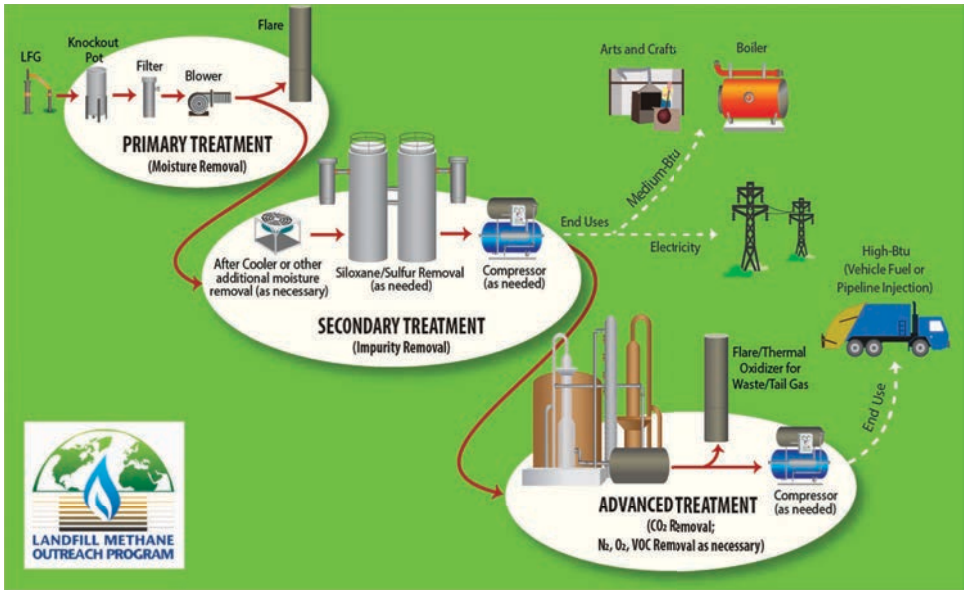
Where does RNG come from? Who are the suppliers?

Landfill gas is the largest source of RNG. There are landfills across North America that produce useable RNG, with more landfills being drilled every day to produce an even greater supply of RNG. One estimate is that there are at least 90 landfill gas projects in operation or process. In order to be useable, the landfill gas must be processed. About 63% of currently operational landfill gas energy projects in the United States generate electricity



Source: US EPA

Most landfill gas is only about 50% methane, while commercial natural gas usually contains 85 to 90 percent methane, with the remainder mainly nitrogen and ethane. Before the landfill RNG can be used as a locomotive fuel, it must have the non-methane gases removed to raise the methane content. (Additional details about landfill RNG can be found at: <https://www.epa.gov/lmop/basic-information-about-landfill-gas>.)



Source: US EPA

As noted earlier, some of the highest carbon reducing RNG comes from dairy manure. More and more dairy farms are seeing the opportunity to take waste stream manure and turn it into profitable RNG through the use of digesters. With the increased value of RINs going to companies wanting to reduce their carbon footprint, previously unprofitable projects can now become profitable and viable. Because the feedstock from dairy farms, namely manure, is virtually inexhaustible, there is no concern that the wells will run dry in the future. As long as there is a demand for dairy products, there will be a feedstock supply! California, Wisconsin, and Idaho are some of the leading potential states for production of RNG from dairy farms.

RNG and its associated RINs from the above sources can be purchased by any NG user in North America. As seen in the diagram above, high BTU natural gas can be used directly at the source to fill vehicles such as refuse trucks, but it can also be directed into a pipeline. Natural Gas fungibility means the buyer doesn't have to be directly connected to the landfill or dairy farm RNG supply to reduce carbon emissions.

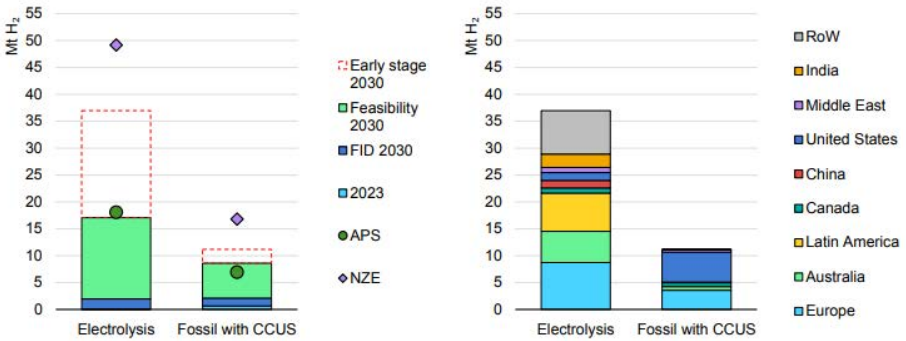
What about “Green” Hydrogen?

Green hydrogen, produced through the electrolysis of water using renewable energy sources such as wind, solar, and hydropower, represents a promising pathway towards a sustainable, zero-carbon future. Unlike traditional hydrogen production methods that rely on fossil fuels, green hydrogen generates no carbon emissions during its production process. This positions it as a crucial component in the global effort to mitigate climate change and transition to cleaner energy systems. The versatility of green hydrogen is remarkable; it can be used as a fuel for transportation, a feedstock for various industrial processes, and a means of energy storage, providing a buffer to balance intermittent renewable energy supply. Production of green hydrogen tends to be more expensive given the early stages of the electrolyzer technology and a need for investment in renewable energy unless its naturally available in the vicinity of production. One such example would be largely renewable power on the grid in British Columbia from its vast hydro electric power reserves. On the other hand, blue or grey hydrogen derived from natural gas and coal tend to be less expensive, but the carbon reduction is low or non-existent.

Just like the discussion around NG, hydrogen is also fungible. Chemically all hydrogen green or blue or grey all perform the same in its application. What is different is its environmental attribute that gets assigned to it during its production process.

Low-GHG emissions hydrogen production has the potential to reach 49 Mt per annum (Mtpa) by 2030 globally based on announced projects. This represents an almost 30% increase compared to the projections made when the Global Hydrogen Review 2023 was released.

As shown on the chart (next page), based on announcements, the United States will remain the frontrunner in hydrogen production from fossil fuels with CCUS or low-GHG emissions hydrogen, with 5.6 Mtpa H₂ by 2030 (more than 3.5 Mtpa if projects at very early stages of development are excluded), followed by Europe with more than 3.5 Mtpa H₂ by 2030 (more than 3 Mtpa if projects at very early stages of development are excluded). This is an increase of almost 30% for the United States since 2023.



Low-emissions hydrogen production by technology, status and region based on announced projects and in the Announced Pledges and Net Zero Emissions by 2050 Scenarios, 2030

RNG Fuel Supply Potential

RNG sources are limited because there are only so many landfills and so much trash to turn into RNG. Dairy farms are limited, and there is only so much manure produced. So how much RNG is being produced now, and how much is it estimated can be produced? According to the Center for Strategic and International Studies in Washington, DC, in 2023 RNG sources break out as follows:

Landfills: 70%

Dairy Farms and other Agricultural Feedstock: 20%

Wastewater: 5%

Centralized Food Waste Facilities: 5%

As of 2023, the US RNG supply only accounted for about 1% of the total U.S. annual natural gas demand. Sources vary in their estimation of how much RNG can be supplied and estimates project that as much as 10-15% of the U.S. natural gas demand could be met with RNG by 2040. In 2023 that equated to about 115 billion cubic feet (BCF) of production with another 55 to 60 BCF under construction and another 115 or so BCF in planned projects.

A rough conversion factor of natural gas to diesel fuel is 139 cubic feet of natural gas equals the energy equivalent of one gallon of diesel fuel. This means that if all the RNG produced in the U.S. in a year was used to replace diesel fuel, a little more than 825 million gallons of diesel fuel could be replaced. US railroads use around 3 billion gallons of diesel fuel, so RNG could replace about 27% of the current requirements.

It is doubtful, however, that all RNG produced in the U.S. today would go to locomotive use. In October 2013 the National Renewable Energy Lab (NREL) produced a paper entitled Biogas Potential in the United States. According to the paper, the methane potential from landfill material, animal manure, wastewater, and industrial, institutional, and commercial organic waste in the United States is estimated at about 7.9 million tonnes per year, which according to the NREL paper is equal to about 420 billion cubic feet. That number would be 3.65 times more RNG than is produced today. And this does not include potential new feedstock sources for RNG such as lignocellulosic biomass resources.

Estimated Methane Generation Potential for Select Biogas Sources in the United States

Source	Methane Potential (tonnes/yr)
Wastewater	2,339,339
Landfills*	2,454,974
Animal manure	1,905,253
IIC organic waste	1,157,883
Total	7,857,449

* Includes candidate landfills only as defined by the EPA's Landfill Methane Outreach Program

Using the NREL projections, if all waste stream produced RNG went to U.S. railroads, they could replace 3 billion gallons of diesel fuel with RNG. It is unlikely that U.S. railroads would be able to corner the entire RNG market, but as pointed out earlier, some RNG, like that produced from cattle manure, can have a carbon offset of 4x that of diesel fuel. In that case, if U.S. railroads purchased just 25% of the potential waste stream RNG, they could essentially become carbon neutral. To meet a 50% reduction in GHG, railroads would only have to purchase

12.5% of the potential RNG projected by NREL to be available in the U.S. from just four waste stream sources.

Locomotive technologies on the horizon for gaseous fuels

Railroads have already tested and proven the viability of natural gas use in locomotives. Substantial testing was done in the last decade on dual fuel locomotives from both GE/Wabtec and EMD/Progress Rail. As a result, an AAR standard was created for both LNG and CNG fuel tenders. Florida East Coast Railway is a railroad that uses LNG regularly. On November 9, 2017, FEC officially unveiled its modified fleet of 24 GE ES44AC locomotives, which operate in pairs with a purpose-built LNG fuel tender. Since RNG is fungible, FEC could theoretically purchase solely RNG and if the carbon intensity of the fuel is low enough, offset its locomotive GHG output. It would not require a change to the fueling infrastructure or equipment to do so. Any railroad could do the same for their line haul locomotives, although they would have to purchase CNG or LNG fuel tenders and build infrastructure for NG refueling.



Progress Rail (EMD) Dual-Fuel Locomotives with LNG Tank Car Fuel Tender



Wabtec (GE) Dual-Fuel Locomotives with LNG Tank Car Fuel Tender

At least one new locomotive company has announced plans for new hybrid locomotives designed specifically around the concept of using high GHG offset RNG along with petroleum diesel to create a zero-carbon locomotive. OptiFuel Systems of Beaufort, SC (optifuel.com) announced a 5000 hp Diesel-RNG Dual Fuel Hybrid line haul locomotive, set to undergo testing at TTC, aiming for FRA concurrence by 2028. According to OptiFuel's website, "The dual fuel series integrates the capability for the power system to run on up to 33% renewable natural gas (RNG), providing greenhouse gas (GHG) elimination in addition to elimination of NOx and PM." The design is different from that of locomotives requiring a tender in that both diesel and CNG fuel tanks are present on the locomotive itself, so no tender is required.

Based on the fuel efficiency projections for the OptiFuel line haul locomotives, OptiFuel claims that a dual fuel diesel/RNG hybrid locomotive would only require one or even no refueling stops to travel from the Port of Los Angeles or Long Beach to Chicago. While this is a projected number, it shows the potential for railroad decarbonization without having to replace all the use of petroleum diesel in a locomotive.



Artist Rendition of Proposed OptiFuel Dual Fuel Diesel/RNG Hybrid Line Haul Locomotive

Why doesn't fungibility work with locomotive diesel like it would with RNG?

Why not just reach our carbon emissions goals by buying the biodiesel or renewable diesel and letting someone else burn it while the railroads keep the carbon credits for themselves and run their locomotives on proven petroleum diesel?

It's a money thing.

While it may seem to make sense to in essence "buy" our way to carbon reduction, for the foreseeable future the cost of biodiesel and renewable diesel is too high to make it a viable option.

For example, in theory a railroad whose locomotive fleet is only capable of using a 5%, 10%, or maybe 15% biodiesel blend could buy an extra million gallons of biodiesel, keep the RINs, and sell the biodiesel to a small trucking fleet that can run a 25% biodiesel blend. A simple example of this might be as follows:

Railroad A uses 20 million gallons of diesel in its locomotives.

Railroad A's locomotives can use a 5% biodiesel blend = 1 million gallons.

Railroad A buys 1 million gallons of biodiesel for \$0.30 more per gallon and uses it in its own locomotives = \$300,000 for the carbon reduction.

Railroad A buys an additional 1 million more gallons of biodiesel for \$0.30 more per gallon = \$300,000 for the carbon reduction credit. It lets the biodiesel producer simply make the biodiesel available to another customer for the cost of regular diesel, but the carbon credit from the biodiesel is transferred to the railroad. Since diesel fuel is fungible, the railroad simply puts petroleum diesel in their locomotive but gets the carbon credit.

The above scenario could work if the cost of biodiesel was not much higher than petroleum diesel and if there was enough supply. There would also have to be a clear audit trail to show that the truck fleet who ends up using the biodiesel does not also claim a carbon credit for their increased biodiesel usage. At this point, to the author's knowledge, no such trading scheme exists.

The competition for lower carbon fuel also comes into play. The feedstocks used to make biodiesel and renewable diesel are the same as those used for Sustainable Aviation Fuel (SAF). Since airplanes have no other options for the foreseeable future other than liquid fuels due to the required energy density of the fuel, this competition between airlines and railroads could keep the cost of biodiesel and renewable diesel quite high compared to petroleum diesel. The economics may not be in the railroads' favor to simply buy more biofuel and let someone else use it.

On the other hand, the competition for natural gas would not be as intense for the railroads. While there is competition, the large users of natural gas have other alternatives to reduce their carbon footprint. For example, electric utilities can install wind and solar farms. By moving from coal to natural gas, many of the electric utilities have already deeply cut their carbon footprint. In these cases, using a higher cost RNG may not be the most cost-effective way to further reduce their carbon footprint. Homeowners are not particularly ready to or being compelled to reduce their carbon footprint, so the utility companies are still very sensitive to cost to the consumer. In this case, the cost differential per BTU of RNG vs. petroleum diesel, or especially biodiesel or renewable diesel, could become a very

compelling business case when it comes to the cost per ton of carbon reduction by using RNG instead of biodiesel or renewable diesel.

Summary

There are multiple roads to carbon reduction for railroads. The options include electrification (both catenary and battery), hydrogen, liquid biofuels (biodiesel and renewable diesel), and Renewable Natural Gas.

The choice of fuels and technologies to reduce a railroad's carbon footprint will be up to each railroad and will have to include a multitude of factors, not just the amount of carbon reduction in the selected fuel. Costs of fuel infrastructure changes, locomotive technologies and ongoing maintenance need to be factored into the cost equation. Then there is the cost per diesel gallon equivalent of the fuel itself. This cost must be based on realistic facts, such as the current cost of the fuel and the projected cost based on actual supply chains and competitive pressure for the fuel in other market sectors. Caution must be used when the projected future price for a specific fuel seems unusually low compared to the current price for the fuel. Is the projected price based on realities of the fuel production cost today and realistic supply projections? Or is it based on a "perfect storm" scenario where if everything works at its peak potential and enough money is poured into the production of the fuel from private and/or government sectors, the price of the fuel *could perhaps* drop to the price level projected?

This paper has primarily looked at RNG as a drop in low carbon fuel option because of its fungibility and the fact that RNG is molecularly the same as non-renewable natural gas. RNG also is being produced in large quantities right now through proven processes, such as landfill gas scrubbing and waste stream (wastewater and manure) digesters. There is definitive pricing for RNG currently available that can be used for fuel cost analysis and there are existing and new development locomotives that can use RNG. While each railroad will have to consider the combined fuel and implementation costs of RNG, and then compare these to the costs of other low-carbon fuel options, it may be that the use of RNG is the most cost-effective pathway to a lower carbon footprint.

Future of Locomotive Engine Oil(s) for Flexible Fueling

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Abstract

Research and testing of alternative fuels, in freight and passenger locomotive fleets in North America and in several international rail networks, was accelerated after the International Marine Organization issued a revised fuel regulation in 2020 (IMO 2020), where the maximum sulfur content in marine fuel was reduced to 0.5%. Sustainability goals have also been established by the North American Class I Railroads to drive a reduction in emissions of their operations.

At present, railroads in North America utilize EPA Tier 0 through Tier 4 locomotives. Approximately 37,600 ⁽¹⁾ locomotives (active service + standby) run mostly on #2 ultra-low sulfur diesel and may run with blends with up to 20% biodiesel and 80-100% renewable diesel. Reportedly, the collective average locomotive age is 27.4 years old in the North American Railway Network.

Flexible fueling considerations are expanding into natural gas, hydrogen, methanol, and other low carbon fuel options. Consumption of alternative fuels in locomotives may have unique effects on engine oil performance attributes and degradation rates which are to be considered.

Introduction

Fuels with lower carbon intensity than #2 diesel have been under consideration to help meet the sustainability goals set by the North American Class I Railroads. In addition to low carbon fuels the industry may see the introduction of alternate technologies like battery hybrids, hydrogen fuel cells etc. in the future. The development time, infrastructure implementation, and fuel availability are key factors in determining what alternative fuels are going to make it to market.

In parallel with the sustainability goals, the railroads must be prepared for potential government regulations. The illustration shown in Figure 1, highlights the timeline that has influenced key stakeholders in the North American Railway

Network. Recent developments in Q4 2024 through present-day may alter the projected paths forward.

N. American Railway Network Considerations



Figure 1: Government Regulations Timeline Considerations

With any change in fuel, an evaluation of the lube oil performance needs to be completed. The locomotive fleets that currently run medium speed diesel engines on LMOA Generation 7 engine oil or run high speed diesel engines on API CK-4 oil, may need to adapt to use a lube oil that matches the needs of alternative fuels or flexible fuels utilization. The known characteristics of each alternative fuel will be discussed, and future research described below.

Current Lube Oil Specifications

The Locomotive Maintenance Officers Association (LMOA) Generation 7 (LMOA GEN 7) locomotive engine oil used in medium speed engines today was developed to meet the performance expectations of EPA Tier 4 locomotives as well as legacy fleet locomotives consuming diesel fuel. Compared to Generation 6 oil, Generation 7 has a higher base number, limited sulfur, ash, and phosphorous content, and revised finished oil viscometrics. The LMOA Generation 7 oil is defined below.

LMOA GEN 7 Performance Category Definition

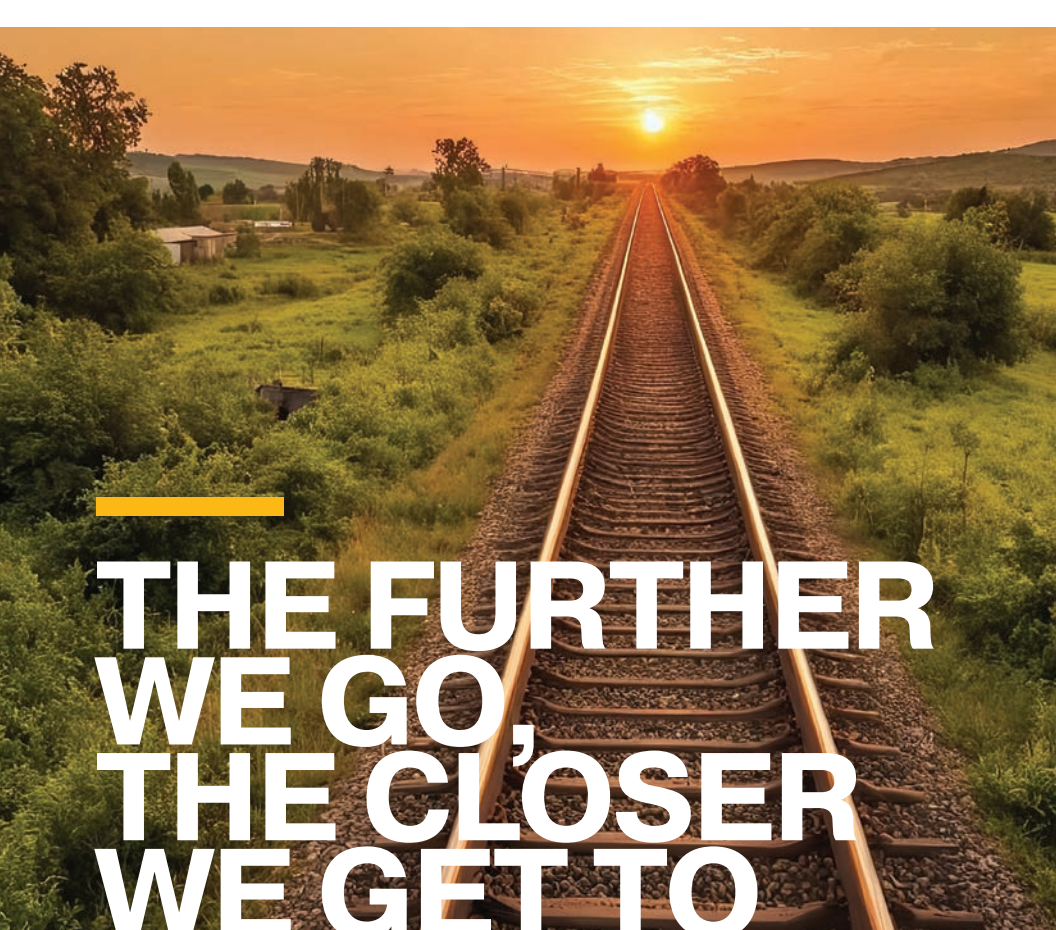
LMOA GEN 7 locomotive engine oils must be able to maintain current performance expectations while operating in locomotives meeting 2015 EPA Tier 4 Emission Standards and legacy fleet locomotives. The Fuels, Lubes, and Environmental Committee (FL&E) defines LMOA GEN 7 diesel locomotive engine oil performance attributes and qualities per the following guidelines:

- The finished oil formulation must be suitable for use in locomotive fleets with Tier 4 and older locomotive engine models.
- The finished oil formulation must demonstrate equivalent or improved performance over the previous generation oil. These performance characteristics include deposit and wear control, alkalinity retention, acid control, viscosity control, thermal and oxidative stability, engine cleanliness, and sludge control.
- The locomotive engine oil formulation must be tested to demonstrate acceptable compatibility with existing original engine manufacturers (OEMs) approved oil formulations.
- Used oil analysis trending of the finished oil formulation must demonstrate the ability to maintain and/or exceed established locomotive maintenance intervals without breaching OEMs used oil condemning limits.
- The finished oil formulations must pass all OEM test requirements which may include laboratory and field testing.
- Issuance of finished oil formulation approval letters by the OEMs is a prerequisite for claiming LMOA GEN 7 performance.

Field testing to demonstrate LMOA GEN 7 performance must adhere to the following:

- Field testing must be conducted in accordance with the procedures prescribed in the LMOA FL&E paper titled “Engine Lubricating Oil Evaluation Field Test Procedure” published in the year 2000^[1]
- The field test protocol must be reviewed and approved by the OEMs.
- Performance must be demonstrated in EPA Tier 4 compliant locomotives.
- The selected locomotives must be operated in a service having a severity level meeting the respective OEM’s requirements.
- Resultant field test data must be reviewed by the individual OEMs for issuance of written approval and recognition.

High speed locomotive engines utilized in low load passenger rail and shunt service are typically lubricated by API CK-4 diesel engine oil. API CK-4 oils are designed to improve oxidation resistance, shear stability, and aeration control. They are effective at helping new diesel engines meet emissions control standards and are backward compatible with older engines that use API CJ-4, API CI-4, API CI-4 PLUS, and API CH standards. API-CK4 oil is not currently approved by any medium speed engine OEMs but presents an opportunity for future research. It can be used in on-highway and non-road diesel engines (i.e. high speed, low horsepower) with diesel fuels up to 500 ppm sulfur content. It is also approved for use by some high-speed engine manufacturers for engines consuming diesel alternative fuels.



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Oil flow characteristics, engine loading, operational factors, filtration methodology and scheduled maintenance intervals can be different between medium and high-speed engines. Multi-viscosity oils can impact boundary layer formation on bearings and bushings which is an important fact to consider on any engine not designed for high-speed diesel oil. Also, CK-4 oils do not consider the use of silver in some legacy locomotive engine bearings. High levels of zinc and phosphorous in CK-4 oils can cause degradation of legacy locomotive engine bearings.

CK-4 oils have demonstrated good performance in some high-speed engines in both diesel and alternative carbon-based fuel (i.e. methane, biofuels, natural gas, etc.) applications. This presents an opportunity for further research on the utilization of these oils with modern locomotive engines.

The high combustibility of hydrogen(H_2) fuel presents a risk in compatibility as some of the constituents present in CK-4 oils can retain heat that allows for preignition in the cylinder, causing engine knock.

API CK-4 specifications include the following:

- **Viscosity:** API CK-4 oils must have a minimum HTHS viscosity of 3.5 cP @ 150°C .
- **Sulfur content:** API CK-4 oils must have a sulfur content of no more than 0.4% .
- **Phosphorus content:** API CK-4 oils must have a phosphorus content of no more than 0.12% .
- **Sulphated ash:** API CK-4 oils must have a sulphated ash content of no more than 1.0% .
- **Viscosity grades:** API CK-4 oils are available in SAE 30 and SAE 40 weight grades, such as 10W-30, 15W-40, and 5W-30 synthetics.

Effects of hydrogen on lube oil and potential solutions

Combustion of H_2 gas can lead to excess water accumulation in the engine crankcase. There are several technologies being explored to mitigate this:

- Developments in crankcase breather technology to filter water out.
- Inclusion of oil additives that trap and separate water for filtration later.
- Oil filtration packages that separate the water from the oil with and without additional oil additives.
- Engine combustion controls to burn off water.

Current and Alternative Fuels

Table 1 summarizes some of the key properties and emissions performance of several types of alternate fuels.

Fuel Type	~ Energy Density (MJ/kg)	Emissions	Pros	Cons	Impact on Lubrication
Diesel (ULSD)	45	Baseline	High energy density and established infrastructure.	High Green House Gas emissions, non-renewable	Good lubrication properties, but can form soot, acids required, and sludge.
B20P80	41.4	Lower CO ₂ and PM, and NO _x increase	Partial renewable feedstock, Improved fuel lubricity, easily additized, minimal changes to infrastructure	Cold weather operation challenges, elastomer compatibility issues, expertise in sourcing required, fuel quality issues and potential for increased H ₂ O content, reduced energy content	LMOA GEN 7 Studies are in progress
R20P80 20% Renewable Diesel, 80% Petroleum Diesel	45	Lower CO ₂ , NO _x , and PM	Partial renewable feedstock, compatible with existing infrastructure for production	Potential for increased H ₂ O content, Reduced energy density	LMOA GEN 7 studies are in progress
R80B20 80% Renewable Diesel, 20% Biodiesel	37	Lower CO ₂ , NO _x , and PM	100% Renewable feedstock, biodegradable	Cold weather issues, potential for increased H ₂ O content, reduced energy density	Can cause increased wear and deposit formation. LMOA GEN 7 studies are in progress
R100 100% Renewable Diesel	44	Lower CO ₂ , NO _x , and SO _x	100% Renewable feedstock, compatible with existing infrastructure	High cetane which can cause knocking on older engines, elastomer compatibility issues, limited additive technology available, reduced energy density	LMOA GEN 7 Studies are in progress

Fuel Type	~ Energy Density (MJ/kg)	Emissions	Pros	Cons	Impact on Lubrication
Dual Fuel with Diesel and LNG substitution rates	55	Lower CO ₂ , higher methane	Abundant in availability, lower CO ₂ emissions	Methane leakage, infrastructure requirement (fuel tenders)	High ash content on gen 7 oil resulted in engine inoperability. Hybrid engine oil formulated and approved for use in dual fuel medium speed engines.
LNG / CNG Liquefied Natural Gas / Compressed Natural Gas	50	Lower CO ₂ , higher methane	High energy density, lower CO ₂ emissions	Methane leakage, cryogenic or compressed storage needed, use of tenders	Hybrid Engine Oil formulated recommended for medium speed compression type engines.
Hydrogen For internal combustion engine (ICE)	120	Lower CO ₂ , water vapor	Nearly zero emissions at point of use, high energy	Storage, transportation and infrastructure challenges	Water handling (corrosion), pre-ignition. LMOA GEN 7 Studies in progress
Ammonia	22.5	Lower CO ₂ and NO _x	Zero CO ₂ emissions, can be made from renewables	Elevated toxicity, NO _x emissions, storage challenges	Can cause corrosion and react with traditional additive chemistry
Ethanol	26.8	Lower CO ₂ , higher aldehydes	Renewable, can be produced from biomass	Lower energy density, infrastructure changes	Can cause corrosion, increase water content, reduce viscosity through dilution and reduce additive effectiveness, may require special engine lubricants
Methanol	19.9	Lower CO ₂ , higher formaldehyde	Renewable, can be produced from various feedstocks	Lower energy density, toxicity, infrastructure changes	Can cause corrosion and may require special engine lubricants

Table 1: Current and Alternative Fuel Properties [2], [3], [4], [5]

Table 2 provides an overview of some critical design factors based on engines designed for different applications.

	Natural Gas Engine	Marine 4-Stroke	On-Road & Off Road Truck Diesel Engines	Dual Fuel Consumption Medium Speed Engines in Marine & Locomotive service
Engine design/Operational differences				
Load Factors	90 % + steady state	Application dependent	Varying loads	Application dependent
Oil consumption rates	Trending lower	Trending lower	Increased for extended ODI	Application & Substitution ratio dependent
Catalyst System	Commonly used	IMO 2020	SCR after treatment Commonly used	Influenced by emissions and fuel regulations
Combustion Regime	Pre-Mix	Diffusion	Diffusion	Combination
Compression Ratio	Low to High	High	Medium	Medium to High
Air : Fuel ratio	Lean & Rich (Fixed AFR)	Load Dependent AFR	Lean	Load Dependent AFR
Maintenance Intervals	Fixed intervals for Hardware Conditioned based Used Oil analysis trending	OEM & Industry established intervals	Typically fixed intervals for hardware & oil drains	Application dependent with adherence to OEM recommendations

Table 2: Engine Design and Operational Differences in various application types

Testing of Fuel and Oil Combinations

The effects of alternative fuel use on an engine lubricating oil are best determined by running locomotives in service while following a robust lube oil sampling plan. Proven field performance in Line-haul operations has been accomplished for traditional B5 diesel consumption and dual fuel consumption (diesel with substitution of natural gas) scenarios. There are studies underway to determine the impact of B20 consumption in a variety of engine models at several railroads to ascertain locomotive engine oil degradation parameters. Three application scenarios are highlighted as follows.

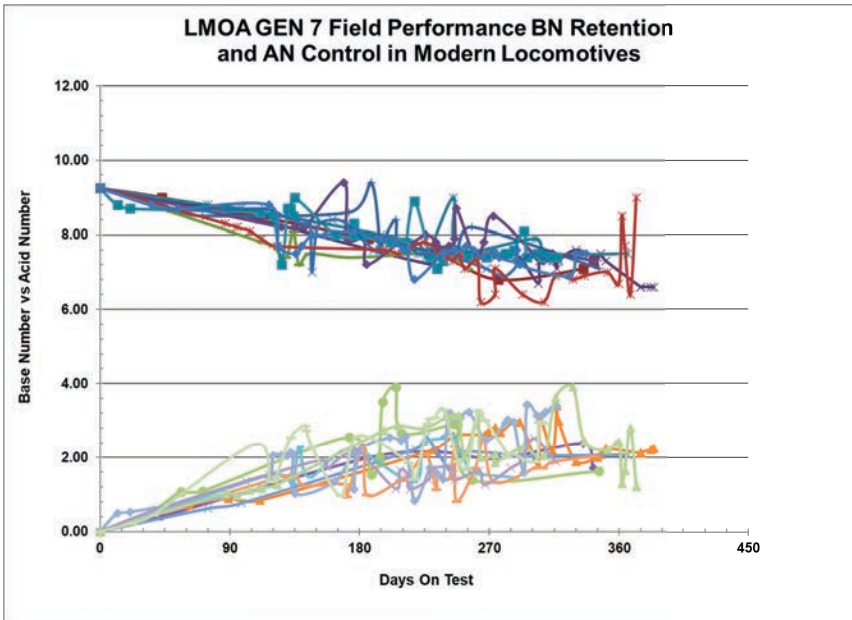


Figure 2: Base Number and Acid Number Control in Modern Locomotives

The graph in Figure 2 illustrates Base Number (BN) retention and Acid Number (AN) control in locomotives operating in severe service (> 400 MWHrs / month). The OEM approved LMOA GEN 7 oil achieved a one-year drain interval utilizing appropriate used oil condition-based monitoring. A robust margin of safety was maintained preventing oil corrosivity. All key used oil parameters were well within used oil specifications.

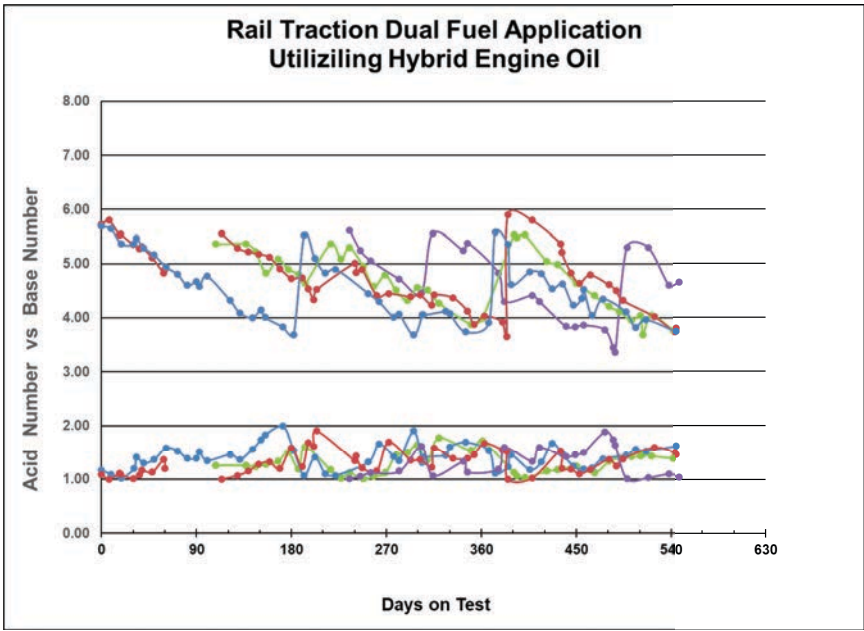


Figure 3: Base Number and Acid Number Control in Dual Fuel (Diesel and LNG) Application Utilizing Hybrid Engine Oil

The graph in Figure 3 illustrates BN retention and AN control in test locomotives operating in freight service maintaining 184-day engine oil drain interval targets. The nominal alkalinity level of the fresh hybrid engine oil is 6 BN by ASTM D2896. The technology was specifically formulated for dual fuel consumption utilizing various substitution ratios of diesel fuel and natural gas. Though this hybrid engine oil is being used in specific locomotive and marine applications with a lower condemning limit of 3.5 BN, it is not currently recommended for use in locomotives consuming neat diesel fuel and biofuel blends. Higher detergency (i.e., BN levels) oils are needed in engines consuming neat diesel and biofuel blends to achieve established maintenance intervals.

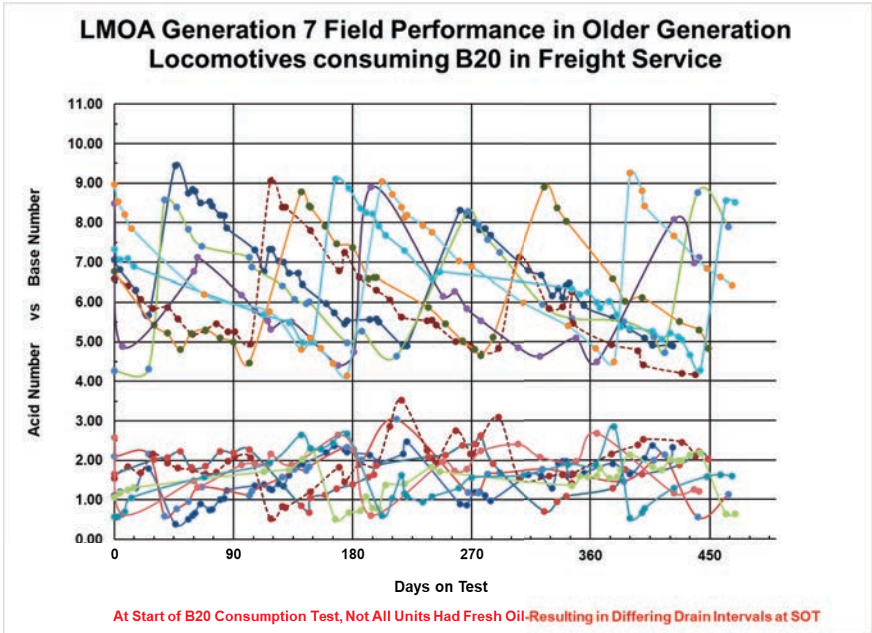


Figure 4: Base Number and Acid Number Control in Legacy Locomotives – Moderate Service

The graph in Figure 4 illustrates BN retention and AN control in legacy locomotives operating in moderate service (~ 300 MWHrs / month). The margin of safety between BN retention and AN control has decreased in comparison to locomotives consuming neat diesel. The 184-day drain interval targets may be compromised for some locomotives; studies continue to evaluate the directional trends observed. Other used oil parameters (such as, oxidation, viscosity, water) remain within used oil specifications. Condition-based used oil trending is critical for measuring oil degradation rates in support of efficient locomotive operations.

Conclusion

Looking forward, consumption of alternative fuels (hydrogen, methanol, ethanol, ammonia, methane) are on the horizon in the North American Railway Network. The rate of change is not certain due to a number of drivers (e.g., government regulations, infrastructure, sourcing, availability). Performance and endurance testing will continue to provide knowledge and shared learnings on the impact of locomotive engine oil degradation rates and suitability of current and future formulations. As illustrated in this paper, efforts are progressing (e.g., theoretical, laboratory data, and field evaluations) and may expand over time to effectively address potential solutions in a cost-effective manner. Many questions remain and given time, they will be addressed.

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Footnotes:

1. Marshall Steam Museum at Auburn Heights

Hydrogen Infrastructure and Refueling Analysis for the Rail Industry: A North American Perspective

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Introduction and Scope

The North American landscape of rail freight is unique given its expansive network, large long-distance operations, distributed fueling networks, and private ownership of the infrastructure. Therefore, the adoption of hydrogen solutions will require significant investment and alignment across industry players, from railroads and locomotive manufacturers to refueling system producers, energy companies, and government organizations.

North America's rail network spans over 140,000 miles, covering vast geographical areas and connecting major industrial hubs. This expansive network presents both opportunities and challenges for the adoption of hydrogen solutions, requiring a comprehensive and coordinated approach. This paper aims to provide a comprehensive view of the hydrogen value chain, highlighting the key areas of focus and the various considerations of adopting hydrogen solutions in the rail industry.

Hydrogen Overview

Physical Properties

Molecular hydrogen (H₂) is colorless, odorless, and non-toxic. It is the lightest and smallest element and is a gas under atmospheric conditions. Hydrogen is about 14 times lighter than air, about 83 times lighter than diesel vapor, and about 8 times lighter than natural gas.

The density of liquid hydrogen (LH₂) is 70.8 kg/m³ (4.4 lbs./ft³) at its boiling point. Higher densities can be achieved by a process called cryo-compression as shown in Figure 1. Cryo-compressed hydrogen is a hybrid technology that combines gaseous and liquid hydrogen properties. It is produced by compressing hydrogen at pressures above 500 bar (7250 psi) at temperatures around -233°C

(-387°F) providing densities of 80 kg/m³ or greater which is higher than gaseous or liquid hydrogen. This is denoted by Zone 3 in Figure 1.

The lower heating value (LHV) of hydrogen is 51,585 Btu/lb (113,725 Btu/kg) on a gravimetric basis or 30,435 Btu/gal for LH2 on a volumetric basis. For comparison, the LHV low-sulfur diesel is 18,344 Btu/lb on a gravimetric basis or 128,488 Btu/gal on a volumetric basis. Since the LHV of a kilogram of hydrogen is only slightly less (~12%) than the LHV of a gallon of low-sulfur diesel a common “rule of thumb” is that “one kilogram of hydrogen has the energy equivalent of about one gallon of diesel.” Expressed another way, 1 kg H₂ = 1 DGE (Diesel Gallon Equivalent) of locomotive fuel. As a gas, hydrogen has about a third of the LHV, 290 Btu/ft³, compared to natural gas 950-1050 Btu/ft³, both on a standard cubic foot basis (SCF).

As a transportation fuel for fuel cell cars and trucks, hydrogen is typically stored onboard as a gas at pressures of 350 bar (5000 psi) or 700 bar (10000 psi). At 20°C (68°F), the density of hydrogen is 23.7 kg/m³ at 350 bar and 39.7 kg/m³ at 700 bar. When compressed for on-board storage, hydrogen has a LHV of 76,322 Btu/ft³ at 350 bar and 128,008 Btu/ft³ at 700 bar, both at 20°C.

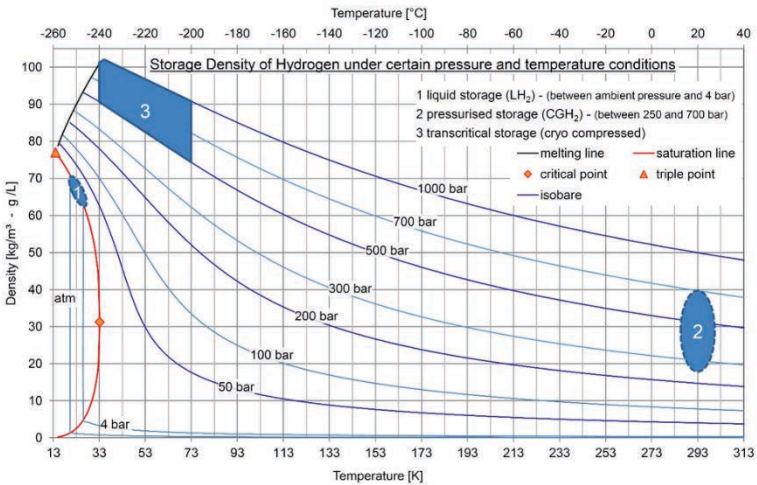


Figure 1. Density of hydrogen as a function of temperature and pressure
 (Source: Wikipedia <https://creativecommons.org/licenses/by-sa/4.0/deed.en>)

Note that the LHV of a gallon of LH2 is about one-fourth that of a gallon of low-sulfur diesel. This lower energy density presents storage challenges requiring considerably more space compared to diesel to store enough hydrogen onboard for line haul applications. A hydrogen locomotive carrying LH2 would require approximately four times the storage volume to hold the same amount of energy

as today's line haul diesel locomotives, thus necessitating the use of a tender car to provide the same operational performance in terms of time or distance between refueling.

Hydrogen is a flammable gas. Hydrogen burns with an invisible, odorless flame unlike diesel or natural gas which burns with a colored flame. It has a wider flammability range in air (4%-74% by volume) than diesel vapor (1.4%-7.0%) or natural gas (5.3-15%). The autoignition temperature of hydrogen, 585°C (1,085°F), is considerably higher than that of diesel vapor, 210°C (410°F), but is comparable to that of natural gas, 539°C (1,003°F). Under the optimal combustion condition (29% hydrogen to air volume ratio), the energy required to ignite hydrogen combustion (0.02 MJ) is considerably lower than that required for natural gas (0.29 mJ) or diesel vapor (0.20mJ); however, at low concentrations in air, the energy required to initiate combustion is similar to that of other fuels. From safety considerations, H₂ will rise when LH₂ leaks and evaporates since H₂ is 14 times lighter than air, whereas diesel vapors will tend to remain at ground level when diesel leaking from a tank evaporates since diesel vapors are about 8 times heavier than air.

Hydrogen Supply Overview

Current Production

The U.S. currently produces about 10 million metric tons (MMT) of hydrogen annually primarily by steam reforming of natural gas^[1] equivalent to 10 billion U.S. gallons of diesel fuel when compared from an energy content standpoint. Petroleum refining and ammonia production consume 68% and 21%, respectively, of the hydrogen produced annually. 60% of hydrogen is produced onsite at the point of use. The remaining 40% is sold by industrial gas companies with refineries consuming 70-80% of the industrial gas sales. Texas and Louisiana account for about 45% of the total U.S. hydrogen production.

Global hydrogen production reached 97 MMT (97B DGE) in 2023. Global hydrogen demand continues to be concentrated in the refining and chemical sectors, primarily supplied by hydrogen produced from unabated fossil fuels. Low-emissions hydrogen has played only a *marginal* role, with production of less than 1 MMT (1B DGE) in 2023.^[2]

Future Production

Several models and analyses for the United States estimate the opportunity for lower carbon hydrogen production to increase from nearly zero today to 10 MMT (10B DGE) per year by 2030, to 20 MMT (20B DGE) per year by 2040, and to 50 MMT (50B DGE) per year by 2050^[6]. Although clearly ambitious, these production estimates are based on demand scenarios that assume cost competitiveness for hydrogen use in specific sectors such as industrial applications, heavy-duty transportation, and long-duration energy storage. Global low-emissions hydrogen



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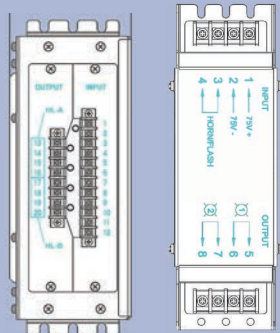
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production has the potential to reach 49 Mt per annum (Mtpa) by 2030 (49B DGE) based on announced projects. This represents an almost 30% increase compared to the projections made when the Global Hydrogen Review 2023 was released [2].

The number of projects reaching final investment decision (FID) is growing. Announced production that has taken FID doubled compared to last year, reaching 3.4 Mtpa (3.4B DGE). This represents a fivefold increase in today’s production by 2030, with the output split almost equally between electrolysis (1.9 Mtpa / 1.9B DGE) and fossil fuels with carbon capture, utilization, and storage (CCUS) (1.5 Mtpa / 1.5B DGE). Hydrogen production from fossil fuels with CCUS has gained traction over the past year. While the total potential production from announced projects grew only slightly compared to last year, several FIDs were made for previously announced large-scale projects, all of which are in North America and Europe. As a result, the potential production in 2030 from projects using fossil fuels with CCUS that have taken FID more than doubled from 0.6 Mtpa (600k DGE) in September 2023 to 1.5 Mtpa (1.5M DGE) today. However, these still will fall short of previously projected demands if the current trajectory continues.

As shown in Figure 2, based on announcements, the United States will remain the frontrunner in hydrogen production from fossil fuels with CCUS, with 5.6 Mtpa (5.6B DGE) H2 by 2030 (more than 3.5 Mtpa / 3.6B DGE if projects at very early stages of development are excluded), followed by Europe with more than 3.5 Mtpa (3.5B DGE) H2 by 2030 (more than 3 Mtpa / 3B DGE if projects at very early stages of development are excluded). This is an increase of almost 30% for the United States since the GHR 2023. [2]

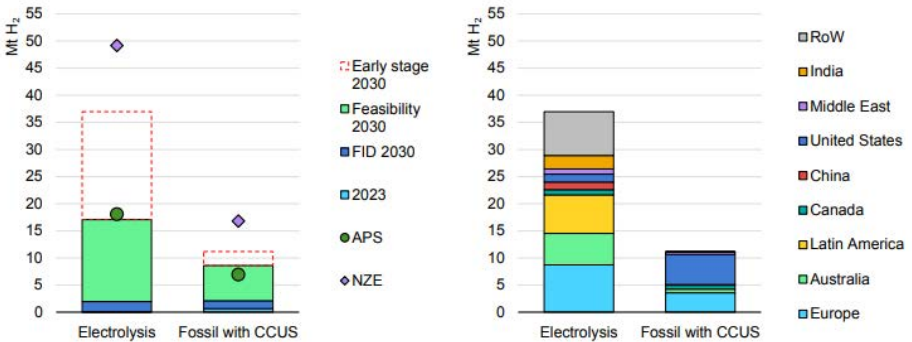


Figure 2. Low-emissions hydrogen production by technology, status and region based on announced projects and in the announced pledges



Figure 3. Global low carbon hydrogen projects at various stages

Challenges and Risks

Despite the progress made, many projects are still in planning or even earlier stages, as shown in Figure 3. For the full projected production pipeline to be realized, the sector would need to grow at an unprecedented compound annual growth rate of over 90% from 2024 until 2030, far exceeding the growth experienced by solar PV during its fastest expansion phases.^[3]

Several projects have faced delays and cancellations, jeopardizing a significant portion of the project pipeline. The main reasons for these setbacks include^[3]:

- *Unclear Demand Signals and Regulatory Uncertainties:*
Investors require clear and stable regulatory frameworks to secure investments. Changing policy position on energy in leading countries may change demand. Lack of long-term consistency and clarity can lead to companies halting their hydrogen programs or postponing projects while awaiting clarity.
- *Delays to Incentives and Financing:*
New vectors of energy like hydrogen require significant investment and lead to higher energy costs. Customer willingness to pay and a mechanism to share investment costs across the value chain is leading to increased cost. One such example is shown in H2 cost curves in Figure 4.
- *Licensing and Permitting Issues:*
Lack of policies and procedures for new greenfield projects continue, however, the processes are far from mature requiring extensive time and resources needing to be spent for gathering permits for such infrastructure undertaking.

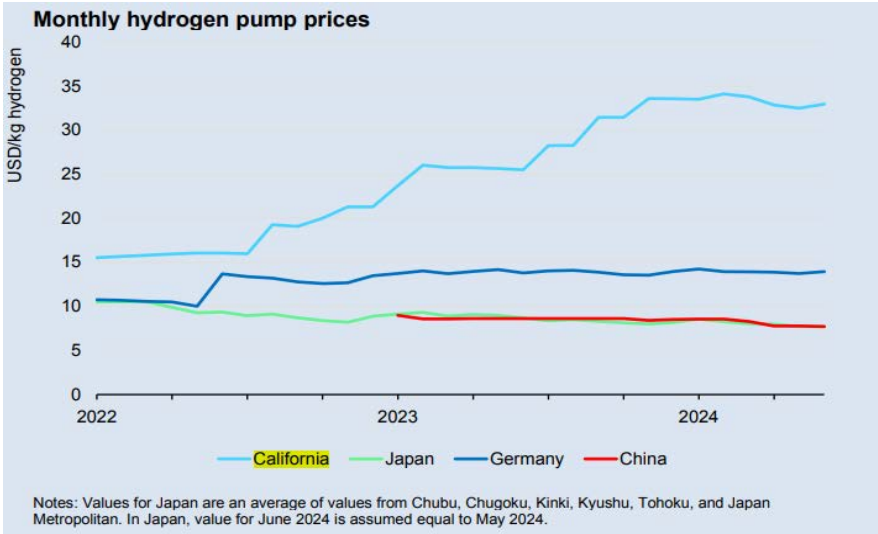


Figure 4. Hydrogen prices at pump in key regions ^[2]

Hydrogen Hubs

In 2021, Congress passed the Infrastructure Investment and Jobs Act which included \$8B for the establishment of at least four hydrogen hubs to accelerate a national network of hydrogen producers, consumers, and connective infrastructure to accelerate the commercial-scale deployment of clean hydrogen.^[4]

In 2023, the Department of Energy's Office of Clean Energy Demonstration (OCED) announced the selection of seven regional hydrogen hubs as shown in Figure 5. Collectively, the seven hubs are expected to invest more than \$40B. Buildout of the hubs will use a stage-gate process with four phases: Phase 1 - Initial planning, analysis, and community engagement, Phase 2 - Finalizing engineering designs, securing site access, and further community engagement, Phase 3 - Construction and installation, and Phase 4 - Full operations and data collection. The hubs are expected to produce nearly 8,000 metric tons of hydrogen tons per day, roughly equivalent to 8 million gallons of diesel. Annually, this equates to 3 million metric tons hydrogen per year (roughly equivalent to 3 billion gallons of diesel) when fully operational.

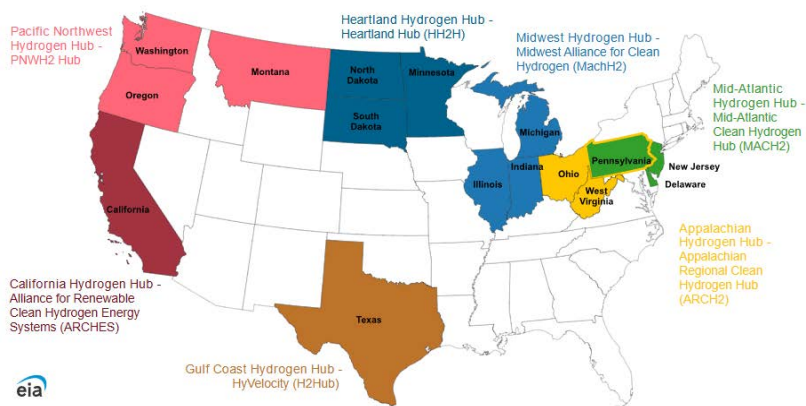


Figure 5. Map of Hydrogen Hubs in United States – Apr 2024
 (Source. U.S. Energy Information Agency)

Hydrogen Storage, Distribution, and Refueling Infrastructure

Today's locomotives carry upwards of 5,000 gallons of diesel and can be refueled at a rate as high as 300 gpm at high volume mainline fueling locations with high fuel rate nozzles. They can be refueled at a fixed location, i.e., a fueling rack or pad, or using a mobile refueling truck.

Gaseous Hydrogen Refueling

Hydrogen-fueled fuel cell locomotives and hydrogen tenders are in the early stage of development. Gaseous hydrogen is currently the primary form for onboard refueling and storage technologies developed for cars and trucks. Gaseous hydrogen is stored onboard the locomotive or a tender in a series of cylindrical storage tanks manifolded together. Gaseous hydrogen storage tanks are classified into "Type I through Type IV" based on their materials of construction with Type I being metal, Types II and III having a metal liner with a hoop or full composite wrap, respectively, and Type IV having a polymer liner with a full composite wrap. Both Types III and IV are used in mobile applications. Type IV tanks are lighter in weight and provide higher storage density but are more costly to manufacture than Type III tanks. Type III tanks are used on buses and trucks where lower storage density is offset by lower costs.

Hydrogen has unique properties unlike other fuels used in the rail industry such as diesel and natural gas. Unlike nearly all other gases, hydrogen heats up when it expands which will cause the temperature inside the storage tank to increase when refueling a locomotive or tender. The temperature rise depends on

many factors including the temperature difference between hydrogen and ambient temperature and the thermal conductivity and thermal mass of the conduit and the storage tank. To maintain the temperature of the storage tank within safe operational limits, for example, Type IV tanks have an upper temperature limit of 85°C (185°F); hydrogen is typically precooled to -10 to -40°C (14° to -40°F). Fueling rates depend on the precooling temperature with an average rate of about 10 kg/min achievable when precooled to -40°C and slower fueling rates when precooled at a higher temperature. SAEJ2601-5 “High-Flow Prescriptive Fueling Protocols for Gaseous Hydrogen Powered Medium and Heavy-Duty Vehicles” establishes the protocols and process limits for hydrogen fueling of on-road vehicles with compressed hydrogen storage.^[5]

Gaseous hydrogen refueling stations for fuel cell automobiles and trucks are currently being deployed with 54 retail stations operating in the U.S. mostly in California as of 2024. ^[6] A typical station consists of bulk hydrogen storage tanks, high-pressure compressors, a cooling system, a dispensing system with a nozzle that connects to the vehicle, and safety features that continuously monitor the refueling process electronically. The experience of refueling with gaseous hydrogen is comparable to that of refueling with gasoline or diesel.

Liquid Hydrogen Refueling

Liquid hydrogen (LH2) is expected to be the predominant form of hydrogen used in the rail industry as the fuel cell locomotive technology matures given its higher volumetric energy density than 350 or 700 bar (5000 or 10000 psi) gaseous hydrogen. Although LH2 will be stored onboard the locomotive or tender, the fuel cell will operate on gaseous hydrogen requiring a vaporizer between the LH2 storage tanks and the fuel cell system.

LH2 is a cryogenic liquid and handling of LH2 presents some unique safety challenges during refueling. Uninsulated piping or LH2 leaks can cause cryogenic burns if they contact unprotected skin. LH2 leaks behave differently than gaseous hydrogen leaks. As leaking LH2 evaporates, the evaporated hydrogen will rise and diffuse quickly in air because its low density results in high buoyancy; however, a white cloud of condensed water vapor will develop due to the cryogenic temperature even in dry climates. The vapor cloud will remain at ground level and may move horizontally but will dissipate and quickly rise as it warms. ^[7] Uninsulated piping or LH2 spills can cause oxygen and nitrogen, the main components of air, to condense out forming an oxygen-rich liquid or solid layer because the temperature of LH2 is below the melting temperatures of oxygen and nitrogen. Oxygen-rich liquids or solids present a significant fire or explosion risk when exposed to flammable materials. LH2 refueling should never be located over asphalt surfaces because the flammable oil-based asphalt can ignite if contacted by an oxygen-rich liquid air formed on uninsulated piping or due to a spill ^[8].

One of the major challenges for onboard LH₂ storage is minimizing hydrogen loss due to evaporation due to heat leakage into the tank. Metallic Type I tanks constructed of either 304SS or 316SS are traditionally the choice for LH₂ storage. The tanks are double shelled with a vacuum insulation layer between the inner and outer shell to minimize conductive and convective heat transfer with multilayer insulation to minimize radiative heat transfer to the inner shell to minimize boil-off losses.^[9]

Refueling itself is another source of hydrogen loss. As LH₂ fills the tank, the gaseous hydrogen in the headspace above the liquid is vented as the tank pressure rises above a preset limit. Depending on the station configuration, the gaseous hydrogen is either vented to the atmosphere or returned to the station where it is either reliquefied or compressed.

Linde is leading a Department of Energy-funded project to develop LH₂ fueling technology for rail capable of delivering LH₂ at a flow rate of 100 kg/min with a minimum of 1500 kg per fill with less than 4% vapor loss during transfer.^[10]

Bulk Compressed Hydrogen Storage

Storage of compressed hydrogen requires the container for storing hydrogen and the compressors needed to achieve the desired storage pressure. Storage of large volumes of compressed hydrogen is generally limited to pressures below 100 bar (1450 psi) in above ground vessels and 200 bar (2900 psi) in underground vessels due to material property issues and operating costs.^[11] Capital costs for large scale above ground storage are significantly higher than underground storage.^[12] Large amounts of hydrogen are already stored in underground salt caverns in Texas; however, not all regions have the appropriate geology for underground storage.

An alternative to underground geological storage is the use of metal containers. While there is little experience with large-scale storage of compressed hydrogen in metallic vessels, there is considerable experience storing natural gas in metallic vessels. Of the various metallic vessel storage options, pipeline storage is the most promising which has been used extensively in the natural gas industry since the 1980s. Based on the existing pipelines used for natural gas storage, about 12 metric tons of hydrogen (12,000 DGE) can be stored per km of pipeline.^[13]

Bulk Liquid Hydrogen Storage

Major refueling locations for the six major Class 1 railroads routinely fuel 100,000 gallons or more of diesel per day. To support this refueling level, many of these locations have large storage tanks storing anywhere from 100,000 to 1,000,000 or more gallons of diesel. For example, BNSF typically pumps on average 750,000 gallons of diesel per day at Belen, NM, and on its busiest days can fuel as much as 1,000,000 gallons utilizing four large diesel storage tanks, each holding 2.7 million gallons of diesel.^[14] The largest liquid hydrogen storage tank is owned by NASA and is located at the Kennedy Space Center in Florida.

This tank has a usable capacity of 4,732 m³ providing storage for 335,000 kg of LH₂, equivalent to about 335,000 gallons of diesel.^[15]

Work is underway to develop larger hydrogen storage tanks capable of storage capacities ranging from 20,000 to 100,000 m³ capable of storing up to 1,400,000 to 7,100,000 kg of LH₂ (equivalent to about 1.4 to 7.1 million gallons of diesel).^[16] Major U.S. manufacturers of LH₂ storage tanks and vessels are CB&I (formerly known as Chicago Bridge and Iron) and Chart Industries. There are 14 liquefaction plants operating in the United States with production capacities ranging from 5 to 32 metric tons per day (mtpd), the equivalent of 5,000 to 32,000 DGE per day, providing a total production capacity of 304 mtpd (304,000 DGE per day) as of May 2024.^[17]

There are four plants under construction and nine plants in various stages of planning and development that could provide an additional 490 mtpd (490,000 DGE per day) of LH₂. A major factor in the cost of LH₂ is the cost of liquefying hydrogen. Liquefying hydrogen is an energy intensive process with most modern liquefaction plants having an energy demand of about 10 kWhel/kg, equivalent to about 30% of the energy of hydrogen. It is thought that the energy demand could be reduced to as low of 6 kWhel/kg in large liquefaction plants with improvements in technology.^[18]

A major challenge for storage of liquid hydrogen at any scale is minimizing evaporation, referred to as “boil-off.” Boil-off represents not only a loss of the hydrogen vaporized, but also a loss of the energy spent liquefying hydrogen. Because liquid hydrogen must be maintained at a temperature of -252.77°C (-423° F) to prevent evaporation, large storage tanks are double-shelled and generally spherical in shape instead of cylindrical to minimize heat inleak. To minimize boil-off, the space between the inner and outer shell serves as insulation. Vacuum insulation provides the highest degree of insulation but is often cost-prohibitive. Filling the space with glass bubbles, such as 3M K-1, coupled with a cryogenic refrigerator with an internal heat exchanger can provide boil-off rates below 0.1% per day.^[18]

Consideration of Existing Pipeline Infrastructure for H₂ Transport

Hydrogen pipelines are the most cost-effective way for transporting the large amount of hydrogen from the hydrogen production facility to major refueling locations along the U.S. rail network. Currently, there about 1,600 miles of hydrogen pipeline in the United States, nearly all located in Texas and Louisiana along the Gulf Coast, servicing the major petroleum and chemical producers in the region. The pipelines are owned by merchant producers.

A recently published Electric Power Research Institute, Inc. (EPRI) study suggests that material costs for new hydrogen pipelines would be about 10% higher than for new natural gas pipelines and capital costs would be 14 - 16% higher per unit energy flow rate for hydrogen compared to natural gas.^[18] These

estimates for pipeline costs likely understated the difference because the cost of compressor stations, which are expected to be higher for hydrogen pipelines than natural gas pipelines, which were not considered.

Hydrogen has a smaller molecular size compared to natural gas, which increases the risk of leaks and embrittlement in existing pipelines, necessitating upgrades or replacements with materials resistant to hydrogen's effects. Recent advancements in materials science and engineering are contributing to the mitigation of risks associated with hydrogen pipelines. Researchers are developing advanced composite materials and coatings that enhance pipeline resistance to hydrogen embrittlement and leaks. These materials combine high strength with flexibility, allowing pipelines to safely transport hydrogen under various pressure conditions. Additionally, innovative sensor technologies are being integrated into pipeline systems to provide real-time monitoring of hydrogen leaks and structural integrity. These sensors, utilizing cutting-edge Internet of Things (IoT) connectivity, can detect minute changes in pressure and composition, enabling rapid response to potential hazards. Furthermore, new welding techniques and joint designs are being explored to ensure robust and secure connections in hydrogen pipelines.

To mitigate the risk of embrittlement of steel, advanced high-strength steel alloys and specialized coatings are being developed to enhance resistance to hydrogen-induced degradation. Additionally, meticulous maintenance protocols and regular inspections are essential to monitor the integrity of steel pipelines in hydrogen service. Recently, Tata Steel developed India's first indigenously produced hydrogen transport pipes designed to transport 100% pure gaseous hydrogen under high pressure (100 bar / 1450 psi).

Potential Challenges of Large-Scale H2 Adoption in Railroads

Proton Exchange Membrane (PEM) fuel cells are highly efficient, reaching a maximum efficiency of around 60%. That is true but only at low power. As power increases FC efficiency drops. Diesel engines are most efficient at high power, high load as shown in Figure 6. Hydrogen as an energy carrier (for fuel cells) or as an alternative fuel (blended with diesel fuel in modified diesel engines) will present unique and significant challenges for the railroad industry.

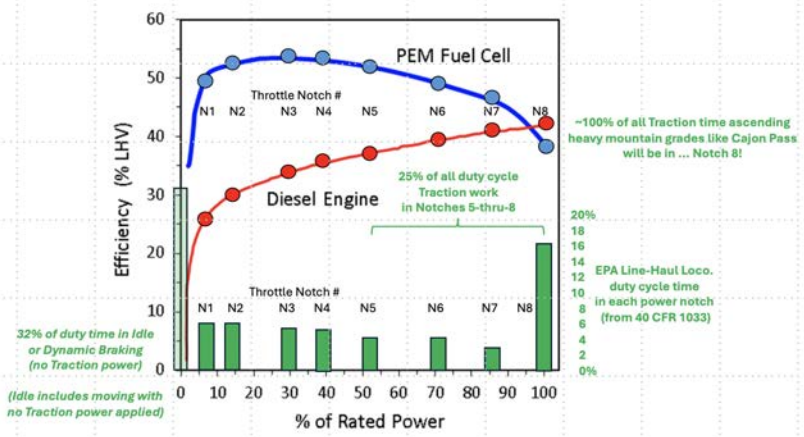


Figure 6. Proton Exchange Membrane Fuel Cell vs. Diesel Engine Efficiency [19]

Assuming hydrogen is made using electrolyzers powered by renewable electricity, it can be a zero-carbon energy carrier or fuel. Renewable natural gas can similarly be low carbon. However, hydrogen has a large “energy cost” due to the efficiencies of processes. The “grid-to-rails” energy efficiency for hydrogen fuel cells is no greater than 25% due to the multiple steps required as shown in Figure 7.

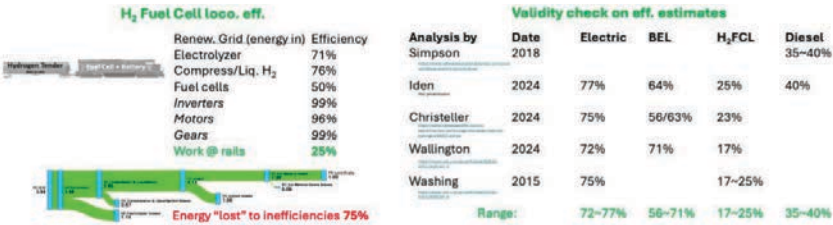


Figure 7. Efficiency comparison of H2 Fuel Cell vs. Battery Electric and Diesel Engine [19]

Even if a railroad does not fund hydrogen manufacturing, compression/liquefaction, transportation and storage, the greater electrical energy required to “make” hydrogen (compared to alternative uses of the electrical energy, such as charging propulsion batteries or powering electric locomotives) translates into relatively high energy costs for a hydrogen propulsion system. Hydrogen will also require a massive investment in manufacturing, storage and transportation capex.

Dedicated Hydrogen Corridors

While the challenges associated with a complete switch from one fuel to another can be daunting, there are options that could make switching to a new fuel less expensive and complex. There is no reason to assume that a new fuel has to be used throughout a rail system. It may be that a particular fuel lends itself to use on just certain lines or corridors. While this does add some operational complexity, that complexity may be outweighed by favorable factors such as cost, or cost offset.

The concept of fuel replacement on just one segment or corridor is not new. In the early 20th century when steam was the motive power of choice the fuel could be wood, coal, or oil. Some railroads found that using oil as fuel in their steam locomotives was better on certain sections of the railroad than coal, either because it was easier to obtain or less expensive than coal. Because the locomotive tender had to be configured for the specific fuel, a railroad might set up a dedicated fleet of oil burning steam locomotives in just a certain sector of the railroad. Other sectors would still use coal. This required dedicated steam locomotives with oil tenders for a specific corridor, but the benefits of using oil outweighed the inconvenience and cost of having a dedicated fleet of oil-fired locomotives.

Later, when diesel locomotives were introduced, railroads like the Santa Fe, rolled diesel locomotives out on dedicated corridors where these new locomotives would have substantial advantages over steam. Deserts were targeted first because of the scarcity of water. The new diesel locomotives made a quick impact even though locomotives had to be changed out (steam to diesel) and new fueling and maintenance facilities needed to be constructed.

Although there would be analysis and costs involved, a similar situation may be arguable for fuels such as hydrogen. Rather than automatically assuming that the use of hydrogen or another fuel has to be rolled out across the entire rail network, looking at specific corridors that could best benefit from hydrogen might be a reasonable way to roll out a hydrogen infrastructure and hydrogen locomotives.

This is exactly the strategy that CPKC appears to be using with its roll out of hydrogen hybrid locomotives. For line haul, CPKC has chosen a route and even a specific commodity. The CPKC line haul locomotives are targeting coal trains. On May 4, 2023, CPKC announced that it entered into a long-term rail agreement

with Teck Coal Limited for the transportation of steelmaking coal from Teck's four operations in southeastern B.C. The agreement builds on existing services in place and runs until the end of 2026. The CPKC press release states:

In support of building lower emission transportation corridors and as a shared commitment to sustainability, CPKC and Teck intend to collaboratively develop a unique pilot program that integrates the use of CPKC's hydrogen locomotives into Teck's steelmaking coal supply chain. It is anticipated that this effort will reduce greenhouse gas emissions, with testing commencing in early 2024.

Note that CPKC specifically mentions the build out of specific "green \ transportation corridors." Rather than assuming that the entire system would be converted to hydrogen, the installation of hydrogen production facilities and refueling infrastructure targets specific areas where hydrogen makes the most sense as a fuel.

Additionally, the fueling stations were built in Calgary and in Edmonton as a partnership with ATCO EnPower, a division of Canadian Utilities Limited. This partnership with existing utility or hydrogen focused supply companies is probably the easiest option for rolling out new fueling infrastructure, even if the per kilogram cost of the hydrogen fuel is a little higher. ATCO EnPower provided engineering, procurement and construction services for each of the dedicated, on-site hydrogen locomotive refueling stations and signed an agreement to operate these facilities. In the CPKC model, each of the facilities includes a 1-megawatt (MW) electrolyzer, compression, storage, and dispensing systems for locomotive refueling.

In Calgary, the electrolyzer is powered in part by renewable electricity from CPKC's existing 5-MW solar power facility co-located at CPKC's headquarters. Working with a partner brings expertise into a fuel program that would not be readily available inside a railroad's mechanical or fuel departments.

Followed by robust pilots, Railroads could target their highest density routes where the investment required for a new fueling infrastructure and new alternative fuel locomotives would pay off the quickest. While dedicated hydrogen locomotives would have to be switched in and out of trains, this inconvenience might be outweighed by the cost or emissions reduction advantages. Or these corridors may be shorter haul routes between major terminals, in a state like California, where there may be significant incentives for reducing criteria pollutants such as NOx and PM.

Conclusion

While there are significant challenges to adopt hydrogen, industry-wide collaboration and investment in research, infrastructure, and regulatory

frameworks can pave the way for a successful transition to hydrogen-powered rail operations over the next couple decades. Collaborative efforts between industry stakeholders and regulatory bodies are also needed to foster the establishment of standardized guidelines and best practices for the safe transport of hydrogen.

The key takeaway needs to be that hydrogen or other alternative fuel options should not be looked at as an all or none option. Opportunities to use alternative are complex, and dedicated freight corridors where these fuels make sense may be the most economical or strategic option.

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Report on the Committee on Mechanical Maintenance

Wednesday, May 21, 2025

1:00 PM



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PERSONAL HISTORY

Frank Jalili

Frank has over twenty-seven plus years of Industrial, Business Development, Business Process Reengineering and Revenue Enhancement, Manufacturing process improvement and Documentation, Strategic Sourcing, Growth Strategy, and Supply Chain Strategy, and experience assisting and serving many of his clients. This includes low to mid-volume and high-mix, engine components, PTC, and Antenna Farms for locomotive, marine, stationary power generated, material handling equipment in mining, and aggregate markets serving OEM -Wabtec (GE Transportation), Progress Rail (EMD) - and Class 1 Railroads, and provided products and Services.

Frank has a diverse range of knowledge and expertise in many industries, including Railroad, Oil & Gas, Electronics/Telecommunication, and Industrial Products. Frank has held C-suite positions and as President of heavy and light industrial manufacturing companies serving Class 1 Railroads, and OEM in Dallas, Texas, and Cleveland, Ohio.

He has extensive Manufacturing Business experience encompassing Business Development, Business Process Improvement, Cost Saving and Turnaround, Operations Efficiency, Lean Manufacturing, Team Building, Manufacturing process improvement, Defect Analysis, and Supply Chain Management. He has established agility in interacting and serving his clients in domestic, and international markets.

Frank initiated and led collaborations with other locomotive component industry companies, resulting in successful meetings and negotiations with the Environmental Protection Agency (EPA) to protect and sustain the business of the aftermarket suppliers in 40 CFR1033 Control of Emission for Locomotives. CFR 1033.625 prevented over 30% lost revenue from the aftermarket suppliers, which is an over \$500,000,000 industry

Frank has successfully and through the Operations strategy, promoted changes and introduced new products and services. Built strategic alliances with a few key OEM and Class 1 railroads, resulting in generating new revenues.

Outside of work, Frank enjoys tennis, bicycling, hiking, and traveling. He has been married to Ana for over 38 years and has a son who graduated with an MS in Bio-Medical Engineering and a daughter currently pursuing her MS in Forensic Psychology.



ON BEHALF OF THE COMMITTEE, I WANT TO EXPRESS OUR GRATITUDE TO BRIAN TAYLOR, TYLER KISSICK, AND THE ELLWOOD CRANKSHAFT TEAM,

THANK YOU FOR HOSTING THE COMMITTEE'S MEETING IN JANUARY, 2025 AND PROVIDING A WONDERFUL TOUR OF YOUR IMPRESSIVE FACILITIES IN HERMITAGE, PA. IT WAS A GREAT OPPORTUNITY TO SEE THE DEDICATION AND EXPERTISE BEHIND YOUR WORK. WE TRULY APPRECIATE YOUR HOSPITALITY AND THE TIME YOU TOOK TO SHARE YOUR OPERATIONS WITH US.



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Crack Monitoring On 7FDL16 Engine Crankshaft

Prepared by :

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1. ABSTRACT

This research focuses on the failure mechanisms of locomotive diesel engine crankshafts, specifically the development of cracks that were identified due to localized heating around the lubrication channel plugs. The primary objective was to develop a methodology for monitoring the condition of crankshafts without disassembly, allowing the engines to remain operational even when cracks were present. This approach not only enabled the continued use of 49 crankshafts with visible cracks for more than six years but also emphasized the importance of managing cracks effectively to extend the service life of these assets. By leveraging non-invasive inspection methods and continuous monitoring, the life expectancy of these crankshafts was significantly prolonged, contradicting traditional views that cracks in crankshafts inevitably lead to catastrophic failure in a short period.

Keywords: Locomotive; Crankshaft; Diesel Engine; Cracks; Non-Destructive Testing; Monitoring; Crankshaft Integrity.

2. INTRODUCTION

Historically, cracks in locomotive diesel engine crankshafts have been associated with an imminent risk of catastrophic failure, often leading to engines being removed from service prematurely. This perception was driven by the belief that once cracks formed, their progression was rapid and inevitable. However, in 2016, two instances of crankshaft fractures occurred in the 7FDL16 diesel engine model, which had been overhauled only two years prior. A detailed investigation of these failures revealed that they shared a common failure mode, and further analysis pointed to localized heating during the overhaul process as a major contributing factor.

Failure Analysis:

Figure 1 - Fractured crankshaft assembled

Figure 1 illustrates a fractured crankshaft still in its operational position, showcasing the area around the lubrication channel plug, which showed typical heating marks. These marks were identified as a result of uncontrolled heating during the plug removal process, leading to changes in the material structure.

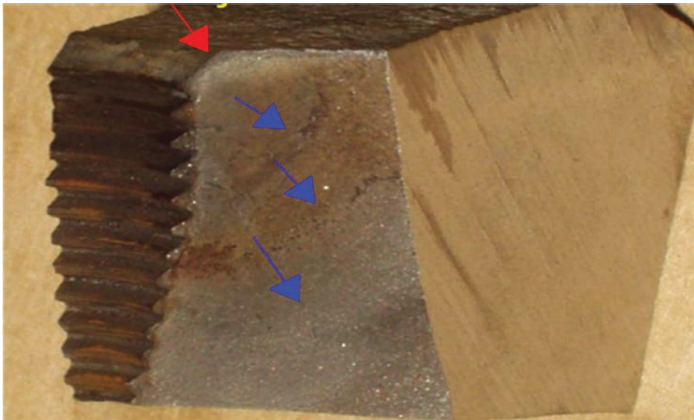


Figure 2 - Section of screw cracked area (Source: MIB-0058-17 report)

Figure 2 presents a section of the cracked area, where beach marks are visible. These marks are indicative of crack propagation, which evolved under the influence of cyclic loading and localized dilation stresses caused by heating.

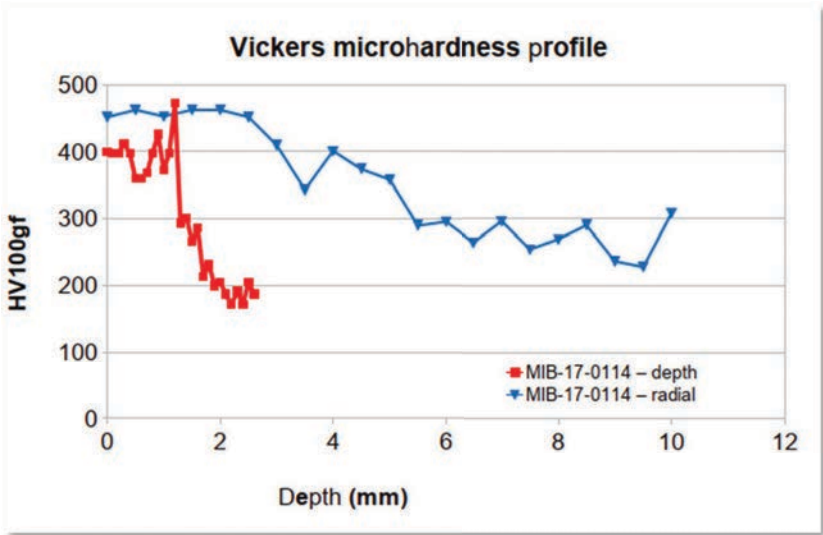


Figure 3 - Sample 1 Hardness Profile (Source: MIB-0058-17 Report)

The hardness profile of the samples demonstrates that there is superficial alteration and up to 2mm due to martensite formation. The martensite formation comes from a fast cooling after heating process and not suitable at this location of crankshaft. It could negatively impact the hardness of the material

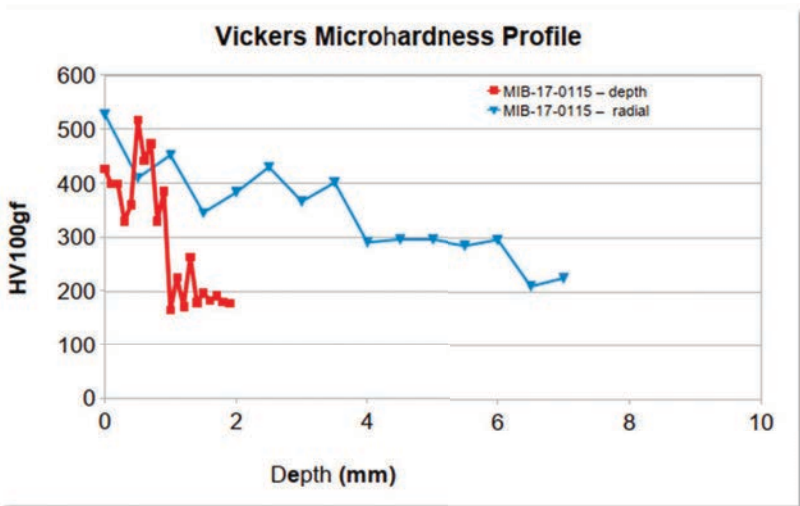


Figure 4 - Sample 2 Hardness Profile (Source: MIB-0058-17 Report)

Figure 3 and Figure 4 show the hardness profiles from the samples, revealing significant changes to the material properties. These changes were due to the formation of martensite in the affected area, further confirming the impact of the heating process on the microstructure of the steel.

The identification of the heating process as the root cause of the failures led to the hypothesis that similar issues might affect other crankshafts in operation, which had undergone the same overhauling procedures.

3. METHODOLOGY

3.1. Root Cause Analysis and Initial Findings

The initial investigation focused on identifying the root cause of the crankshaft fractures. The key factor was determined to be the removal of the lubrication channel plugs during the crankshaft overhaul process. Previously, the removal was carried out using uncontrolled heating around the plug area to facilitate its extraction, which left heating marks, as shown in Figure 1, and which caused changes in the structure of the material, as shown in Figure 2, which unintentionally altered the material properties of the crankshaft. These thermal alterations introduced stresses that initiated crack formation, which could evolve into catastrophic failures over time.

With this understanding, it became apparent that other engines may have been subjected to the same defect. Therefore, a non-invasive methodology was required to assess and monitor the condition of these crankshafts without requiring disassembly, thus ensuring minimal disruption to engine operations.

3.2. Choosing the inspection method - Non-Destructive Testing Selection

In the context of assessing the integrity of locomotive diesel engine crankshafts, it was essential to choose a non-destructive testing (NDT) method that would allow continuous monitoring without interrupting engine operations. Several NDT techniques were evaluated, and each was considered for its potential suitability. Below is a detailed examination of three main NDT methods used for crack detection in mechanical components, particularly in crankshafts.

1. Ultrasound Testing

According to Andreucci (Jun/2018), ultrasound testing is used to detect internal discontinuities and defects within components, whether they are ferrous or non-ferrous. This method works by sending high-frequency sound waves through the material and analyzing the echoes that return. This technique can effectively identify internal cracks or voids that may not be visible on the surface.

However, it was ruled out for the crankshaft inspection due to the **complex geometry** of the crankshaft and the **region of interest**. Ultrasound testing would require an extensive initial mapping of the component to interpret the

results, which is time-consuming and impractical in an operational environment where quick, continuous monitoring is necessary.

2. Magnetic Particle Testing

Magnetic particle testing is another commonly used method for detecting surface and subsurface discontinuities in ferromagnetic materials. The process involves magnetizing the component and applying iron particles that will collect around defects, highlighting cracks or other flaws. This method is particularly effective for detecting cracks that are open to the surface. Furtado et al. (2013) noted that for defects to be detected, they must intersect the magnetic field lines. The test must also be conducted in two directions that are 90° out of phase, ensuring accurate detection. While magnetic particle testing is highly effective for ferromagnetic components, it was deemed **infeasible** for use on the crankshaft in this case due to two critical factors:

- **Inaccessibility of the component:** The crankshaft cannot be easily accessed when the engine is operational, making the test difficult to perform.
- **Potential contamination:** The use of magnetic particles could result in contamination of the diesel engine lubricant oil, which would compromise the engine's performance. This issue could not be overlooked, especially in an operational setting where engine performance is critical.

3. Liquid Penetrant Testing

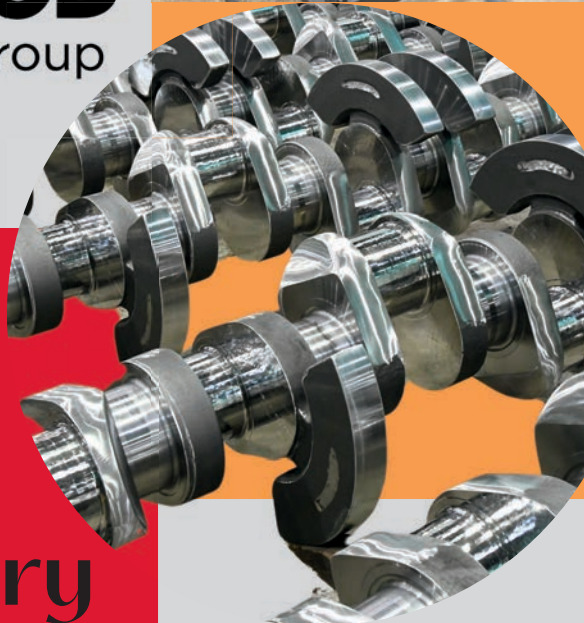
The liquid penetrant test, as described by Andreucci (2019), is designed to detect surface discontinuities such as cracks, pores, and folds. It works by applying a liquid penetrant to the surface of the material, which seeps into any open cracks or defects. After a set period, excess penetrant is removed, and a developer is applied to draw out the trapped liquid, making the discontinuities visible. This technique is well-suited for detecting surface flaws that may not be visible to the naked eye. Liquid penetrant testing is applicable to a wide range of materials, including those that are not highly porous and have relatively smooth surfaces.

In the case of the crankshaft, the liquid penetrant method was **selected** for the following reasons:

- **Non-invasive:** It allows the inspection of the crankshaft while it remains operational, without requiring disassembly of the engine.
- **Surface defect detection:** It is ideal for identifying surface cracks, which are often the primary concern in crankshaft failures.
- **Ease of application:** The method can be easily applied on-site with minimal equipment, making it a practical choice for continuous monitoring in an operational environment.



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After analyzing the three NDT methods, it was clear that **liquid penetrant testing** offered the most practical, efficient, and effective solution for detecting and monitoring cracks in the locomotive diesel engine crankshafts. The ultrasound and magnetic particle methods were dismissed due to their limitations in the operational environment and the complexity of applying them to the crankshaft without disrupting engine operation. Consequently, liquid penetrant testing became the preferred method for ongoing crack monitoring and assessment.

3.3. Fleet Segmentation and Inspection Protocols

To begin the monitoring process, engines that had not undergone the relevant overhaul procedures were excluded from the study. The focus was placed on engines that had undergone the specific heating procedure during overhauls, as these were at risk of suffering from similar failure mechanisms. The fleet was segmented based on visible signs of heating or cracking:

Table 1 - To do List

Crankshaft conditions	Action	Details
No heating marks and out of range of heating procedure	No Exam	
Heating marks	Follow Up	Continuous follow up
Heating marks and cracks	Follow Up	Continuous follow up
Long cracks with heating marks and loose plug	Follow Up	Schedule crankshaft replacement

Crankshafts exhibiting heating marks were subjected to continuous follow-up inspections, while those with visible cracks or loose plugs were flagged for scheduled replacement. This classification allowed for targeted monitoring based on the severity of the crack formation.

3.4. Liquid Penetrant Application and Handling

When conducting liquid penetrant testing (LPT) on the crankshaft, it was crucial to observe specific parameters, such as **temperature** and **cleanliness**, to ensure accurate results. These factors significantly influence the effectiveness of the test and the visualization of defects, as they directly affect the ability of the penetrant to seep into cracks and reveal surface discontinuities.

Temperature Control

For LPT to yield accurate and reliable results, the temperature at which the penetrant is applied must be carefully controlled. Maintaining the appropriate temperature ensures that the **capillarity characteristics** of the penetrant are not altered. These characteristics allow the liquid to flow into cracks or voids, which

is essential for defect detection. Any deviation from the required temperature range can lead to improper penetration or evaporation of the liquid, thus compromising the accuracy of the test.

Cleaning Process

Proper cleaning of the crankshaft prior to the application of penetrant is another critical factor in the success of the testing process. The cleaning procedure is conducted in two distinct phases to ensure that the crankshaft's surface is free of contaminants that could interfere with the test.

1. Phase 1: Removal of Oil and Contaminants

The first phase of cleaning involves removing any extreme oiliness or other contaminants from the crankshaft surface. Oil residues can prevent the penetrant from adhering to the surface, which would hinder its ability to seep into cracks. By thoroughly cleaning the surface, the test can be performed with optimal results.

2. Phase 2: Removal of Excess Penetrant

After applying the penetrant, it is essential to remove any excess liquid from the crankshaft's surface. This ensures that only the penetrant trapped in surface cracks or defects is visible during the inspection process. Any residual penetrant left on the surface could obscure the cracks, leading to false negatives.

Lubricant Oil Analysis

After conducting the liquid penetrant testing, an analysis of the **lubricant oil** was performed to evaluate any potential contamination or changes in its properties due to the testing process. The analysis focused on the **viscosity** and **dilution characteristics** of the lubricant, which are crucial for engine performance. The results indicated that no significant changes were observed in the lubricant's viscosity or dilution properties. The relative volume of materials used during the tests was minimal, accounting for only 0.0057 parts per million (PPM) of the total lubricant oil volume. This confirms that the testing process did not cause any harmful effects on the lubricant, and the engine could continue to operate without any risk of performance degradation.

In conclusion, by adhering to strict temperature control, cleaning protocols, and ensuring the lubricant's integrity, the liquid penetrant testing was carried out efficiently, providing reliable results without compromising the operational status of the crankshafts or the engine. This method of non-destructive testing proved effective in identifying surface cracks, ensuring the continued safe operation of the locomotives.

3.5. Crack Measurement Attempts

Once cracks were identified in the crankshaft, the next critical step was to assess their behavior, including determining their growth rate and the maximum allowable length before failure. This information is vital for assessing the remaining useful life of the asset and ensuring that the crankshaft can continue to operate safely up to its resistance limit without catastrophic failure.

Crack Growth Rate

One of the primary concerns was determining the rate at which the crack would grow. To do this, several potential methods were explored, including direct measurement of the crack size over time. However, given the operational constraints, such as limited access to the cracked areas and the fact that the crankshaft must remain in its operational position, direct measurement was not feasible. These limitations prevented the use of traditional tools or instruments that could directly measure crack growth.

Because of these access challenges, it was not possible to establish a reliable method to monitor crack progression continuously, thus making the crack growth rate difficult to determine with precision. This lack of real-time, direct measurements made it challenging to predict when the cracks might reach a critical size that would jeopardize the crankshaft's integrity.

Resistance Limit of the Crankshaft

In addition to monitoring the crack growth rate, it was crucial to assess the crankshaft's resistance limit in the areas affected by cracks. Observations from previously failed crankshafts provided useful insights into how cracks behave under operational stress and the limits of the material. Notably, the fractures in two of the failed crankshafts revealed that the cracks could exhibit different behaviors based on factors such as improper heating processes or lack of control during maintenance procedures. These varied crack patterns were critical to understanding the range of potential failure modes.

In some instances, the cracks extended over **2 inches** in total surface length. This highlighted the importance of closely monitoring such critical cracks to prevent further damage or failure. The cracks were found to propagate differently depending on their location and the initial cause, suggesting that the crankshafts' resistance limits were not uniform across all sections. The length and orientation of the cracks, especially those exceeding 2 inches, were indicative of significant damage and required immediate attention.

Conclusion on Crack Measurement

Ultimately, while the precise measurement of crack growth was not feasible due to the limitations of the operational setup, the overall behavior of the cracks was studied. These findings informed the strategy for ongoing monitoring and

maintenance. By identifying the critical areas of the crankshaft and understanding how cracks evolve, it was possible to implement a more effective inspection regime, focused on preventing catastrophic failure and maximizing the asset's operational life.

Despite the inability to measure the cracks directly, this knowledge allowed for a more controlled approach to managing the cracks, ensuring that the crankshafts remained operational without risking failure before their resistance limit was reached.

3.6. Monitoring and Inspection Interval

At the outset of the monitoring process, the exact rate of crack propagation was uncertain. Therefore, crack inspections were conducted at 15-day intervals. During each inspection, photographic records were taken to track and compare any developments over time.

As time passed and more data was collected, it became apparent that the crack growth rate was slower than initially expected. Consequently, the inspection frequency was adjusted. For smaller cracks, the intervals between inspections were extended, and as the cracks grew at a slower pace, the inspection frequency decreased. This strategy allowed the assets to remain operational without requiring immediate intervention, all while maintaining a comprehensive monitoring approach.

The ability to extend the inspection intervals without compromising safety or functionality demonstrated the feasibility of keeping the equipment in service for longer periods, effectively managing the risk associated with the cracks while minimizing downtime.

3.7. Types of Cracks

Throughout the monitoring process, various types of cracks were observed, each with distinct characteristics and implications for the overall structural integrity of the crankshafts. These cracks varied in terms of their location, orientation, and stage of progression.

Initially, small cracks were identified, primarily around the areas where heating occurred. As inspections continued, more advanced forms of cracking were detected. The progression of these cracks was carefully documented, enabling the identification of patterns that could inform future assessments of crack growth and behavior.

Among the types of cracks observed, some were localized and relatively shallow, while others became more severe, affecting larger portions of the crankshaft. The combination of visual inspections, crack measurements, and periodic assessments allowed for the categorization of cracks and the establishment of an effective monitoring protocol. These insights were crucial in determining the continued viability of each crankshaft and in deciding whether more intensive

intervention would be necessary. As the monitoring progressed, some forms of cracks were observed.



Figure 5 - Initial and small cracks

In **Figure 5**, it is possible to see evidences of typical cracks around the orifice, with the beginning of the cracks coming from inside the tapped hole in the crankshaft.



Figure 6 - Cracks around the hole

Figure 6 shows cracks around the tapped hole in the crankshaft. A result of overheating without significant progression. The plug shown is tightened and its apparently most external position than others but it's in normal condition.



Figure 7 - Advanced single crack leg

Figure 7 shows a single extended crack.

A single crack or one leg crack as shown in figure 7, can be found and the length of the crack must be monitored.



Figure 8 - Two crack legs

In **Figure 8** it is possible to identify that there are 2 cracks. It looks like there is a single crack that crosses the threaded hole in the crankshaft. The evolution of these two cracks will culminate in the fracture seen in **Figure 1**.



Figure 9 - Cracks are too long

In **Figure 9**, two cracks are visible, with one of the crack legs changing direction and growing perpendicularly to its original path. This change in crack orientation marks a critical stage in the fracture process. At this point, it is essential to monitor the cracks more frequently to assess their progression. Additionally, it is crucial to ensure that the plug remains tightly secured, as any loosening could exacerbate the stress concentration and contribute to accelerated crack propagation.

When comparing **Figure 9** with **Figure 1**, the corner visible in the crack illustrates the terminus of the cone-shaped fracture, which was formed by alterations to the crystalline structure of the steel. This pattern is consistent with the fracture observed in the crankshaft in **Figure 1** and **Figure 2**.

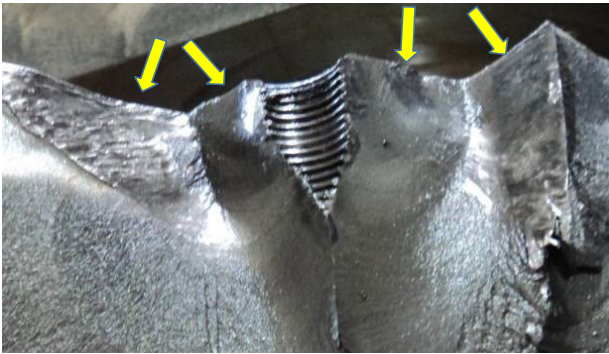


Figure 10 - Crack frontal view

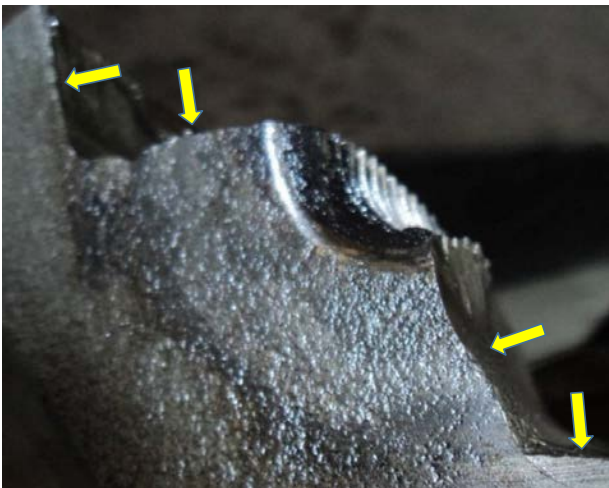


Figure 11 - Top crack view

It can be seen that Figure 1 and Figure 2 have fractures consistent with the crack identified in Figure 10 and Figure 11, which is still assembled in an operational engine.



Figure 12 - Four legs crack

From **Figure 12**, it is possible to identify four legs of cracks in one crankshaft. In this condition, when overhauling the diesel engine, the crankshaft needs to be replaced.

3.8. Next Steps Post-Crack Identification

In addition to the visual inspections, it was observed that the socket male pipe plug could loosen over time. It was determined that as the shaft's cross-sectional strength diminished and the crack propagated through the hole, the hole itself expanded, causing the socket screw to lose its grip. Consequently, in cases where cracks were approaching or exceeding 2 inches in length, and after repeated attempts to tighten the plug, the replacement of the shaft was scheduled.

In certain instances, the socket screw could be rotated by approximately 45° with ease in either direction (tightening or loosening). Upon examining one of the fractured shafts, it was noted that the plug had become ovalized due to the cyclic loading on the crankshaft during operation.

In cases where there was minor crack evolution or where overheating had occurred without significant progression (as seen in **Figure 5** and **Figure 6**), the affected crankshafts were reassembled into overhauled engines and continued to operate without restrictions. Continuous monitoring of crack development was maintained to ensure safety and optimal performance.

4. RESULTS AND DISCUSSION

Since the onset of monitoring in 2016, following two catastrophic crankshaft failures, no further catastrophic events have occurred. While actions to eliminate smaller cracks, such as machining the heated region, could be considered—especially by addressing the depth of material degradation indicated in **Figure 3** and **Figure 4**—this approach would require the development of specialized tooling to ensure a smooth surface post-machining. Additionally, this would necessitate demobilizing the asset and removing it from service for repairs, which would impact operational availability.

Nonetheless, by opting to monitor the cracks without removal, Table 2 illustrates the number of assets that have been kept in service or returned to service without the need for scrapping. This approach challenges the traditional assumption that cracks in crankshafts inevitably result in a short lifespan.

Table 2 - Cracked crankshaft resume

	Reassembled	Still working	Total working	Waste
Heated and cracked axles	18	31	(18+31) = 49	13

To prevent the plug from loosening and avoid unnecessary heating processes, a drilling machine has been used to remove the plug as shown in **Figure 13**, allowing lubrication channel to be appropriately cleaned. Subsequently, a pipe taps, as shown in **Figure 14** is used to clean the female threads in the crankshaft.



Figure 13 - Drilling the plug



Figure 14 - Cleaning the thread with a threading bit

5. CONCLUSION

The research demonstrates that cracks in locomotive diesel engine crankshafts can be managed effectively without the need for immediate disassembly and asset replacement. By employing liquid penetrant testing and maintaining a rigorous monitoring protocol, it is possible to extend the service life of crankshafts with cracks, contrary to traditional beliefs that cracked crankshafts should be immediately discarded. This approach has successfully kept 49 locomotives in operation for over six years, significantly prolonging the lifespan of critical components. The methodology developed in this study offers a sustainable solution for managing crankshaft integrity in locomotive engines, allowing for continued operation while minimizing the risks associated with crack propagation.

Future work may focus on refining the monitoring intervals based on additional data from long-term inspections, developing more advanced tools for precise crack measurement, and exploring other non-destructive testing techniques to further enhance the effectiveness of the monitoring process.

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System Cleanliness: Engine Lube Oil, Air, Water and Fuel

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There are many aspects to ensure top locomotive performance such as scheduled maintenance, proper assembly, parts made to specification and environment to name a few but one often overlooked area is proper system cleanliness. While following scheduled maintenance for filter changes are key to maintaining cleanliness, there are other areas that need attention when building, repairing and performing other maintenance on locomotives and engines. This paper will cover defining cleanliness, reviewing locomotive lube, intake air, water and fuel systems, and go over some best practices at various stages such as manufacturing, scheduled maintenance and component change out. And lastly, will go over how cleanliness tests are performed.

Defining cleanliness for various locomotive systems is not a simple task and depends on many factors such as which system is being looked at, is the system pre or post filter, how much contamination can they system tolerate, what size contaminants and what type of contaminants such as hard particles, fibers, flakes, etc. A lube system supplying oil to turbo bearings, for example, will not be as tolerant to debris as a cooling water system. Establishing requirements for the various systems needs to balance those requirements along with the means to get them clean. Setting the same stringent standards for all systems would not be cost effective as getting systems clean requires wash systems, fixtures, monitoring, and packaging to maintain cleanliness.

One of the most critical systems to keep clean is the engine lube oil system. Whether a new or remanufactured engine any component post lube oil filters that is not properly cleaned will go directly to the bearings and power assemblies. Figure 1 is a diagram of a 710 engine lube system which shows the yellow lines of the main lube system in which oil travels through various passages such as the main lube channel and various manifolds. The passages end at the components where lubrication is needed including main and cam bearings, rocker arms, valve bridges to name a few. If there is debris in this system it will go directly to the tight clearances of the bearings which can compromise oil flow impact oil film thickness and score critical bearing surfaces. The blue line represents the piston cooling system and if there is debris in this path, debris would go to the piston pin bearing along with lube oil used for lubrication of the liner and piston which may cause

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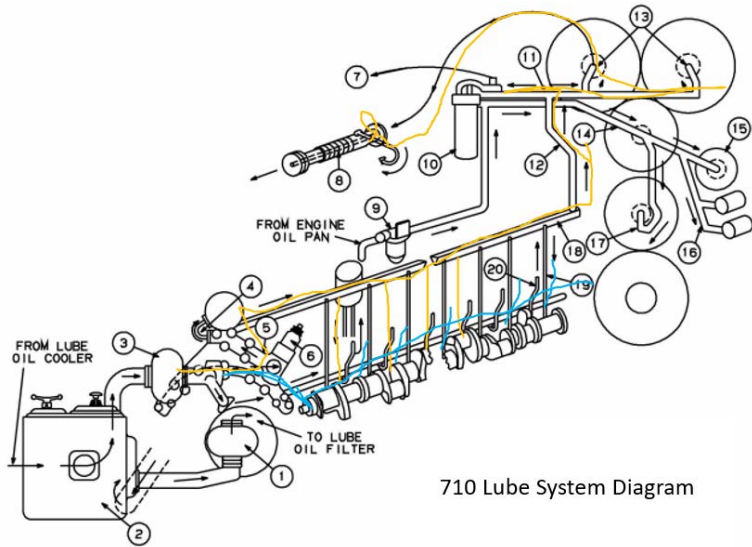
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scoring or scuffing. It is also critical during manufacturing and remanufacturing to keep the lube oil housing clean and piping from the lube housing to the engine clean. Note that the oil strainer in the lube oil housing is not fine enough to keep small debris from entering the engine.



710 Lube System Diagram

Figure 1: 710 Engine Lube System

Many components and engine passages post filters require special attention to ensure they are properly cleaned and often entails using custom washers with proper filtration and directed nozzles and/or direct flow through oil carrying passages. The filters and wash solution will also need to be monitored including any rust preventive needed to make sure parts do not rust after they are removed. Proper packaging of these parts, including usage of Vapor Corrosion Inhibitor (VCI) as needed, is critical to maintaining cleanliness until they are needed at point of use. These parts should not be removed from packaging until ready to be applied to engine. It needs to be clear when purchasing critical lube system components as to cleanliness and packaging requirements whether on a component drawing or in purchase order details. Assembly lubricants should be kept in clean containers applied with clean brushes and properly covered when not in use. Examples of damage to cam and main bearings due to debris are shown in Figures 2 and 3 below. Debris damage is not always easy to identify following a failure as the evidence is often gone and all that is left are failed parts. Analyzing other bearings for debris can help point to where the issue originated. Removing and cutting open the turbo lube filter to see what it captured can help determine source of debris. For example, steel shot, grit blast, silicon can all relate to a cleaning process.



Figure 2: Damaged Cam Bearings

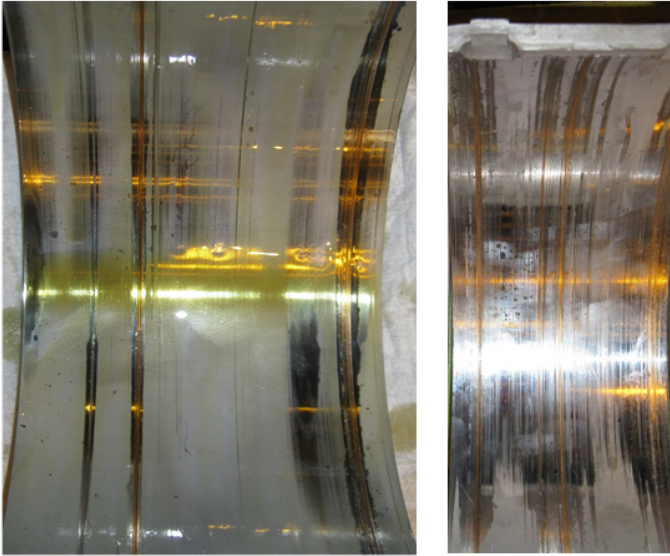


Figure 3: Damaged Main Bearings

It's important to perform scheduled maintenance as required per maintenance instructions as oil circulates through the engine it picks up tiny bits of dirt, carbon, and various wear metals and debris. The lube oil filter traps these contaminants before they can circulate back through the engine and cause damage. Lube filters need to be replaced according to the scheduled maintenance program or earlier based on pressure monitoring or laboratory analysis of the oil dictates earlier replacement. Usage of the recommended micron size filters will ensure

proper filtering of contaminants. Conduct lube oil analysis to determine if other inspections are needed. When changing filters, ensure that the lube oil housings are properly cleaned prior to applying new filters and don't take clean filters out of their packaging and lay them onto the shop floor or locomotive walkway as that may introduce contaminants into the system.

When doing maintenance on any lube system component lube system parts should be properly protected from environment when removed (bagged, covered, capped). If there was a component failure, properly clean out debris, strainers and drains. Cover lube system openings from potential of dropping bolts, nuts or washers. If these are dropped into lube oil piping or the strainer housing they will go directly into the pressure side of the pump and not only damage the pump but send debris into the lube passages. It is also important to remember to prelude engine before start.

The cooling system is a system that is often overlooked when it comes to debris. Many engine components with water cooling passages are difficult to produce without leaving chips in those passages when drilled. This debris is minimized by washing and flushing parts during the process. These wash processes may not be as customized as those used to flush lube systems but directed flow may be needed. Debris can restrict flow and clog cooling passages resulting improper cooling in cylinder heads, liners, radiators and lube oil coolers.

Maintenance of cooling system coolant is important to ensure no rust builds up which may result in corrosion in the system and particles may clog up cooling sensors resulting in improper readings and faults. This will also result in wear/leaks on the water pump seals. Since various manufacturing processes on new components may result in chips or other debris to enter into the cooling system it is recommended at first 184 day maintenance to clean out radiator screens, then every year after. Testing coolant on a regular basis will help identify issues with the cooling system.

Engine air intake system cleanliness is also important to ensure power assembly components or the turbocharger are not damaged. During manufacture it is important to keep airbox and intake manifolds clean as debris in those passages can go into cylinders causing liner scoring. Make sure that intake and exhaust ports are covered so no debris such as nuts, bolts and washers fall into them which can damage turbochargers, valves and heads. Clean the air filter compartment prior to application of filters. Larger particles can be sucked into the turbo and damage the impeller reducing turbocharger efficiency or possibly causing damage that will cause a turbo rotating assembly imbalance resulting in vibration, rubbing and possibly bearing failure.

Following scheduled maintenance is important to the air intake system as clogged filters can impact engine performance. Damaged, ripped or unseated filters will allow dirt to enter into the engine. When changing out components during maintenance, make sure exhaust and intake openings are properly covered

to eliminate potential of dropping parts into those passages. Make sure to clean airbox or other areas if there was a component failure. If the turbo was damaged by foreign material, it is important to check upstream for other debris and properly clean out. It would be very costly to put a new turbo on only to have it fail again from not properly identifying a failure mode and cleaning as needed.

The fuel system has some of the tightest tolerances and is most susceptible to debris damage and component longevity therefore there are strict limits on post filter components. Diesel fuel injectors are an assembly of various components with very tight tolerances and even the smallest particles can cause significant damage and failure of the injector. Older mechanical injectors (MUI) have tolerances as tight as 50 millionths (≈ 25 microns) while electronic injectors can be as tight as 2 microns. Even a very small particle that is introduced into an injector assembly can cause internal components to lock in place and cause decreased injector performance and/or completely stop operating. See figures 4-7 for examples of debris scoring of fuel injector components.



Figure 4: Scored plunger due to contamination

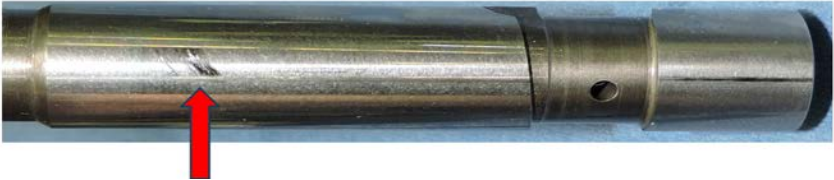


Figure 5: Scored plunger due to a small piece of dirt causing the plunger to "stick"

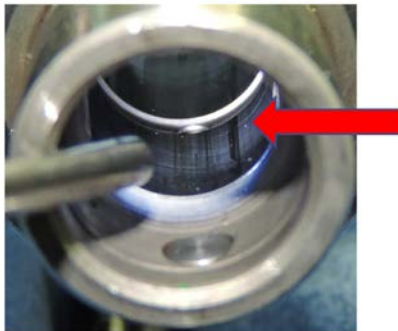


Figure 6: Scoring on the inside of the barrel due to contamination

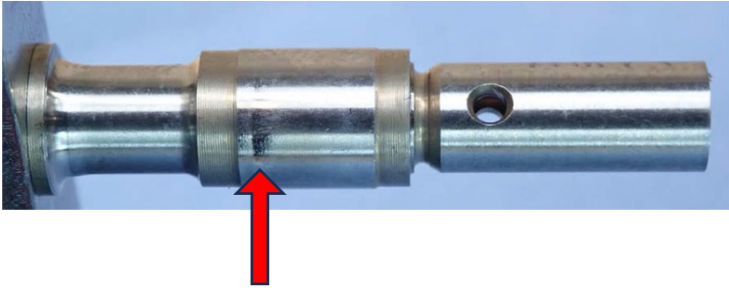


Figure 7: Premature wear caused by debris in fuel

There are various ways in which contamination can enter a fuel injector with the most common being via fuel and fuel piping. Just like the lube oil system components, keeping control of piping cleanliness is important post filter as contaminants will go directly into fuel injectors. Packaging of components is important including capping fuel lines and manifolds and only opening at time of application. Clean sealing surfaces are important to avoid fuel system leaks and is very critical for common rail fuel system applications due to the high system pressures.

Maintenance of fuel filters is important in preventing fuel contamination which may exist in the fuel tank from entering the system and need to be changed out at prescribed intervals. Clean system strainers and monitor fuel supply for contaminants. Also during fuel system component or injector change out, make sure no debris enters into the fuel inlets from clothes, hands, rags, etc. Use clean gloves when handling system components and make sure exposes fuel openings are covered. Before installing replacement fuel rails, jumpers or hoses, be sure the insides are completely clean even if they are brand new as shavings left over from manufacturing can and will cause problems.

Knowing that cleanliness is important to various engine systems, the question now becomes how clean is clean and how can cleanliness be checked? As noted before, cleanliness specifications are not a one size fits all and will have to be determined using experience and engineering knowledge of the various systems and limits are therefore not included with this paper. Cleanliness of components can be checked via Millipore testing, named after the Millipore Corporation that developed membrane filters for particle analysis, and is sometimes called patch testing. This test is used to determine the amount of contaminants from components via weighing. This is done by collecting a sample, prepping sample and analyzing. Components of the filter system is shown in figure 8.



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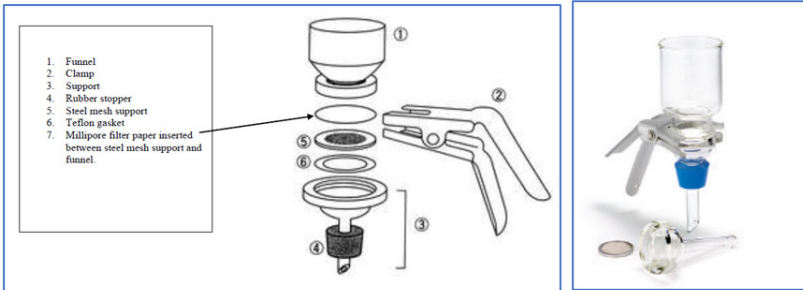


Figure 8: Components of Millipore test filter

Collection of the sample is the first step and done by using an approved filtered solvent such as mineral spirits and running it on the part and through the surfaces being analyzed. A dispensing vessel with filters can be used, Figure 9, to ensure the solvent used does not already contain contaminants which can cause errors in your analysis. Using clean collecting pans, funnels and collection bottles, run fluid over part, through passages as needed and use a brush and/or bottle brush on the surfaces that are being checked. Collect the sample in a pan, then funnel into sample container using more filtered solvent to rinse down pan to make sure all the sample fluid and debris is collected.



Figure 9: Dispensing Canister with Filter

Prepping the sample requires weighing the filter prior to using, running the sample through Millipore filter using a vacuum, using an approved solvent to wash down the funnel and sample and then allowing the filter to dry. To analyze the sample, calculate weight change and also view under scope to get particle size. Other analysis can be done on particles to determine source/type such as what type of metal or individual particle sizes or shapes such as machining debris, casting

flakes, cleaning media etc. Trending data can help determine when maintenance should be scheduled on washers or information to be shared with suppliers.

In conclusion, cleanliness is critical for all locomotive systems and following scheduled maintenance and using proper system filters will help maintain system cleanliness. Working with suppliers is key to make sure parts are clean prior to application. Shop maintenance should utilize good practices to minimize/eliminate contaminants on the clean side of the filters. Cleanliness and oil sampling analysis along with monitoring data trends can help make decisions on required maintenance and update maintenance practices.

Fuel Spill Prevention

Prepared by :

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Abstract

This paper examines locomotive fuel delivery systems, focusing on design elements, failure points, and emerging technologies. Beyond the fuel hose, considerations include drip pans, recovery systems, and the interplay between locomotive and fuel crane geometries. Common leak points—such as fuel inlets, engine components, multiple fuel ports, and piping are analyzed alongside mitigation strategies like maintenance protocols, advanced connection technologies, and optimized fueling locations.

Advancements in fueling technology, including auto-shutoff systems, fuel metering, and innovative nozzle designs like dry disconnects and high-flow vacuum shutoffs, are discussed for their potential to enhance safety, efficiency, and reliability. The study concludes with recommendations for fueling operations, emphasizing proactive maintenance, tailored technology selection, and the integration of fail-safe mechanisms.

Introduction

Fueling locomotives is a critical aspect of rail operations, with significant implications for efficiency, safety, and environmental protection. The process involves more than simply connecting a nozzle to a fuel tank; it encompasses an interconnected system of components, including storage tanks, fuel cranes, piping, and auxiliary equipment, all working in unison to ensure reliable fuel delivery. However, the complexity of these systems also introduces challenges, such as leaks, spills, and equipment failures, which can disrupt operations and pose environmental risks.

This paper provides an in-depth examination of locomotive fuel delivery systems. It extends beyond the more visible components, such as hoses and nozzles, to analyze the role of less apparent but equally important elements, including drip pans, fuel recovery systems, and the layout of fueling facilities. By exploring system design and identifying potential failure points, this study offers strategies to enhance safety, reliability, and operational efficiency.

The paper also investigates advancements in fueling technology, such as ultrasonic auto-shutoff systems and innovative nozzle designs, which aim to

reduce spills and improve performance. Additionally, it discusses the importance of routine maintenance, strategic fueling locations, and the implementation of fail-safe mechanisms to prevent accidents and minimize risks.

The goal of this paper is to provide an understanding of fueling systems as well as actionable recommendations for optimizing locomotive fueling operations. These recommendations focus on maintaining equipment, adopting appropriate technologies, and implementing proactive measures to support safe and efficient fuel management while mitigating environmental impacts.

Fuel delivery system layout

When considering fuel systems and managing fuel spills it is important to remember the whole system that delivers fuel to the locomotive. Most of our focus is on the fuel nozzle and delivery to the locomotive and somewhat rightfully so. These are the most visible and used parts of the fuel delivery system, but they are just one link in the chain. The general process is outlined in the Chart 1 below and is described in detail in this section.

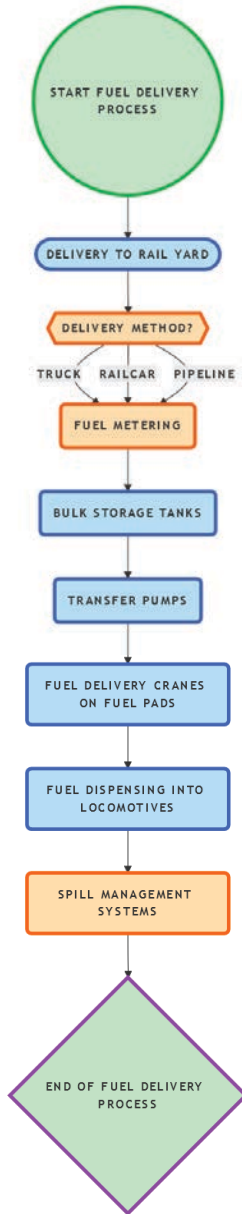


Chart 1 Fuel Flow Process at a Facilities Level

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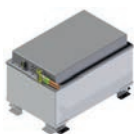
Fuel Operated Engine Heater

No more idling to maintain cooling water.



Handbrake Sensor

No more idling to maintain reservoir pressure.



Battery Energy Storage System

No more idling to maintain battery voltage.



The first step in the process, from the railroad's perspective, is the delivery to the railyard. This can happen in several different ways; fuel trucks, tank cars, or pipelines being the most common. In each case, the fuel is measured for billing purposes and transferred to a bulk storage tank at the rail yard. Depending on the size of the fueling terminal, these bulk storage tanks can be quite large (tens to hundreds of thousands of gallons) and facilities typically have capacity for three days of fuel reserves. These tanks are often above ground surrounded by large earthen berms to provide secondary containment in the event of a release. The area is required to hold the whole volume of the storage tank(s) if they are to be released.

From the storage tanks fuel is routed to a pumping station. These large fuel transfer pumps move the fuel from the tanks to the fuel delivery cranes on the fuel pads. Multiple fuel cranes are often connected via a common header. All of which are sized based on the flow rate needs and size of the fueling terminal. The associated piping and pumps are enclosed in a containment housing which may take the form of double wall pipes, containment bunkers, or leak free buildings.

The final stage of the fuel delivery process is the "fuel pad", shown in Figure #1. This is the facility that is most often associated with locomotive fueling. It consists of fuel cranes positioned adjacent to a section of tracks dedicated to fueling and servicing locomotives. These cranes are typically positioned so that a locomotive can be fueled anywhere on the fueling track and not have to be repositioned to reach a fuel crane. This geometric arrangement is impacted by the reach of the fuel crane, usually 15 to 25 feet. A specialized "catch pan" is installed under the track to catch small leaks or spills that may occur during fueling operations. These catch pans drain back to a wastewater treatment facility to ensure any lost fuel and oil is captured and disposed of. Oil, water, and sanding equipment are often installed in these facilities to provide all the typical locomotive servicing needs.



FIGURE #1 Locomotive on Fueling Pad (BNSF Railway in Lincoln, NE image courtesy of Chris Palmieri)

Often locomotives are refueled from road tanker trucks. At larger facilities, these trucks are supplied with fuel via a dedicated fuel pad. While smaller facilities will use outside contractors to supply single truck loads as needed. This allows locomotives to be fueled in a variety of locations without the need for costly facilities, but their mobile nature increases the reliance on spill prevention processes as fuel spill containment mechanisms are often unavailable leaving little room for error.

Vacuum Shutoff Function

The automatic shutoff function operates on a vacuum principle as shown in Figure 2. During fueling, a stable operating vacuum is created within the diaphragm located near the nozzle latch mechanism. That stable operating vacuum keeps the latch assembly open.

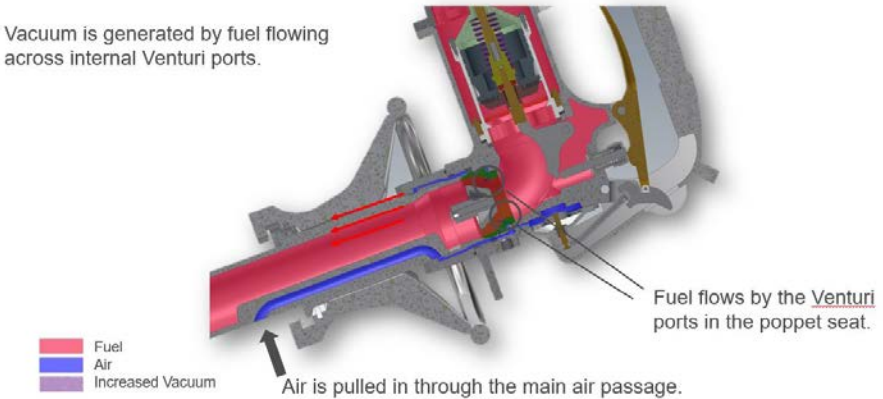


FIGURE #2 Automatic Shutoff Function Operating On Vacuum Principle

When the fuel tank fills enough to cover the inlet tube inside the tank, air no longer be pulled in through the main air passage in the nozzle. The vent line that runs between the tank adapter and the tank (“D” in Figure 3) is now the only source of air to maintain the operating vacuum.

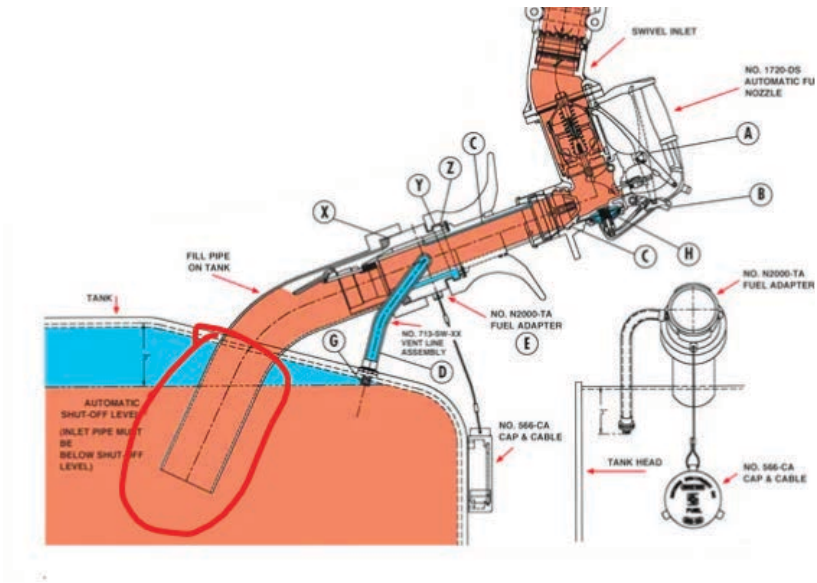


FIGURE #3 Fuel Tank Filler Neck Layout for Vacuum Nozzle

Once all paths of air to the nozzle are closed off, an instantaneous high vacuum is created that automatically shuts off the nozzle by releasing the latch as shown in Figure #4.

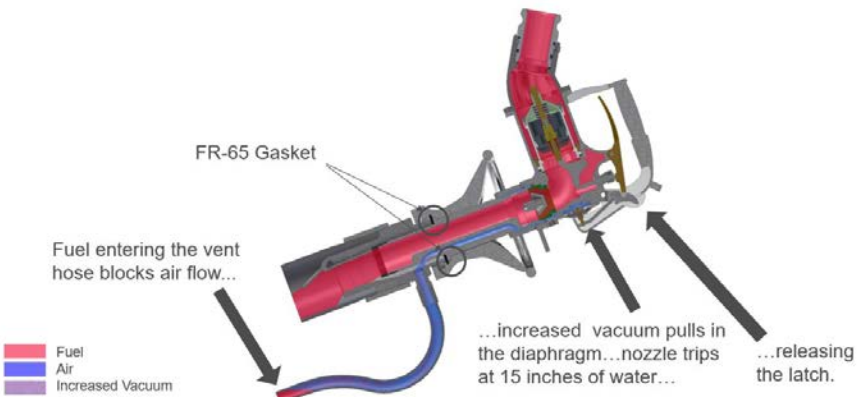


FIGURE #4 Detail of Vacuum Fuel Nozzle

When the flow rate is too low for the nozzle design, the venturi effect is reduced. The operating vacuum becomes too low to provide stable fueling performance, and the high vacuum required to shut the nozzle off may form too slowly or fail to form at all.

Leak Points & Mitigations

Fuel spills in locomotives can originate from various points within the fuel system. Addressing these issues requires preventative maintenance, technology solutions, and operational best practices. This section examines the major potential leak points and outlines effective mitigation strategies.

Fuel Inlets

Fuel inlets are critical points where fuel enters the system and are key to the operation of the vacuum shutoff system. Most importantly the inlet needs to be correctly clocked and the vent hose in good condition. Clocking refers to the correct position of the flapper hinge, which must be installed between the 11 and 1 o'clock position. If not, fuel can splash back off the flapper and potentially cause the automatic shut off to fail. The vent hose, shown in Figure 5, should be positioned between the 9 and 3 o'clock position on the inlet. Vent hoses may degrade over time, leading to leaks during refueling or failure of the shut off mechanism.

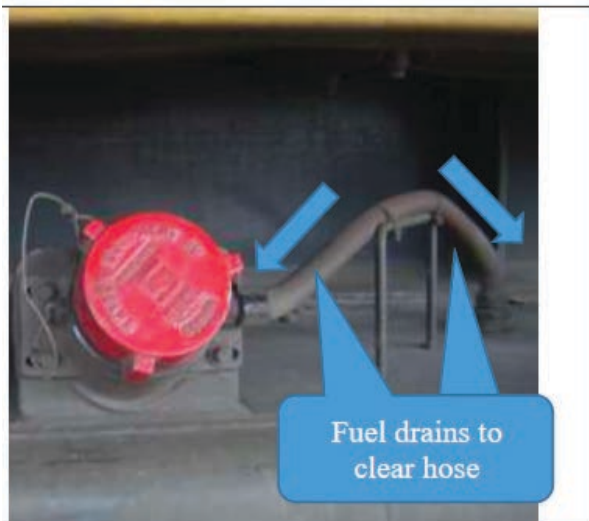


FIGURE #5 Location of Vent Hose on Fuel Filler Neck and Fuel Pump (note the position of the vent hose which may cause shut off issues)

Mitigation strategies include routine maintenance to inspect and replace worn or damaged components. Although regular operation should not affect the position of the inlet, they should be checked at least annually to ensure they are correctly positioned and not damaged.

On-Engine Leaks

The engine itself is another potential source of fuel leaks. Improper maintenance, incorrect torque settings, and deteriorating gaskets can all contribute to fuel escaping from the system. These leaks not only waste fuel but can also pose fire hazards and environmental risks.

Mitigating on-engine leaks involves following the Original Equipment Manufacturers (OEMs) maintenance practices and specifications. Additionally, the implementation of fuel flow metering systems, either from OEMs or aftermarket providers, enables detection of overflow anomalies, allowing for automatic intervention. Ensure to consult the OEM when running bio and renewable diesels as these fuels may have compatibility issues with hoses, gaskets, seals, and other polymer materials, particularly on older locomotives and high blend mixtures of these fuels.

Multiple Fuel Ports

Locomotives equipped with multiple fuel ports can experience overflow issues, particularly when refueling occurs on significant grades or canted tracks. Fueling on uneven surfaces can lead to fuel spilling out of the opposite port, causing wastage and potential environmental contamination. To address these challenges, operators should carefully select fueling locations to ensure they are level.

Piping and Delivery Systems

The piping and delivery systems that transport fuel throughout the facility are prone to wear and tear over time. This degradation can lead to leaks at joints, fittings, and along the piping itself, especially in older systems. While rare, the impact of these failures can be very significant, often resulting in thousands of gallons of lost fuel and costly and difficult environmental remediation.

Regular inspections are essential to identify vulnerable areas within the piping system. Proactive replacement of aging or damaged components can prevent leaks before they occur. Good material and design selection for piping systems can also enhance durability and environmental resistance.

Locomotive Drive-Offs

Drive-offs, where a locomotive inadvertently moves away during refueling, can result in significant fuel system damage. This scenario poses risks not only to the equipment but also to personnel and the surrounding environment.

Mitigation measures include the installation of automatic disconnect systems for fueling hoses. These systems can disengage safely if a drive-off occurs,

minimizing damage. Operator training programs and the use of blue signal protection should minimize the occurrence of drive-off events.

Fuel Truck Deliveries

Fuel spills during the transfer of fuel from trucks to locomotives are another potential leak point. Inadequate couplings or improper handling can lead to spills that contaminate the environment and pose safety risks.

To mitigate these risks, secured couplings and connections should be used during fuel transfers. Delivery personnel must receive regular training on spill prevention techniques and emergency response procedures. Establishing clear protocols for fuel delivery can further reduce the likelihood of spills.

By addressing these potential leak points with targeted mitigations, the rail industry can enhance the reliability and safety of locomotive fuel systems. These strategies not only protect the environment but also improve operational efficiency and reduce costs associated with fuel loss, system repairs, and spill mitigation.

Advancements in fueling technology -

Automatic fuel flow shutoffs

Automatic fuel flow shutoff systems are an emerging technology aimed at reducing fuel spills and improving fueling efficiency. These systems primarily operate through two methods: fuel metering and fuel sensing.

Fuel metering is the more widely used approach, requiring input from either the operator or remote fuel measurement systems, such as ultrasonic fuel level sensors. This method limits the amount of fuel dispensed to match the locomotive's required or desired fuel level, reducing the risk of overfilling. By integrating real-time fuel data, operators can ensure precise fueling while minimizing waste and environmental impact. Figure 6 depicts a representative interface for a fuel metering system.

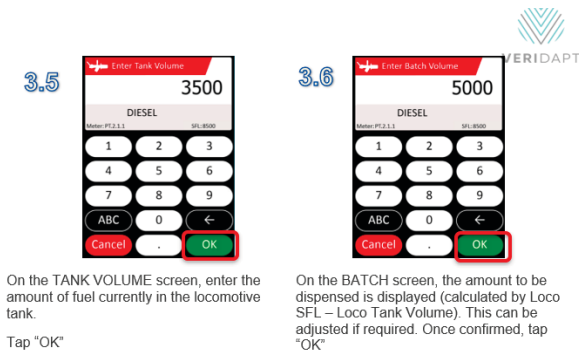


FIGURE #6 Interface for Fuel Metering System (courtesy of Veridapt)

Fuel sensing, while less common, relies on fuel level sensors mounted directly on the locomotive tank. Technologies such as ultrasonic or capacitive sensors detect the fuel level and automatically shut off fueling once the desired capacity is reached. While this approach has potential, its effectiveness is dependent on the accuracy and reliability of the sensors. Current limitations in sensor technology have restricted its widespread adoption, though ongoing advancements may improve its feasibility in the future.

As rail fueling technology continues to evolve, both fuel metering and fuel sensing systems present opportunities for reducing spills, improving fuel efficiency, and enhancing safety in locomotive fueling operations.

Aircraft Style Connections - SpillX

The SpillX locomotive fueling system applies aviation fueling technology to the rail industry. This system is designed to improve fueling times and reduce environmental risks associated with fuel spills. Utilizing a dry-break connection and their jet-level fuel sensor, SpillX aims to minimize fuel leakage during fueling operations and allows for flow rates of up to 600 gallons per minute (GPM), which is higher than conventional locomotive fueling systems.

SpillX was developed in alignment with the Association of American Railroads (AAR) Locomotive Fueling Recommended Practice (RP-5503), which emphasizes higher fueling rates, reduced spillage, and improved overfill protection. The SpillX system does not require electronic sensors or specialized controllers and is a completely mechanical design. The installation process is straightforward but does require modifications to existing locomotive fuel tanks and can be completed within minutes provided existing fueling ports are available. Installation of additional SpillX receivers while retaining existing nozzles requires drilling and modifying the locomotive fuel tank.

The system is designed for compatibility with current fueling infrastructure. The SpillX nozzle connects to fuel cranes or tanker trucks via a standard 2.5-inch cam lock connection. The nozzle and receiver have a lower pressure drop compared to conventional systems, allowing for increased fueling efficiency without raising fueling pressure. SpillX can also accommodate the higher fueling pressures allowing for higher flow rates while preventing diesel foaming within the filler neck. Note that these high flow volumes can cause issues with splash back and mixing if not correctly positioned among the tank baffles. Sediment stirring may also occur at high flow rates.

A key feature of the SpillX system is its hydraulic automatic shutoff mechanism or “jet-level” sensor. Once the tank reaches full capacity, the jet level sensor triggers a shutdown over 5-10 seconds, preventing pressure spikes and mitigating infrastructure wear. This controlled shutoff reduces the “fluid hammer” effect, which can cause mechanical stress on fueling components. The dry-break nozzle technology ensures that the nozzle cannot be disconnected while fuel is flowing, helping to reduce the risk of accidental spillage.



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The SpillX receiver, installed in the locomotive's fill port, incorporates a military-grade MS 24484 dry-break sealed poppet connection to prevent fuel backflow and unauthorized fuel access. This connection also helps protect against foreign object contamination and fuel spillage in case of a derailment. Additionally, the SpillX jet level mechanism ensures that once the fuel tank reaches capacity, no additional fuel can be introduced, preventing overfilling and ensuring precise fuel management.

Implementations of SpillX must consider modifications to fueling infrastructure, including pump capacity, fuel crane geometry, and, most importantly, compatibility with existing locomotive configurations. Existing deployments have primarily focused on areas requiring high flow rates and locomotives equipped with both SpillX and Snyder receivers. Adapters also exist to allow cross compatibility between the two connection systems. By incorporating advancements in fueling technology, SpillX provides an approach to locomotive fueling that prioritizes speed, safety, and spill mitigations.

Connected and High Flow Vacuum Shutoff Nozzles - Snyder

The style of nozzle chosen must match the pumping capacity of the overall system, including fluctuations in flow rate from multiple fueling stations operating at the same time with a shared pumping system. High-flow nozzles have slightly enlarged internal openings to extend the curve to 380 GPM.

Fuel management systems introduce another variable into the nozzle's automatic shutoff capability. If a fuel management system closes off the upstream fuel supply through a control valve or manually operated valve (MOV) before the tank is full, the nozzle's normal automatic shutoff will not occur because the shutoff vacuum never forms without a full tank. It is necessary to manually shut off the nozzles in this case to prevent a potential spill, in case the fueling system is activated at the next fueling event before the nozzle is locked in place in the tank adapter.

The Snyder SMART nozzle is designed to prevent this potential problem. It works like a regular fuel nozzle, with the added capability of Bluetooth communication with a fuel management system or alternate control to trip the shutoff assembly in the nozzle at a preset limit before the tank is filled. The standard vacuum shutoff still works in the SMART nozzle, acting as a fail-safe mechanism in case of communication failure.

By directly interacting with a fuel management system, the SMART nozzle can potentially eliminate the need for upstream control valves or MOVs to manage the flow. With a corresponding fuel crane upgrade, the SMART nozzle can be supplied with a crane position auto-lock feature. Pressing a button on the SMART nozzle will lock the crane into place once the crane is pulled out to the proper distance. After fueling and removal of the nozzle from the fuel tank, press the button again to release the auto-lock and allow the crane to retract.

Conclusion and Recommendations

The management of locomotive fueling systems presents both challenges and opportunities for improvement. By addressing common failure points and adopting emerging technologies, the rail industry can significantly enhance the safety, efficiency, and environmental sustainability of its operations.

One of the most critical recommendations is the implementation of routine maintenance protocols. Regular inspection and timely replacement of aging or damaged components can prevent leaks and reduce the risk of system failures. Maintenance practices should include a focus on key areas such as fuel inlets, engine components, and piping systems, ensuring that all parts of the fuel delivery process remain in optimal condition.

In addition, the adoption of advanced technologies can play a pivotal role in improving fueling operations. Innovations such as ultrasonic auto-shutoff systems, fuel flow metering, and advanced nozzle designs, including dry disconnects and high-flow vacuum shutoffs, provide opportunities to reduce fuel loss, enhance safety, and streamline operations. The selection of these technologies should be tailored to the specific needs and infrastructure of each fueling facility, ensuring compatibility and long-term effectiveness.

Another vital consideration is the strategic planning of fueling locations. Ensuring that fueling sites are level and equipped with adequate containment systems can minimize the risk of spills and environmental contamination. The integration of secondary containment measures, such as catch pans and wastewater treatment systems, further supports environmental protection.

Finally, a proactive approach to training and operational practices is essential. Educating personnel, both railroad employees and fuel delivery contractor(s), on best practices, spill prevention techniques, and emergency response procedures enhance overall operational safety and minimizes human error.

By combining these strategies, routine maintenance, advanced technologies, strategic site planning, and comprehensive training, the rail industry can achieve a more efficient and sustainable approach to locomotive fueling. These efforts not only improve operational reliability but also align with broader goals of environmental stewardship and safety excellence.

First Article Inspection Process – Best Practices

*Prepared by :
Tom Kennedy, Kennedy Rail Consulting*

This is a best practice paper addressing the First Article Inspection (FAI) Process for new or rebuilt hardware and products. A classical definition of an FAI is: “A process that verifies that a new or modified production process produces parts that meet the required specifications”. An integral part of an FAI is to ensure that the product as built meets the specifications. However this paper will focus on the quality of the final product as built and detect and correct defects that would degrade reliability, durability and safety of the end product. To this end, multiple in build process inspections are best to ensure defects are detected early before their discovery is prevented by follow-on build activity. The more integrated and complex the final product the more critical it is that multiple in-process build inspections are conducted.

This paper will not provide a detailed process on how to inspect a locomotive or infrastructure equipment which are unique products that require different processes and are too variable and beyond the scope of this paper. Rather, this paper will address specific areas that could affect product quality, reliability, durability and safety. Because of paper limitations not all areas will be discussed; the primary areas of focus of concern will be discussed in this paper. As a general note safety issues are typically not operational issues but more of a service and maintenance concern although if an operational safety issue is detected it should definitely be identified and documented. As a final note, safety concerns may be encountered during the production build and test process, and these should be documented and supplied to the OEM or supplier for corrective action to ensure employee protection. Safety concerns could be in the final product, the manufacturing process or the field service maintenance tooling.

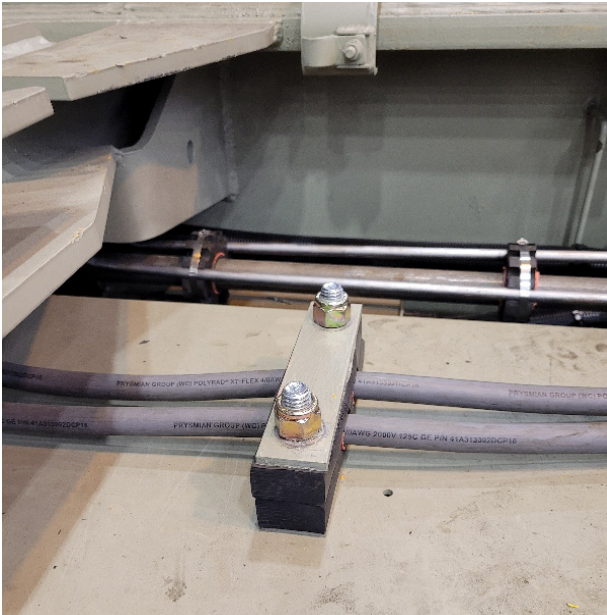
The following sections will provide specific areas for inspection along with potential quality or reliability consequences along with illustrating pictures as appropriate. The following examples are typically mechanical in nature but there are some examples in the electrical area, typically wiring and connector defects. There are more areas that can be inspected in the electrical area but these are referred to the LMOA Electrical Committee to address in a future paper. The topical areas to be discussed are noted below, in alphabetical order. It is noted that there are additional inspection areas but this paper is limited in scope so the areas

selected are the most common based on past inspection findings.

- Bolt Torque Marks
- Carbody & Door Latches
- Electrical Wiring
- Fluid Leaks
- Fuel Tank
- MU Receptacle Pin Condition
- Pipe Debris, Contamination
- Cab Amenities
- Electrical Connections
- Emissions Decal Placement
- Fouls, Wiring and Piping
- Headlight Orientation
- Oil Condition & Sampling
- Weld Defects

Bolt Torque Marks:

Inspect all mechanical bolted joints to ensure that the nuts and bolts have been marked with a paint stick, ensuring that the mechanic verified that the bolt had been properly torqued. Any bolts not marked should be re-torqued to ensure proper bolt torque has been achieved. If a bolt was installed with Loctite it needs to be removed and cleaned, and the Loctite reapplied and the bolt properly torqued. Performing a re-torque on a fastener with Loctite will destroy the Loctite function. The picture below shows multiple nuts not torque marked. Also the nut should be marked, not the bolt head, since the nut should be torqued whenever possible, not the bolt head. Torque values can change when torquing the bolt head. Exception to this rule is for machine bolts and if there is poor access to the nut for proper torquing.



Cab Amenities (Seats, Floors, Ice Box, Refrigerator, Toilets and HVAC):

Inspect the cab seats for proper installation and operation, reclining, rotation and height adjustment. Inspect for damaged seat material and missing or damaged arm rests. Inspect the cab floor for uneven and damaged floor material. Inspect the ice box or refrigerator for proper installation and operation and that ice and condensate drains are properly routed to prevent water on the cab floor. Inspect the toilet for proper installation and operation including the toilet room vent fan. Inspect the HVAC for proper operation and that the condensate drain line is properly routed. Defects with cab crew amenities are a major complaint of crews and can be an FRA defect and possibly lead to a crew safety issue.

Carbody & Door Latches:

Inspect carbody latches and door locks to ensure that they are functional. Check each carbody latch to ensure it operates smoothly and does not bind or require excessive force to open or close. A binding carbody latch can also be caused by a warped carbody door or a sprung hinge. Inspect the cab door lock, required by an FRA directive, for presence and operability. Cab lock picture below.



Electrical Connections, Loose and Corroded:

Inspect all electrical connections to ensure they are secure. Particular attention should be paid to faston and Wago block connections. Fastons should not come loose with a ten-pound pull. If the connection is not secure the wire should have the female connector and/or male pin replaced, never repair by pinching the connection with pliers. For Wago blocks the wires should be pinned before inserting into the Wago block socket to ensure a secure connection, see picture



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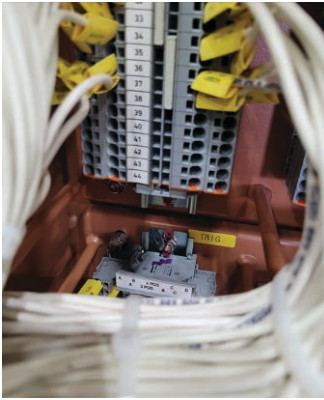


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below left. Corrosion is also a problem that can lead to intermittent connections, see the 74 vdc charging receptacle picture below right. Use of a contact cleaner and dielectric spray is recommended for corrosion prevention. A few contact cleaners and dielectric sprays are shown with recommendations made. Conduct your own research for what is best for your application.



Electrical Wiring, Tight Bend Radius and Securement:

Inspect for tight bend radiuses on wires and harnesses. Recommended standard for non shielded wire and harnesses is a ten to one bend radius and a twenty to one for shielded wire and harnesses. Fiber optic cables are very sensitive to the bend radius and depend on whether it is glass or polymer. Consult the fiber OEM for bend radius. Bend radius can cause a stress point leading to failure.



Zip ties used to secure wires and harness must be trimmed properly to avoid safety issues. Improperly trimmed zip ties can create a cut issue to maintenance personnel. Use an appropriate tool to trim the zip tie not wire cutters. A typical zip tie trimming tool is shown below.



Emissions Decal Placement:

Inspect for the presence of the locomotive EPA engine emission decal. For new production units these decals are installed on the cab nose engineer's side. For rebuilt and remanufactured locomotive engines the decals may be in the cab or on the exterior depending on OEM instructions. Also inspect for the EPA emission decal on the engine. Location of these decals will vary between the OEMs. The presence of these decals is critical for EPA 1033 regulation compliance.

Fluid Leaks:

During engine idling and after operation inspect for fluid leaks: fuel, oil, water and air. Do not inspect inside the carbody during a load test. Leaks should be classified using SAE J1176 leak classification, shown below. Corrective action should be taken for any fuel or oil leak with a classification of 3 or greater. Corrective action for water leaks is more subjective, based on the customer. Fuel and oil leaks are a potential fire hazard and an FRA defect. Once a leak initiates it will get worse. Air leaks are detected audibly or with an ultrasonic tester.

SAE Class	Leakage Term	Leakage Description
0	Dry	No indications of moisture
1	Weep	Any nonrecurring fluid
2	Seep	Recurring fluid not forming a droplet
3	Droplet	Recurring nonfalling droplet
4	Drip	Recurring falling droplet
5	Flow	Recurring stream forming volume
Per SAE J1176 Recommended Practice (Under Dust-Free Conditions)		

Figure 5. Leak Classification

Fouls, Wire and Piping:

Wire and piping fouls are common and can lead to premature failures resulting from abrasion during operation which can cause an electrical short circuit or open circuit or an air, fuel, oil or water leak. Fuel, oil and electrical fouls can not only result in locomotive failure but also pose the risk of a fire. These conditions do not typically result in an early failure but ultimately they can fail. The pictures show electrical wiring fouling but others are similar. On the second picture the fouling can be removed with better routing and proper restraint.



Fuel Tank (Sense Hose, Flapper Valve Clam Lock and Condensate Drain):

Inspect orientation of the fuel sense hose and tank filler neck flapper valve to prevent fuel spills. Per Snyder, the fuel sense hose is to be installed between the 10 and 2 O'clock position with no droop in the hose and the flapper valve is to be installed with the hinge at 12 O'clock position. Failure to do so can result in premature shutoff of the fueling nozzle. Oft times when this happens the F&O (fuel and oil) will block the nozzle to continue fueling. If the tank overfills a fuel spill will occur as fuel is pumped overboard through the fuel tank vent line. Inspect for proper application of Clam Lock on locomotives being stored or transported DIC (dead in consist). Inspect fuel tank condensate drain to ensure it has been serviced, the picture shows significant dirt build up indicating that the condensate was not drained. Pictures show the sense hose properly installed, the flapper valve is not and the Clam Lock properly installed and dirty a condensate drain. For a paper on fuel spills see 2016 paper, Best Practices Locomotive Fuel Spill Prevention by Greg Wilson and Steve Wiegel.



Headlight Orientation:

For proper track illumination per 49 CFR 229.125 the headlights and auxiliary lights (ditch lights) must be properly installed. The arrow or the “TOP” mark on the lens must be installed at the 12 O’clock position. In these pictures the upper headlight has the “TOP” label installed at the 3 O’clock position and the lower headlight the arrow is at the 7 O’clock position and the auxiliary light is at the 6 O’clock position. When headlights and auxiliary lights are not installed correctly the track and auxiliary lights will not properly illuminate the track compromising crew down track visibility, which is an FRA defect.



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MU Receptacle Condition:

Inspect the MU receptacles for pin condition and corrosion. Depending on the MU connector there are different style male pin covers that can be corroded, damaged or missing (most likely pulled off in the MU cable). Corroded, damaged or missing pins can lead to an open or intermittent connections affecting locomotive control. As previously discussed, the application of a contact cleaner/dielectric spray is recommended. Dielectric spray provides the best long term protection especially on connectors exposed to the external environment.

**Oil Condition and Sampling:**

Take engine (prime mover and APUs) and air compressor oil samples and submit to a lab for analysis. Review the lab report for condemning criteria per OEM criteria. For both samples, wear metals should be monitored since they are an indicator of potential failures. For engine oil samples monitor for water and fuel dilution on-site using a crackle and a fuel sniffer test. Water and fuel contamination can lead to a bearing failure from loss of boundary lubrication. The contamination can be low enough that a CCOP (crankcase over pressure) will not trigger but damage can still occur. For rebuilt or remanufactured engines it is recommended to use a magnetic stick to probe the crankcase for potential debris such as steel chips. If detected, the oil and filters should be changed. The crankcase should be drained and cleaned if the debris is significant. Additionally if significant copper

or zinc is detected in the engine oil analysis check the engine maintenance history. Anti-seize compounds, which are typically copper or zinc based, can lead to false lab positives. For MUI engines also sample the governor oil to ensure it is zinc free. Zinc can have an adverse effect on mechanical governors.

Pipe Debris, Contamination:

Inspect air, fuel, oil and water piping during assembly and remanufacturing for debris. Contamination in the air lines can migrate downstream and damage the air brake system and block mag valves resulting in malfunction of the horn and pneumatic crossing bell which are FRA defects that can result in a locomotive setout. Contamination in the fuel system can result in an injector failure resulting in engine derating, shutdown or damage. Contamination in the oil system can result in bearing and ring liner damage and possibly oil pump damage. If the debris is of significant size it could block oil flow resulting in loss of lubrication and an LOP shutdown. Debris in the water system can inhibit proper cooling resulting in engine derating. The picture shows contamination in an air line. Before assembly run a bore snake through the pipe to clean it. After cleaning install plastic end caps to prevent contamination re-entry.



Weld Defects:

Inspect structural welds to discover potential failure points. Inspect for missing, undercut, blow-through and cold welds. Poor welds are not an imminent failure but can over time precipitate to failure due to fatigue caused by a stress concentration. Weld defects can be corrected by grinding, filling and blending. Also inspect for structural warpage that can be caused by weld heat from improper welding voltage and current settings and insufficient or unsecured weld fixtures. Weld warpage can cause stress concentration points potentially leading to a fatigue fracture. The picture below is of an undercut weld. To best detect weld defects the inspection should be done during underframe build.

**Conclusions:**

This paper addressed significant areas for inspection to detect defects for product quality and reliability improvement. Fourteen areas were identified to focus on but there are many more. As this paper was being prepared, with data from past inspections, it became evident that many more issues had been discovered that could not be fit into this paper due to scope limitations. To that end, the most significant and typically common cause issues were included. There



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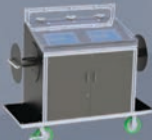
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will always be special cause defects that could be a one off but they must still be inspected for. The inspector needs to have in depth locomotive knowledge and experience in design, manufacturing, product test and field service. Typically, it is best to conduct these inspections as a team with electrical and mechanical team members. As a concluding comment the inspectors have to have a very discerning eye and look upon everything as to how it can fail, when it can fail and what the consequences are. The inspection information, once corrected, will improve quality and performance. Finally, information from the inspection will add to the knowledge of the inspectors providing continuous improvement.

Report on the Committee on Facilities, Material & Support

WEDNESDAY, MAY 21, 2025

3:00 PM



Chair

Tim Bernat

Director of Business Development

Powerhouse Rail, Dallas, TX

Vice Chair

Andrew Waltz

Asst Director of Material

Mid America Car, Kansas City, MO

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	Locomotive Reliability		
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Brandon Teal	Director-Railway Machine Systems	NSH USA Corporation	Albany, NY
			<i>Regional Executive</i>

PERSONAL HISTORY

Tim Bernat

Director of Business Development

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Longview, TX

Tim Bernat is the Director of Business Development for Powerhouse Rail in Longview, Texas. He started his new role in January 2024 after spending 13 years with LinkUp International in Fort Worth, TX. In Tim's new position he works closely with Short Line Railroads and Industrial Rail customers promoting locomotive rebuilds, mobile services, and offering new Tier 4 locomotives built by Powerhouse. Tim works closely with other Marmon Rail organizations such as Union Tank Car (UTLX), Procor, RAILServe, Ameritrack, Transco, McKenzie Valve, and Trackmobile. They are all backed by the stability of Berkshire Hathaway.

Tim has developed a broad network with Class I Railroads, Original Equipment Manufacturers, and Suppliers within the Rail Industry. For over a decade he supplied PTC and Communication equipment to the industry to help complete the Rail Safety Improvement Act of 2008. He works closely with Engineers, Sourcing, Project Managers, and Operations from project inception to completion.

He is an Iowa native that transplanted in the Dallas/Fort Worth area over 21 years ago with his wife Nicole who has been putting up with him for over 35 years. He has four adult children and two grandchildren that all live in the Fort Worth area.

Best Practices in Tool Management

Prepared by :

Andrew Waltz, Assistant Director - Materials at Mid-America Car, Inc.

Jason Mann, Rail Business Development Manager at Enerpac.

Introduction:

This paper emphasizes the critical importance of effective tool management in railroad mechanical maintenance facilities, highlighting best practices gathered from across North America. Our aim is to raise awareness of common safety hazards and inefficiencies, while offering actionable strategies to improve tool management, employee safety, and operational efficiency.

In maintenance operations, both directly and indirectly related to rolling stock repair, tools play a vital role. Proper tool management is essential for ensuring safety, efficiency, and cost control. Key components include documentation of tooling requirements, adherence to standards, new tool adoption, and ensuring employee qualifications. Storing and tracking tools properly enhances control, while managing tool condition and compliance with safety standards helps mitigate risk.

After reading this paper, we hope that both management and employees will reflect on their current tool management processes, identify areas for improvement, and implement the best practices shared here. Additionally, we will highlight safety hazards commonly overlooked in the rail industry, with the hope of preventing future injuries. Even preventing a single minor injury is considered a significant success.

In nearly every mechanical shop, whether railroad-owned or contractor-owned, as well as at railcar RIP tracks, a common issue is the condition of tools, particularly special tools that are not used daily or are shared by multiple workers. These tools are often well-worn, aged, and may be described as past their useful life—beaten down, poorly maintained, and, in some cases, borderline unsafe. It is often unclear whether these tools have ever been properly re-certified. For the purpose of this paper, we will refer to these tools as “unmanaged items”—tools that are present in every maintenance facility but seem to have no clear ownership or accountability.

One prime example of these “unmanaged items” is hydraulic tools. Many repair facilities have a designated area, such as a cart, cabinet, or pegboard, where hydraulic tools are stored. However, these tools are often left unsecured, not stored

in a designated tool room, and are rarely monitored or maintained properly, even in facilities with a tool room attendant (a position that is becoming increasingly rare).

For example, at one facility we visited last year, drop table workers were performing a routine maintenance task on the trucks (bogies). This task seemed to be repeated on every unit, and the mechanics used a plastic rolling cart to hold the hydraulic tools required. The cart contained an electric hydraulic pump, a three-foot rubber hydraulic hose, and a small hydraulic cylinder. Upon inspecting the setup, we discovered that a twelve-inch section of the three-foot hose had worn completely through the rubber coating, exposing the steel braided line underneath. The hose was immediately cut in half and disposed of to prevent any potential injuries from a hose failure.

Safety is deeply ingrained in every facet of North American railroading, driving processes and procedures at all levels—It is a key part of how tasks are completed, and it shapes the culture across all departments. How often have you passed by a non-rail business proudly displaying a sign showing the number of injury-free days their employees have worked?

However, one area where the lack of proper tool management can have profound consequences is in the use of hydraulic tools, which are prevalent across the rail industry. Despite our strong safety culture, what is shocking is that many Railroad Mechanical Department employees do not fully understand the risks associated with high-pressure hydraulic tools, which can operate at pressures up to 10,000 psi. Damaged or degraded hoses are just one part of these systems that can cause significant injuries. Hose condition is one of the most commonly overlooked aspects of hydraulic systems. Just because a hose is not leaking at the moment does not mean it is safe. Misconceptions regarding proper hydraulic tool usage are not only prevalent among newer employees but also affect more experienced staff. Furthermore, the knowledge gap surrounding specialized tools—or ‘unmanaged items’—has been amplified by the “brain drain,” the retirement of the Baby Boomer generation, contributing to a lack of expertise in many mechanical facilities.

In many cases, tool management is treated as an afterthought, yet improving these processes can significantly impact both operational efficiency and safety. Effective tool management in locomotive and railcar repair facilities is not just about improving safety—it is about optimizing operations and reducing costs.

To drive improvements in employee safety, operational metrics, and cost control, it is essential for railroad mechanical departments to adopt best practices in tool management.

1. Inventory Control Practices

Use of Technology: You may not think of vending machines as a “high-tech” innovation but adapting them to supply necessary consumables—like leather gloves, flashlights, safety glasses, Tyvek suits, and raincoats—can vastly improve labor efficiency. (See figure 1. *Consumable Items Vending*). Consider how much time can be saved by eliminating long lines at the tool room. After employee job briefings at the start of a shift, instead of waiting in line for consumable items, they can directly access what they need through automated vending machines and go to work. If your facility has not explored this yet, it is time to consider this technology to improve workflow.

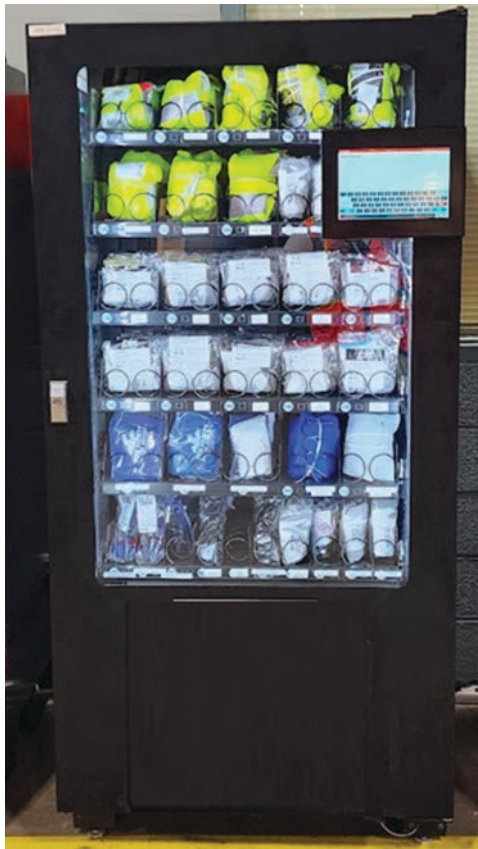


Figure 1. Consumable Items Vending.

Regular Tool Audits: Perform regular tool audits to ensure tools are accounted for and properly maintained. Tool audits are similar to “Plant Walkdowns,” but with a focus on tools and tooling used in the facility. Audits involve inspecting tools, checking compliance with safety regulations, observing the condition of equipment, and ensuring proper maintenance has been carried out. Regular audits can be beneficial for:

- **Routine inspections** for safety and compliance with rules and regulations.
- **Pre-maintenance assessments** to plan out plant repairs or upgrades.
- **Post-incident investigations** to understand the causes of tool failures or incidents.
- **Quality control** to ensure the plant is utilizing, storing, and maintaining tools as intended.

During a tool audit, personnel should check for the condition of all tools, including safety equipment, lifting jacks, cranes, and job carts. Audits are also essential for spotting “unmanaged items” like expired lifting chains, hydraulic hoses in poor condition, or unauthorized tools.

When performing an audit, remember that fresh eyes can often spot issues that may have been overlooked, making audits a proactive approach to safety. Finding defects in tools during an audit is far better than discovering them during an incident investigation.

What tools should NOT be found in your shop or tool room? There are certain tools that should never be found in a railroad mechanical facility. For instance, homemade or “unauthorized” tools—whether fabricated at home or within the facility—are a major safety concern and are prohibited. Most railroads have a process in place for employees to submit ideas and designs for new tools, and these tools must go through an official approval process. Many railroads operate a “Tool Committee” that evaluates new tool recommendations, assesses relevant regulations, conducts testing, and establishes procedures for tool use within the organization.

One such example of a tool that has no place in a mechanical facility is the Track Jack. Track Jacks, with their century-old design, are intended to “slam down” quickly by Maintenance of Way workers to clear tracks immediately when a train is approaching. These tools are not suited for lifting machinery or equipment and should never be used inside a mechanical shop.



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2. Tool Organization

Standardized Storage: Tools should be organized in a manner that promotes easy access and return. Shadow boards or designated storage bins for each tool help ensure that tools are stored properly. Shadow boards make it easy to identify when a tool is missing or out of place. (See *Figure 2. Shadow board within a tool cabinet*)



Figure 2. Shadow Board in a Tool Cabinet.

Tool Check-Out System: Implement a formal requisition system where tools must be signed out and returned. This helps track tool usage and availability. Implement a digital inventory management system to track tools in real-time. Barcoding or RFID tags can help in identifying, checking in, and checking out tools efficiently. Organizations should implement a formal method for tracking the locations of tools removed and returned to their tool storage areas, including the tool room. These systems should track who has possession of tools at all times and where that tool is located. Many of these systems also allow for employees to note conditions related to the tools such as defects or noted maintenance needing to be completed.

Modern Electronic Check-Out Systems utilize an employee pin code or a QR coded Employee ID Badge to track the sign out and return of tools. (See Figure 3. *Outside Contractor provided Tool Check-Out System*). The Modern Electronic Check-Out Systems can limit tool access to various employee groups, such as those employees who may not yet be qualified to utilize specific tools and can likewise restrict certain high-cost or other specialized tools to only trained or certain authorized personnel to help prevent misuse and prevent risk of injuries.



Figure 3. Outside Contractor provided Tool Check-Out System.

Tool Stations - Job-Specific Required Tools: Set up dedicated workstations for specific tasks, ensuring tools are organized according to job function. A well-known saying in the railroad industry is, “use the right tool for the job.” Given the complexities of rail operations, it is crucial to properly manage job-specific tools. A best practice is to use job-specific tool carts or location-specific toolboxes that are actively maintained.

Over time, companies have emerged that specialize in engineering and testing tools designed specifically for railroads, manufacturers, and remanufacturers. These companies dedicate countless hours to designing, testing, manufacturing, and certifying new tools that either enable tasks to be completed or make tasks safer. However, these tools are designed for specific purposes. For example, a C-frame should never be used to lift a locomotive engine because the tool is not compatible with such a task. Before using any tool, always check whether its intended use aligns with the manufacturer’s specifications.

Color Coding: Implement a color-coding system for tools to easily identify them by category, function, year of certification, or size. One simple and effective approach is to apply different colors to tools, with each color representing a specific piece of information. For example, some organizations use color coding to indicate the year a tool was purchased. In other cases, paint may be applied based on when the tool was last maintained or inspected. Alternatively, colors may be assigned to tools depending on which department is responsible for them. Regardless of the approach, it is crucial that this system is communicated clearly

across the entire company and applied consistently throughout all facilities to ensure its effectiveness.

3. Regular Maintenance & Calibration

Preventive Maintenance: Schedule regular inspections and maintenance for each tool to ensure it remains in optimal working condition. Organizations should have clear protocols for verifying the condition and operation of power tools and extension cords. This protocol should outline when and how extension cords or electrical cords on tools can be repaired, as well as the circumstances under which they should be replaced. It should also include standard procedures for routine maintenance and checks. These protocols should prioritize employee safety while adhering to local codes and industry standards.

LOTO (Lock Out, Tag Out): Facilities must have a comprehensive Lock Out, Tag Out (LOTO) procedure that accounts for all potential sources of energy in use at the facility. The procedure should be easy to communicate and implement across all employee levels. A culture that prioritizes LOTO and makes it difficult to bypass helps prevent accidents and reduces the occurrence of near misses, ensuring the safety of workers when handling or servicing machinery.

Torque Wrenches: Torque wrenches are essential tools in the rail industry, with variations including pneumatic, electric, hydraulic, and battery-powered models. They are used in a wide range of applications, and proper use is critical. Incorrect usage or failure to properly calibrate a torque wrench can lead to costly equipment failures.

To ensure accurate and safe operation, users should adhere to specific procedures for calibrating and using torque wrenches. The 80% Rule is a widely followed guideline: avoid using a torque wrench above 80% of its rated capacity. This ensures that fasteners reach the desired torque value with confidence and reduces the risk of overloading the tool.

Regular maintenance is essential for torque wrenches, which may include re-certification, lubrication, component repairs, and tool cleaning. Always refer to the manufacturer's maintenance requirements, as some tools may have specific care instructions, while others may require minimal upkeep.

Calibration: Regular calibration of precision tools is crucial to ensure accuracy in measurements, especially in locomotive repairs. Many organizations now use specialized systems to manage their calibrated and certified tools. These systems typically include modules for tracking maintenance, tool re-certification, and usage history.

In recent years, software solutions for tool management have become more advanced and integrated with other platforms, providing a more comprehensive approach at little to no cost to the company or end user. These systems help minimize hidden costs like time spent manually tracking tools and documenting maintenance.

By maintaining a history of each tool's usage and calibration status, the organization can spot instances of damage beyond normal wear and tear. Usage statistics also allow for better planning of maintenance schedules and forecasting the lifecycle of tools, ensuring they remain accurate and safe for use.

Certifying Gauges and Tools: The National Institute for Standards and Technology (NIST) emphasizes the importance of certification, stating, "Certification of equipment is important because technical standards keep us safe, enable technology to advance, and help businesses succeed. They quietly make the modern world tick and prevent technological problems that you might not realize could even happen." (Stein, 2022)

In most cases, no two gauges are identical in their readings 100% of the time. For this reason, critical gauges should be sent to accredited laboratories for inspection and evaluation. The readings from these inspections are compared against specific standards to ensure the tools perform correctly. The standards used during the calibration process depend on the type of equipment and its intended use. Manufacturers typically provide the necessary requirements and tolerance allowances for each specific tool.

If any defects or discrepancies are found during calibration, it is essential to assess how they may impact the gauge's accuracy and reliability. If a gauge fails calibration or a defect is identified, it should not be used in production until it has been reconditioned, re-tested, and confirmed to meet the same standards (prior to failure).

Establishing a standardized process for certifying gauges is essential for ensuring their accuracy. Industry-recognized organizations, such as NIST, provide the necessary benchmarks for certifying tools. By using certified gauges, organizations can rely on the fact that the measurements taken are within an accepted range of accuracy. Failure to certify tools and gauges can lead to costly mistakes, including premature failures, potential injuries, and warranty issues.

Tool Condition Tracking: Tracking tool wear and tear is crucial to ensuring both safety and efficiency within a mechanical facility. Organizations should implement a system that monitors the condition of tools and gauges over time, identifying when they begin to deteriorate and need repair or replacement. As tools are used, their condition naturally declines, and at some point, decisions must be made about whether a tool can continue to be used safely or should be retired. A robust Tool Condition Tracking system allows organizations to track the total cost of ownership of tools, which includes repair costs and maintenance history. By establishing this system, organizations can better estimate when tools will need replacement or repair, leading to more informed decisions about tool procurement and replacements over time. Additionally, this system can highlight common tool failures or patterns, enabling companies to address recurring issues through better training or the establishment of best practices. Tracking these patterns helps prevent future damage and ensures that safety hazards related

to tool failure are minimized. This approach ensures that tools are properly maintained and replaced at the optimal time, reducing downtime and improving overall operational efficiency.

4. Tool Standardization

Tool Selection Criteria and Consistency in Tool Types: When selecting tools for mechanical maintenance, it is essential to prioritize durability, ergonomics, and cost-effectiveness, while ensuring the tool is designed for the specific task at hand. The right tools improve both safety and productivity, so it is important to select equipment that can withstand the demands of the job and offer comfort during use.

Standardization across the shop is key. By using consistent tools, organizations ensure compatibility and simplify maintenance, while reducing the likelihood of losing tools or dealing with mismatched parts. Standardizing tools across the organization can also prevent unnecessary inefficiencies.

Organizations should carefully consider the long-term costs of tool selection. Choosing multiple brands or models may initially seem like a good idea for variety, but it increases complexity. When different tools from different manufacturers are used, it often leads to the need for multiple types of batteries, chargers, and accessories. This not only adds to the cost but also creates logistical challenges. By consolidating on a single brand or model line, organizations can streamline resources and reduce the number of spare parts needed to support their operations.

Investing in a standardized selection of tools may have a higher initial cost, but it simplifies tool management and ensures greater overall efficiency and ease of use. It is crucial to consider the total cost of ownership, including accessories and consumables, when making decisions about which tools to acquire for the year ahead.

Access to Tool Documentation: There should be a clear process in place to ensure that employees have access to the necessary resources for proper tool use. The way tools, especially precision equipment like gauges, are used can significantly impact the outcome of their application. For this reason, it is crucial to minimize variables that might affect their effectiveness.

Organizations must ensure that employees have ready access to comprehensive documentation related to the tools they use. This documentation can include user manuals, tool test records, organization-specific job aid cards, and other resources that reduce the risk of tools being used outside of their intended specifications. By providing this information, employees are more likely to understand the correct procedures and safety protocols associated with each tool.

It is important to regularly evaluate what resources employees have access to at all times, day or night. If employees do not have the capability to access documentation—such as instructional videos on devices, written materials, or assistance from experienced colleagues, they may use certain tools incorrectly.



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Ensuring that resources are easily accessible reduces the likelihood of improper tool usage, thus ensuring both safety and effectiveness.

Tool Adoption: Companies should establish a well-defined tool adoption process that aligns with the organization's needs. In some cases, there may be a dedicated team whose primary responsibility is evaluating and approving tools for implementation. In other instances, external authorities or suppliers may play a key role in assessing tools for production. Regardless of the approach, the evaluation process should incorporate engineering standards, test records, and a pilot phase to assess the suitability of new gauges and tools.

As part of the adoption process, the designated authority should have the ability to inspect tools for compliance with engineering specifications or prints. They should also be able to assess the tool for potential damage, whether it occurred during manufacturing, shipping, or handling. This thorough evaluation helps ensure the tool's functionality and safety before it is approved for use.

Clear policies should be in place to outline the requirements that must be met for tool adoption, as well as the steps for managing the process. By ensuring that only properly vetted and compliant tools are adopted, organizations can set the expectation that tools will perform as required and meet project standards. Additionally, it is important for companies to stay vigilant about recalls that may be issued for any adopted tools, taking swift action to remove or replace tools if necessary.

5. Employee Training, Qualification, and Certification

Employee Training: It is crucial to ensure all personnel working in the tool room and all employees who utilize tools are properly trained. Safety procedures, proper tool handling, storage, and usage are essential components in maintaining a safe work environment. Adequate training is critical for preventing accidents, ensuring employees understand how to use tools safely and efficiently, and guaranteeing compliance with regulatory standards.

Additionally, maintaining detailed and accurate records of employee training and certifications is key to monitoring ongoing compliance and readiness. These records should track the completion of both initial and ongoing training, ensuring that every individual is up to date with the latest procedures and standards.

Safety Training: Safety training should be provided regularly to reduce the risk of injuries. This includes offering refresher courses to keep up with evolving safety practices and industry standards. Ensuring that employees are always informed about the latest safety protocols helps mitigate potential risks.

Many organizations also implement tribal knowledge or mentor-style training programs. In this model, employees are paired with experienced workers or supervisors for hands-on, on-the-job training. This approach allows the trainee to ask follow-up questions, learn in real-time, and benefit from direct observation of experienced professionals. Once the employee demonstrates competence in

using tools or machinery with minimal supervision, the supervisor can confirm the employee’s readiness to work independently.

It is critical to document the completion of this training in each employee’s human resources record, ensuring that the company has an accurate log of all training completed and certifications earned.

Qualification and Certification: As employees acquire the necessary knowledge and certifications to perform their specific tasks, it is vital for the organization to keep track of each employee’s qualifications and certifications, as well as any follow-up recertifications. In facilities with a diverse workforce across various crafts and skill levels, it can be challenging to stay organized and ensure that employees are qualified for specific duties. Without proper tracking, an organization may lose visibility into which employees possess the required certifications or knowledge for certain tasks.

Additionally, some certifications require ongoing maintenance through tests, procedures, or refresher courses. Therefore, it is crucial for the company to have an organized system in place to monitor certification status, including tracking renewal dates for recertifications.

To further enhance accountability, some organizations go the extra mile by establishing an Employee Training and Certification Board or chart that is publicly displayed within the facility for all employees to view. This system not only ensures visibility but also fosters a competitive and motivating culture around training completion and certifications. By displaying progress, employees can see where they stand in relation to their peers, and management can promote positive attitudes toward continuous learning and professional development within the workforce. (See Figure 4. Employee Training and Certification Board).

Employee Training & Certification								
NAME	CRAFT	Shop Safety 101	Welding Awareness	Switchman Training	MSDS	Dangers of High Voltage	Hydraulic Tools 101	Hydraulic Tools 102
Mike Smith	Mechanic	1/1/2024	1/11/2025	10/13/2024	2/14/2025		5/17/2025	
Miriam Nilsson	Electrician	2/19/2020	3/1/2021	12/1/2020	4/4/2021	4/23/2021	7/5/2021	
Victoria Lindqvist	Mechanic	4/30/2024	5/11/2025	2/10/2025				
August Bergqvist	Painter	6/19/2023	6/29/2024		8/2/2024	8/21/2024	11/2/2024	
Alexander Martinson	Mechanic	8/1/2010	8/12/2011	5/14/2011	9/15/2011		9/11/2014	
Angelica Astrum	Fabricator	3/27/2017	4/7/2018		5/11/2018		8/11/2018	8/24/2024
Tim Tebow	Supervisor	12/12/2018	12/23/2019	9/24/2019	1/26/2020	2/14/2020	8/14/2021	9/6/2023
DJ Watts	Manager	5/14/2015	5/24/2016	2/24/2016	6/27/2016	7/16/2016	6/24/2019	5/17/2023

Figure 4. Employee Training and Certification Board.

Proper Tool Handling: It is essential to train staff on the correct usage, maintenance, and storage of tools to prevent damage and ensure safety. Employees should be educated on how to handle tools with care to avoid unnecessary wear, damage, or loss. Emphasis should also be placed on proper storage techniques to

prolong the life of tools and prevent accidents. Encourage employees to report broken or damaged tools immediately to prevent further damage or risk to safety.

Tool Safety Protocols: Employees must fully understand and adhere to safety protocols, including the proper use of Personal Protective Equipment (PPE) when operating specific tools. A notable best practice comes from a shipbuilding contractor in Virginia who implemented a Tool Safety Protocol and Limited Tool Access for a particularly dangerous tool associated with previous injuries. To improve safety, the company invested in creating an orientation and operational training video specific to the tool. They also applied a QR code label to the tool, which links to the video, and established a process that requires employees to watch the training video before checking out the tool from the tool room. This practice ensures employees are properly educated on the risks and safe handling of the tool before use.

Inventory Management Training: In addition to training on tool usage, staff responsible for tool management must be trained in proper inventory practices. This includes how to check tools in and out, as well as the correct procedures for reporting and tagging damaged or lost tools. Employees managing tool inventories must be proficient in the organization's tool tracking systems to maintain accurate records and ensure tools are consistently available and in good condition. A clear understanding of the organization's inventory practices is essential for minimizing errors and ensuring efficient management of the toolroom.

6. Tool Requisition and Check-out Systems

Tool Check-Out System: A formal requisition system should be established where tools must be signed out and returned to ensure proper tracking of tool usage and availability. This system helps organizations maintain accountability and ensure that tools are used and returned in an organized manner. It should log not only which employee checked out each tool but also the specific project or task the tool was used for. By tracking this information, the team responsible for tool maintenance and storage can easily monitor tool status, ensure tools are returned on time, and quickly identify any tools that may be overdue or missing. This approach also supports proper tool maintenance by providing a record of usage, allowing for timely inspections or servicing when necessary.

7. Tool Repair and Replacement – Life Cycle Management

Repair Program: Establishing a repair program for tools, rather than immediately replacing damaged items, can result in significant cost savings and help prolong the life of valuable equipment. Tools naturally experience wear and tear with regular use, and harsh working conditions can accelerate this process. It is crucial for organizations to implement a periodic recertification program that ensures tools are functioning within their required specifications. The recertification schedule should be tailored to different tool types and should be

reviewed regularly to ensure intervals are sufficient to prevent safety hazards or inaccurate readings. During the recertification process, tools should be tested for performance against industry standards, and records of each inspection should be maintained for future reference.

Tools Removed from Service: When a tool is removed from service due to wear, damage, or misuse, it is vital that the tool undergoes repair or replacement without delay. Leaving tools in a “bad order” status, without repair or replacement, creates significant risk. Not only does it increase the chance of a tool being forgotten, but it also opens up the possibility that employees may inadvertently use damaged tools or borrow parts for other tools, potentially causing failures or safety issues. For this reason, tools that are deemed unfit for use must be repaired or replaced promptly. If repair is not an option, the tool should be removed from circulation completely to prevent any accidental use.

Replacement Plan: To maintain uninterrupted operations, it is essential to have a well-defined replacement plan for worn-out tools. Having a steady inventory of replacement tools helps avoid downtime and ensures work can continue without disruptions. Tools that are no longer usable due to damage or inability to be repaired should be promptly removed from service. Red tags may be used to identify defective tools, but they can deteriorate over time or fall off, which means relying solely on visual identification can be problematic. To prevent tools from being inadvertently used, it is important to have a robust system for disposing of or scrapping tools that can no longer be repaired or calibrated, preventing them from being forgotten or overlooked.

Tool End of Life: Organizations should have a clear and standardized protocol that outlines when tools should be removed from service. In some cases, these protocols may be defined by the manufacturer’s specifications, but they can also be established by regulatory bodies, certifying authorities, or company policy. Regardless of the origin of these standards, it is essential for the company to implement a process that ensures tools are not used beyond acceptable tolerances or safety limits.

Standards and Guidelines: At a minimum, there should be clear guidelines that identify the specific point at which a tool should be removed from service. These guidelines should include:

- **Manufacturer Specifications:** Follow the tool manufacturer’s recommendations for wear and tolerances.
- **End-User or Regulatory Guidelines:** Some organizations might rely on regulatory boards or authorities that set safety and calibration standards to determine when tools should be taken out of service.
- **Company Policy:** Companies may develop their own internal standards based on operational needs, financial considerations, and safety requirements.

Preventing Tolerance Bypassing: Once a tool is identified as outside of its tolerance range, the organization must ensure that the tool is immediately removed from use. There should be no bypassing of these tolerances in production, as doing so can result in errors, equipment failures, or safety hazards.

Disposal and Decommissioning: When tools are removed from service, they should be made unusable to prevent accidental use. This can be done by marking the tool as “out of service,” rendering it inoperable, or decommissioning it according to company policy. Tools that cannot be repaired should be disposed of in a manner consistent with environmental regulations and company procedures.

Verification Before Reuse: Under no circumstances should a tool be returned to service unless it can be safely verified that it has been repaired or re-certified to meet the required standards. This includes ensuring that any gauges or precision tools are calibrated back within tolerance before they can be used again.

Financial Considerations: In some cases, the decision to keep a tool in service may be influenced by its financial cost. Organizations may assess the cost of repairs and maintenance versus the cost of replacing a tool. If the cost to repair exceeds the replacement cost or the tool is no longer viable for continued use, it should be retired and replaced.

8. Optimizing Tool Utilization

Tool Sharing and Rotation: Optimizing Tool Utilization: Maximizing tool utilization is essential for operational efficiency and cost management in today’s maintenance environment. Traditional methods, where each employee or craft is assigned a full set of tools, often lead to underutilization, excess inventory, and wasted resources. By implementing an effective tool sharing and rotation system, organizations can enhance resource allocation, reduce overall expenditures, and improve productivity.

Tool Sharing: A centralized tool-sharing system ensures that tools are readily accessible to various teams and across different shifts. This eliminates the need for each individual to have their own set of tools, reducing excess inventory and freeing up capital for other investments. For example, instead of equipping every machinist with a personal rolling tool chest, tools can be shared and tracked through a central management system. This is especially beneficial when workloads fluctuate between crafts. If one department experiences a temporary lull, its less-used tools can be made available to another department facing higher demand. This dynamic allocation ensures resources are deployed where they are most needed, preventing critical shortages and maximizing overall productivity.

Tool Rotation: Rotating high-demand tools among different crafts further optimizes their usage and extends their lifespan. Different crafts tend to use the same tools at varying frequencies, resulting in uneven wear. For instance, welders and fabricators may use welding machines more intensively than mechanics, while mechanics may rely more heavily on impact wrenches. By tracking tool usage patterns and identifying which tools experience the most wear, organizations can create a rotation schedule. After a period of heavy use, a tool can be transferred to a craft that uses it less frequently. This helps spread the wear more evenly, prolonging tool life and reducing the need for replacements. In turn, this proactive maintenance approach not only saves money but also ensures tools are available when needed, contributing to increased efficiency across all craft groups.

9. Tool Loss Prevention

Tool Securement: To protect high-value tools and prevent theft, it is crucial to implement secure storage solutions. Locomotive repair and overhaul facilities often possess expensive, essential tools that are vital to completing tasks. Unfortunately, there are occasions when tools are used without permission or are intentionally retained. To mitigate this risk, organizations should invest in lockable cabinets and secure lockers for smaller tools, while larger tools can be locked down with heavy-duty locking mechanisms. Additionally, modern tracking devices, such as Bluetooth tags or Apple AirTags, can be attached to tools that are difficult to secure in cabinets. These devices provide an added layer of security by alerting the organization when tools are removed from designated areas. Although these tracking systems are not foolproof, they increase the likelihood of recovering stolen tools and can serve as a deterrent to theft.

Tool Accountability: Fostering a culture of tool accountability is essential to maintaining the integrity and availability of tools. Employees should be held responsible for returning tools promptly and in usable condition, ensuring that each tool is ready for the next user. A robust Tool Inventory and Accountability Program ensures that every employee is aware of their responsibilities when it comes to the tools they use. One effective practice is issuing tools with a signed hand receipt, which formalizes the understanding that employees are accountable for the equipment in their possession. This system encourages personal responsibility and creates a consistent standard across the organization, helping to protect valuable tools from misuse or loss. By fostering an environment of respect for company resources, organizations can prolong the life of their tools and reduce unnecessary costs associated with tool replacement.

10. Performance Metrics and Continuous Improvement

Track Tool Usage: Track tool usage to identify patterns. Use data to identify underutilized tools that might be unnecessary, helping to reduce costs, excess inventory, and improve efficiency. For tools that are used frequently, ensure they

are always in working order and available for operations reducing costs and improving efficiency. Having essential or high frequency use tools, (essential tools being those tools that are essential to mechanical operations and the facility), always available and in working order is much easier said than done. Depending upon the reliability of the essential or frequently used tools, consider the creation of a float pool to establish how many of each tool you will need in inventory so as not to disrupt operations:

1. Investigate the Mean Time Between Failures (MTBF) of each essential and frequently use tools.
2. Establish the total average time to repair the tool and have it back on the shelf ready and available for use.
3. Learn the amount of time required within your organization for purchase approval(s) and delivery lead time(s) for replacement of essential and frequently used tools.

The formula above will give you a general understanding of the total quantity, justification, and need for a float pool of your essential/high frequency usage tools.

Track Tool Usage: Effectively tracking tool usage is crucial for optimizing inventory and ensuring operational efficiency. By analyzing usage patterns, organizations can identify underutilized tools and reduce excess inventory, which in turn helps lower costs and improve overall efficiency. For tools that are in high demand or essential to daily operations, it is critical to ensure they are always available and in working order. Maintaining a steady supply of these essential tools, especially those that are frequently used, can be challenging. However, through careful planning and data-driven decisions, it becomes possible to streamline tool management.

One effective strategy is creating a float pool for essential or frequently used tools. This approach ensures that enough tools are always available, even during maintenance or repair downtime. To calculate the optimal number of tools required in your float pool, consider the following steps:

- 1. Investigate Mean Time Between Failures (MTBF):** Determine the average time between failures for each essential or frequently used tool. This data will help you predict when tools are likely to require repairs or replacement.
- 2. Establish Average Repair Time:** Assess the total average time it takes to repair a tool and have it back in circulation. Knowing this will give you a clear idea of how many spare tools you will need to keep operations running smoothly.
- 3. Understand Seasonal Lead Time for Tool Procurement:** Understand the seasonal lead time for purchasing and receiving new tools. Tool procurement processes can be delayed depending on the time of year, so having this knowledge allows you to better plan for potential shortages.

By applying these metrics, you can gain a clearer understanding of how many tools to keep in inventory and when to replace or repair them. This strategy ensures that high-demand tools are always available, helping to reduce operational disruptions and improve productivity.

Employee Feedback: Effective tool management leadership fosters a culture of continuous improvement by actively engaging employees in the process. Regularly gathering feedback from staff regarding tool management systems and practices is essential for identifying areas of improvement and ensuring that the tools meet the needs of the workforce. Employees who use tools daily often have valuable insights into potential inefficiencies, tool performance, and the overall effectiveness of the tool management system. By creating a system for collecting and acting on employee feedback, organizations can make informed adjustments that enhance tool availability, safety, and overall efficiency.

Encouraging employees to share their thoughts and suggestions not only improves the tools and processes but also fosters a sense of ownership and accountability in the workforce. This collaborative approach to tool management ensures that leadership is responsive to staff needs and that the organization remains adaptable to changing requirements and challenges. Regular feedback sessions, surveys, or informal discussions can help uncover opportunities for streamlining operations, improving tool tracking, and addressing any issues that could affect productivity or tool longevity.

By prioritizing employee feedback, organizations demonstrate their commitment to ongoing improvement and create an environment where staff feel empowered to contribute to the success of the tool management system.

Summary:

Effective tool management is vital to the success and productivity of organizations, particularly within Mechanical Maintenance facilities. Adopting best practices in tool management leads to increased productivity, reduced downtime, improved safety, and enhanced operational efficiency.

To make a meaningful impact on the operational performance of your facility, start by conducting a thorough tool audit. Tool audits are the foundation of effective tool management, helping identify inefficiencies, safety hazards, and areas for improvement. Consider engaging a third-party expert for the audit. An external perspective can uncover blind spots and provide valuable insights that internal teams may overlook.

Tool audits should be viewed as an ongoing process, not a one-time task. By continually assessing and improving tool management practices, organizations can achieve lasting gains in safety, productivity, and cost efficiency.

To drive sustained improvements in operational metrics, employee safety, and cost control, Railroad Mechanical Operations departments should implement well-defined best practices in tool management.

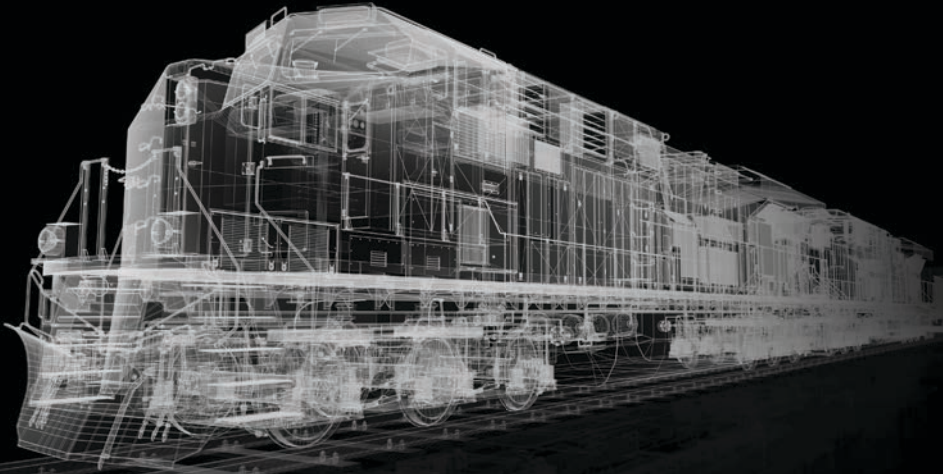
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Remanufacturing in the Railway Industry

Prepared by :

Brandon Teal – Director Railway Machine Systems, NSH USA Corporation

Remanufacturing is a vital part of the railway industry, particularly for locomotives, freight cars, and maintenance equipment. By restoring used components to like-new condition, railroads can reduce costs, minimize downtime, and extend the life cycle of critical equipment. This paper explores the role of remanufacturing in the railway industry, focusing on best practices, core availability challenges, sustainability, and future trends.

The railway industry has historically relied on remanufacturing to maintain operational efficiency and extend the life cycle of the locomotive. The concept of remanufacturing in rail dates to the early 20th century, when railroads pursued solutions to maximize the longevity of steam locomotives by refurbishing worn-out components instead of replacing them with costly new parts. As diesel-electric locomotives became the standard in the mid-20th century, remanufacturing practices evolved to include advanced machining, precision engineering, and non-destructive testing, ensuring that refurbished parts met or exceeded OEM (Original Equipment Manufacturer) specifications.

Today, freight and passenger rail operators aim to maximize return on investment while keeping pace with new and enhanced environmental regulations, making remanufacturing a critical practice than most of us know. In recent years, we have experienced global supply chain disruptions, increasing raw material costs, and a growing emphasis on sustainability. To keep pace with the ever changing economics of running a business and turn a profit, railroad operators and suppliers must innovate their remanufacturing strategies.

This paper will cover the definition and importance of remanufacturing, critical best practices, supply chain challenges, the environmental benefits of remanufacturing, and real-world case studies demonstrating the economic and operational advantages of locomotive, component, and equipment remanufacturing. Additionally, it will highlight future trends, including AI-driven predictive maintenance, automation in remanufacturing, and advancements in materials.

The Role of Remanufacturing in Rail Today

Remanufacturing plays a pivotal role in ensuring the reliability and efficiency of the railroads, particularly the locomotives. Railroads rely heavily on the supply chains ability to re-use essential components such as engines, generators, traction motors, and axles through the remanufacturing process. These components experience significant wear and tear due to continuous operation and require periodic restoration to maintain peak performance. Additionally, mission critical maintenance equipment, such as the underfloor wheel truing machine, contains several remanufacturable components and assemblies that contribute to long-term operational reliability and efficiency.

The adoption of remanufacturing in rail is driven by three major factors: economic benefits, supply chain stability, and sustainability. The economic aspect is perhaps the most compelling, as remanufactured components typically cost 40% to 60% less than new parts, offering railroads significant savings on maintenance and repairs. These savings can easily accumulate to millions of dollars annually, making remanufacturing a strategic necessity rather than just an alternative to buying new.

Railroads depend on highly specialized components that are often not readily available as new from manufacturers due to long production lead times or limited production runs. By remanufacturing key parts, railroads can reduce procurement lead times and ensure a steady supply of critical components, thus preventing costly disruptions to railroad operation.

From a sustainability perspective, the remanufacturing process reduces the environmental impact of locomotive maintenance by decreasing the demand for raw materials such as steel, aluminum, and copper. Manufacturing new components from raw materials consumes significant amounts of energy and generates greenhouse gas emissions. Remanufacturing is said to reduce material waste by up to 85% and lower carbon emissions by approximately 60% compared to producing new parts.

Key locomotive components that benefit most from remanufacturing include:

- Engines: Locomotive diesel engines are subject to extreme stress and wear over time. By remanufacturing power assemblies, turbochargers, fuel injectors, and crankshafts, railroads can restore engine performance at a fraction of the cost of a new engine.

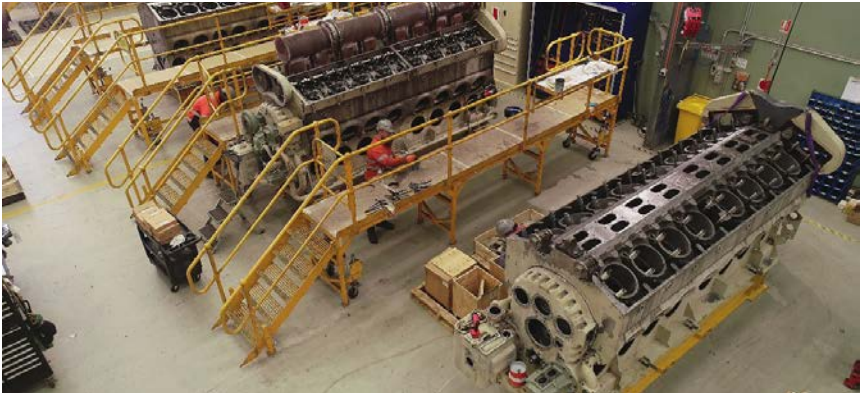


Figure 1 Locomotive Engine Plant (Source: Progress Rail Services 2025)

- **Traction Motors:** Essential to locomotive propulsion, a remanufactured traction motor undergoes a complete rebuild, including rewinding, bearing replacement, and armature reconditioning, ensuring peak efficiency and reliability.
- **Generators and Alternators:** The electrical power system in locomotives relies on generators and alternators to supply electricity to traction motors. Over time, windings degrade, and insulation breaks down. Remanufacturing these components involves rewinding, replacing insulation, and load testing for performance.
- **Axles, Wheelsets, and Bearing:** A crucial part of locomotive safety, axles, wheelsets, and bearing undergo significant wear and tear. Remanufacturing these vital components includes non-destructive testing, fatigue analysis, and re-machining to ensure compliance with safety standards.



Figure 2 Locomotive Combo Units Post Inspection and Wheel Truing

- **Braking Systems:** Locomotive braking systems, including air compressors, valves, and brake shoes, are regularly remanufactured to maintain stopping power and safety. Modern remanufacturing techniques incorporate new materials that extend component lifespan.
- **Maintenance Equipment:** Underfloor wheel truing machines are a critical part of locomotive maintenance practices. In North America, locomotives are designated for wheel truing after planned or unplanned inspection. These machines, which restore worn profiles of locomotive wheels, contain numerous wear components that require periodic remanufacturing, including large driveshafts, and precision screw and nut subassemblies.



Figure 3 Remanufactured Stanray® Wheel Truing Machine

The combination of cost savings, supply chain resilience, and sustainability makes remanufacturing an essential component of modern railway operations. Railroads that integrate remanufacturing into their business models benefit from extended equipment lifespans, reduced operating costs, and improved reliability.

Best Practices in Remanufacturing

To meet the growing demand for remanufactured locomotive components, the railway industry has established a series of best practices to ensure quality, efficiency, and guidelines including the American Association of Railroads (AAR) Manual of Standards and Recommended Practices and American National Standards Institute (ANSI) RIC001.2-2021. Best practices include:

Standardized Inspection and Disassembly Procedures

- Core components are inspected using non-destructive testing (NDT) methods, including ultrasonic testing, magnetic particle inspection, and radiographic analysis, to detect surface and subsurface flaws.

- Wear patterns and failure modes are documented to refine predictive maintenance models and improve future remanufacturing processes.
- Disassembly is performed in a controlled environment to prevent contamination and damage to reusable components.



Figure 4 Axle Undergoing Magnetic Particle Station

Precision Cleaning and Reconditioning Techniques

- Components undergo chemical baths, high-pressure water jet cleaning, and ultrasonic degreasing to remove contaminants.
- Advanced coatings and treatments are applied to restore wear surfaces, increasing durability and extending the lifespan of remanufactured parts.
- Precision machining ensures that components are restored to OEM tolerances, reducing the risk of premature wear or failure.

Testing and Quality Assurance

- Dynamometer testing simulates real-world operational conditions for traction motors and generators.
- Load testing and fluid analysis ensure that remanufactured engines meet OEM performance specifications.
- Remanufactured components are serialized and tracked, allowing for comprehensive lifecycle management and performance monitoring.

By following these best practices, railroads and suppliers can ensure that remanufactured components deliver performance, reliability, and longevity comparable to new parts while reducing costs and environmental impact.

Core Availability

One of the most significant challenges in remanufacturing is ensuring a steady supply of cores remains in circulation, as they are the components that serve as the foundation for remanufacturing. Without a reliable pool of cores, remanufacturing operations can quickly become inefficient, leading to delays and increased costs, and the need to source new components. Some key challenges which impact core availability include aging fleets and components, poor management of materials, variability in component condition, and logistical challenges.

Aging Fleet and Component Scarcity

- When locomotives are retired, their components are scrapped or sold to secondary markets, limiting the number of cores that would have otherwise been used for remanufacturing.
- Low volume of components originally manufactured by the OEM means the core components also exist in small numbers.

Core Condition and Usability

- Not all components are suitable for remanufacturing due to catastrophic damage or poor condition.
- A part that is worn beyond repair falls out of circulation when scrapped.
- Fall out is inevitable and it has a direct impact on the number of core components in circulation.

Reverse Logistics and Core Recovery

- Railroad and suppliers must work together and utilize efficient systems for collecting, transporting, and processing the old core components to maintain a steady supply of cores.
- Suppliers incentivize the return of used components by offering discounts or credits toward new or remanufactured parts, as part of a UTEX (unit exchange) program.
- Efficient recovery can reduce core losses by up to 30%, ensuring a more sustainable and cost-effective remanufacturing process (GreenRail Journal, 2023).

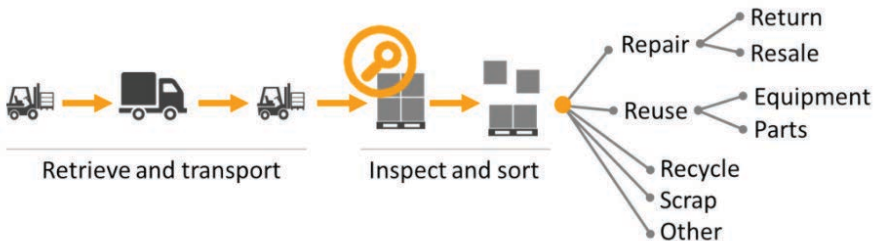


Figure 5 Reverse Logistics Flow (Source: Alynn International 2025)

Strategies for Improving Core Availability

- Lifecycle or asset tracking in the form of RFID tags, GPS trackers, or blockchain-based systems can provide end-to-end visibility into component lifecycles.
- Railroads can establish partnerships with known industry recyclers and third-party remanufacturers to attempt to reclaim cores that would otherwise be scrapped.

By addressing core availability challenges through strategic retention programs, advanced inspection methods, improved reverse logistics, and innovative restoration techniques, the railway industry can enhance efficiency, reduce costs, and promote sustainability.

Long-Term Sustainability of Remanufactured Locomotives

The sustainability benefits of remanufacturing extend far beyond cost savings, offering significant advantages in environmental conservation, resource efficiency, and long-term economic viability. As railroads seek to align their operations with modern sustainability goals, remanufacturing plays a critical role in ensuring a reduced carbon footprint and responsible resource management.

Environmental Benefits and Emissions Reduction

- Extending the lifecycle of existing parts, remanufacturing significantly reduces the need for new production and, in turn, minimizes its environmental impact.
- Studies show remanufacturing can reduce carbon emissions by up to 60% compared to manufacturing new parts. Additionally, the remanufacturing process itself typically consumes 85% less energy than producing new locomotive components from raw materials.
- By upgrading remanufactured engines, railroads can improve fuel efficiency while reducing NOx and particulate emissions, ensuring compliance with modern environmental standards.

Lifecycle Extension and Resource Conservation

- Without remanufacturing, many locomotives would be retired prematurely, leading to increased demand for new units and additional strain on natural resources.
- By implementing remanufacturing programs, railroads can extend the service life of locomotives and their major components by 15 to 20 years.
- Remanufacturing supports the circular economy, where materials and components are continuously repurposed rather than discarded.

Economic Sustainability and Cost Savings

- Remanufacturing can lower maintenance expenses by 40% to 60%, making it a financially viable option for large fleet operators. These savings allow railroads to reinvest in their operation.
- By maintaining a steady flow of remanufactured parts, railroads can minimize locomotive downtime and improve fleet availability, ensuring that trains remain in operation without extended delays.



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- Remanufacturing requires high-skilled jobs in areas such as precision engineering, advanced machining, and quality assurance, supporting the development of a more robust and resilient industrial workforce.

Supporting Sustainable Rail Operations

- To reduce their environmental footprint while maintaining cost-effectiveness, several major railway operators have committed to increasing their use of remanufactured components as a sustainability initiative.
- Some locomotive repowering programs have demonstrated a 25% to 30% improvement in fuel efficiency while reducing emissions by up to 50% compared to legacy locomotives.
- Closed-loop remanufacturing, where used components are collected, remanufactured, and reintroduced into the supply chain, ensures that materials remain in circulation, reducing waste and improving utilization of existing resources.

Investment in remanufacturing will continue to be a key driver of sustainable rail operations, ensuring that locomotives remain viable assets for decades to come. Future advancements in engineering, automation, and predictive analytics will continue to drive the sustainability of remanufactured components.

The Future of Remanufacturing in Railway

The railway industry is undergoing significant transformation as technological advancements, regulatory pressures, and sustainability initiatives drive innovation. Emerging trends in remanufacturing are focused on enhancing efficiency, improving material utilization, and leveraging automation to streamline processes.

Artificial Intelligence and Predictive Analytics

- Machine learning algorithms analyze data from onboard sensors to predict failures in engines, traction motors, and braking systems.
- Digital twin technology creates a virtual replica of components, allowing engineers and machinists to simulate different wear scenarios and determine optimal remanufacturing cycles.
- By leveraging AI-driven diagnostics, railroads can transition from reactive maintenance to proactive, condition-based maintenance, maximizing the effectiveness of remanufacturing efforts.

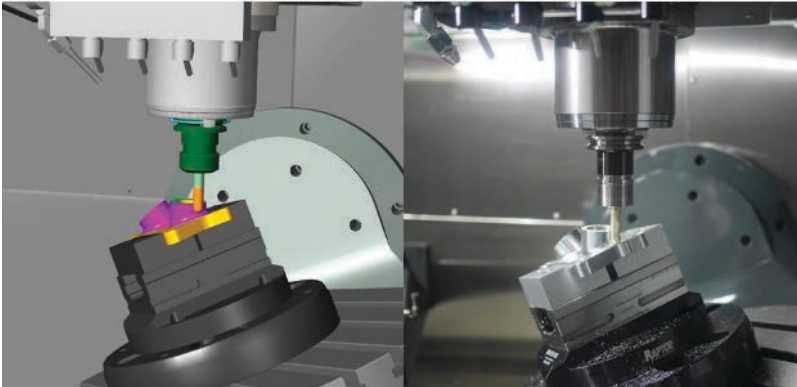


Figure 6 Side by Side Comparison of Digital Twin Simulation and Real Machining Process (Source: Hexagon 2025)

Automation and Robotics in Remanufacturing

- Automated disassembly of complex locomotive components, improving efficiency and reducing damage to reusable parts.
- Robotic welding to restore worn-out engine blocks, traction motor housings, and other components.
- CNC machining and 3D printing to restore or enhance the structural integrity of components.

Circular Economy and Closed-Loop Remanufacturing

- Recover and refurbish materials from end-of-life locomotives for reuse in new or remanufactured products.
- Optimize core collection programs to ensure steady core availability and minimize component waste.
- Standardize remanufacturing practices across different rail operators to create a more consistent supply chain for refurbished locomotive parts.

Regulatory and Policy Development

- Emissions reduction: Regulations such as the U.S. EPA's Tier 4 emissions standards.
- Incentives: Governments tend to offer tax credits and financial incentives for rail operators that invest in remanufacturing infrastructure and green technologies.
- Standardization: Industry groups such as the American National Standards Institute (ANSI) and the Association of American Railroads (AAR) continue to work on establishing standardized testing and guidelines for remanufactured components, ensuring the highest quality and safety compliance.

Digital Integration in Remanufacturing

- Real-time tracking of locomotive components, ensuring visibility into their lifecycle history and condition.
- Secure and transparent record-keeping for remanufactured parts, reducing the risk of counterfeit components entering the supply chain.
- Automated inventory management, optimizing the availability of remanufactured parts and minimizing supply chain bottlenecks.

By continuing to leverage these areas the railway remanufacturing industry is poised for continued growth.

Conclusion and Recommendations

Remanufacturing plays a crucial role in the railway industry, providing a cost-effective, sustainable, and efficient means of maintaining locomotives and their essential components. As railroads face increasing economic pressures, environmental regulations, and supply chain disruptions, the ability to extend the lifespan of high-value asset, such as locomotives, through remanufacturing has never been more important.

Advancements in AI predictive maintenance, automation, engineering, circular economy initiatives, and digital integration will no doubt revolutionize remanufacturing, making it even more effective. As these innovations continue to develop, rail operators must proactively invest in and refine their remanufacturing strategies to remain competitive.

To maximize the benefits of remanufacturing and ensure continued success, the following strategic recommendations are proposed:

- Continue to invest and support advanced technologies.
- Enhance core availability through reverse logistics by collaborating between railroad operators and suppliers.
- Create meaningful initiatives towards improving sustainability and a circular economy.
- Designate key personnel to participate in regulatory compliance and industry groups to be involved in changes that may impact your operation.
- Promote workforce development and training to keep pace with emerging technologies, such as AI and advanced manufacturing.

Final Thoughts

As the railway industry continues to evolve, remanufacturing will remain a cornerstone of rail operations and supplier networks, extending the lifespan of their assets while minimizing costs and environmental impact. Through strategic investment, industry collaboration, and a commitment to sustainability, the railways and their suppliers can ensure that remanufacturing remains a key driver of efficiency and resilience.

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Report on the Committee on Electrical Maintenance

Thursday, May 22, 2025

9:00 AM



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NOTE: SHANE SLEDGE, NORFOLK SOUTHERN, STEPPED DOWN FROM THE COMMITTEE AND WILL BE REPLACED BY DENNY BOWERMAN

PERSONAL HISTORY

Brent Brown

Director of Locomotive and Car
Transportation Products Sales Company
O'Fallon, MO

For the past six years, Brent has served as the Director of Locomotive & Freight Car for Transportation Products Sales Company. He has established business relationships with locomotive OEMs and railroads, focusing on solutions-based technology. He promotes best in class products and processes for battery maintenance, battery testing, and training within the North American rail industry. Brent is deeply involved in the business development of TPSC products used throughout the Locomotive segment.

Before joining TPSC, Brent held multiple leadership roles at a Class I railroad. He was part of the Mechanical Finance team for Kansas City Southern Railroad. His last role was managing mechanical contracts for the locomotive and freight car fleets in both the US and Mexico.

He also brings valuable experience from his tenure as the Operations Manager at Wabtec Global Services, where he was responsible for lean initiatives within the organization.

Brent began his career supporting the overhaul program at a class one for GE, where he discovered his passion and dedication to the industry—a commitment that continues to drive him today.

He has been a member of the LMOA for six years and takes pride in serving the industry, alongside respected predecessors. He currently serves as the Chair of the LMOA Electrical Committee and has authored a white paper on Battery Maintenance Practices. His enthusiasm for the field is evident in his belief that the people in the industry are its most important asset. Brent is committed to upholding and representing the traditions of the LMOA.

Brent received a Bachelor of Business Administration degree from Baker University. He resides in Liberty, Missouri with his wife Ashley, and their daughters. In his free time, Brent enjoys hunting, fishing, and kayaking.



THE LMOA ELECTRICAL COMMITTEE WOULD LIKE TO THANK SOUTHWEST RESEARCH INSTITUTE (SWRI) FOR HOSTING THE SPRING ELECTRICAL COMMITTEE MEETING IN SAN ANTONIO, TX ON MARCH 11, 2025; ORGANIZED AND LED BY RANDY HONC. SWRI SERVES SEVERAL MARKETS, BEYOND RAIL TRANSPORTATION SUCH AS DEFENSE, AEROSPACE, FUELS, ENERGY AND ENVIRONMENTAL RESEARCH TO NAME A FEW.

THE ELECTRICAL COMMITTEE WOULD LIKE TO THANK MICHAEL MURPHY FOR SHOWING THE SWRI ENERGY STORAGE TECHNOLOGY CENTER NEAR THE SWRI MAIN CAMPUS AND PRESENTING AN OVERVIEW OF THE ROLE THEY PERFORM IN THE DEVELOPMENT OF ENERGY STORAGE SYSTEMS. THE ENERGY STORAGE TECHNOLOGY CENTER INTEGRATES MULTIDISCIPLINARY EXPERTISE IN AUTOMOTIVE, ELECTRICAL, CHEMICAL AND MECHANICAL ENGINEERING IN RESEARCHING WAYS TO IMPROVE STORAGE FOR BATTERY SYSTEMS SUCH AS LITHIUM ION, ADVANCED LEAD ACID, FLOW BATTERIES, ULTRA-CAPACITORS AND BATTERY MANAGEMENT SYSTEMS.

IN ADDITION, WE WOULD LIKE TO THANK STEVE FRITZ FOR TOURING THE SWRI LOCOMOTIVE TECHNOLOGY CENTER (LTC) IN DOWNTOWN SAN ANTONIO AND PRESENTING A LITTLE HISTORY AND SYNOPSIS OF THE TESTING PERFORMED AT THE LTC.

IT IS WITH GREAT SADNESS THAT SHANE SLEDGE OF NORFOLK SOUTHERN WILL BE LEAVING THE LMOA ELECTRICAL COMMITTEE. SHANE HAS ASSUMED ADDITIONAL RESPONSIBILITIES AT NORFOLK SOUTHERN AND CAN NO LONGER COMMIT THE RESOURCES NEEDED. THE ELECTRICAL COMMITTEE WISHES SHANE ALL THE BEST IN HIS NEW ROLE AT NORFOLK SOUTHERN AND THANKS HIM FOR ALL THE YEARS OF SERVICE HE GAVE TO LMOA. HOWEVER, IT IS WITH GREAT PLEASURE THAT DENNIS BOWERMAN OF NORFOLK SOUTHERN WILL BE ASSUMING HIS PLACE IN THE ELECTRICAL COMMITTEE. THE ELECTRICAL COMMITTEE WELCOMES DENNIS AND HIS PARTICIPATION IN FUTURE EVENTS.

Diesel Electric AC Locomotives

Prepared by :

Randell L. Honc – Southwest Research Institute (SwRI)

Shane Sledge – Norfolk Southern Corp. (NS)

Introduction

A diesel-electric transmission system is composed of a diesel engine connected to an electric generator, which then powers electric motors. The beauty of this system lies in the fact that the electric motor speed is independent of diesel engine speed, allowing the diesel engine to run at optimum speed for either power or fuel economy. Railroads adopted this technology because it offered greater flexibility and performance over steam locomotives, along with lowering operating and maintenance costs.

DC Locomotives

DC bus voltage is related to the traction motor speed.

$$E(s) = kI\omega \Rightarrow \frac{E_1}{\omega_1} = \frac{E_2}{\omega_2}$$

Where E(s) is the back EMF (volts) and ω is angular speed (rpm). Thus, the DC bus voltage is directly proportional to motor speed and therefore linear speed (mph).

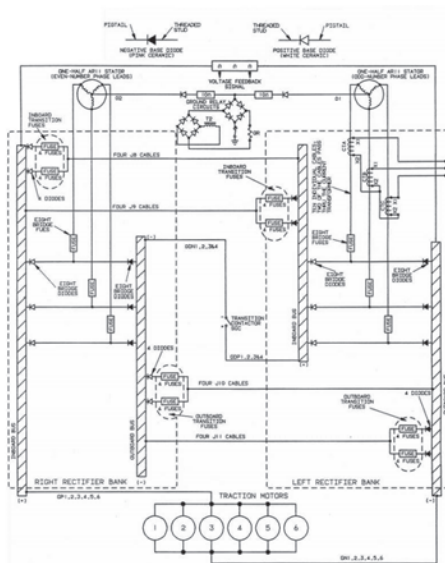
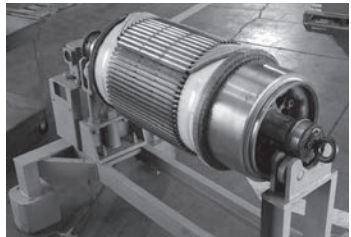
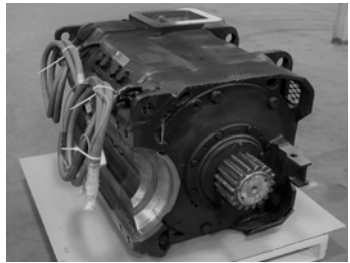


Figure 1. AR11 Transitioning Alternator



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Dir. Engineering, Quality & Cust. Service
jhustedt@national-electric-coil.com

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There are little tricks that you can do to with a DC drive motor system to optimize starting torque while maintaining top speed. A transitioning alternator (EMD AR11) is composed of two sets of windings and is presented in Figure 1. At low speed, the two sets of windings are placed in parallel, doubling the current (torque) produced by the alternator. At around 16 mph, the alternator is reconfigured so that the two sets of windings are in series, doubling the output voltage of the alternator and allowing for higher traction motor speed. Additionally, the traction motors can be configured to optimize starting torque and top speed. Two traction motors are placed in series for starting the train, when lots of torque is needed to start from stop, and later switched to a parallel configuration for high speed. A Series Motor configuration, shown in Figure 2, provides high starting torque. The traction motors stop accelerating when the drag of the train matches the torque produced by the traction motors and maximum speed is achieved.

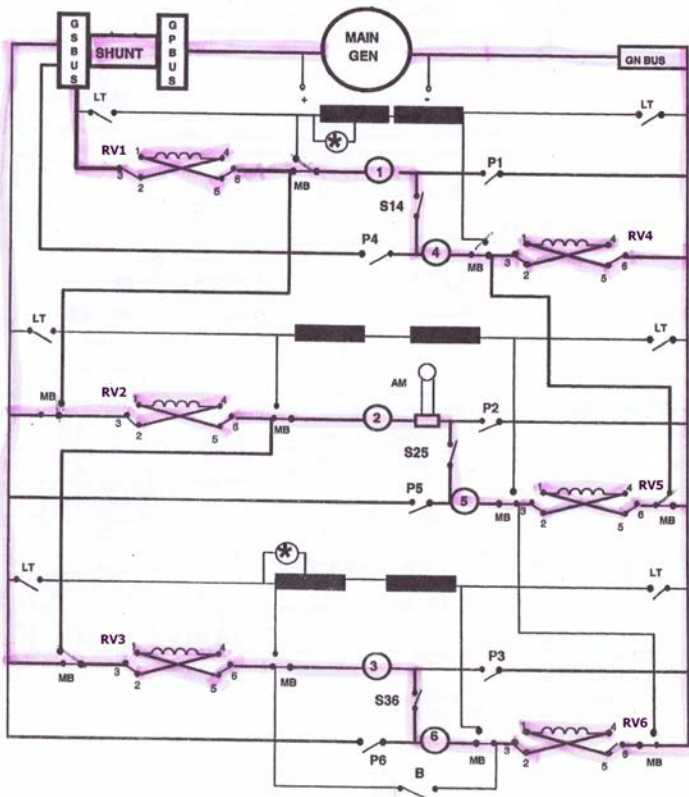


Figure 2. DC Traction Motor Series Motor Configuration

AC Locomotives

AC locomotives are essentially DC locomotives equipped with AC Variable Frequency Drives (inverters) and AC traction motors. The AC inverters convert the DC power at the DC bus into three-phase AC power to run the AC traction motors. This arrangement allowed locomotive electricians a smooth transition from DC to AC locomotives, leveraging their existing knowledge of DC locomotives to repair and maintain new AC locomotives.

The different notches (1 through 8) produce progressively higher DC bus bar voltages, which the inverters convert to three-phase AC voltage to power the AC traction motors. Typically, each traction motor has its own inverter, allowing each traction motor to be optimized to produce maximum torque without wheel slip.

AC traction motors fundamentally differ from DC traction motors in that the frequency of the AC voltage determines the speed of the AC traction motors, whereas the magnitude of the DC voltage determines the speed of DC traction motors. The ability of the AC inverter to produce AC voltages at various frequencies is why inverters are also known as Variable Frequency Drives (VFDs).

The AC traction motors are designed for a rated current and frequency, but the AC inverters are where the magic happens.

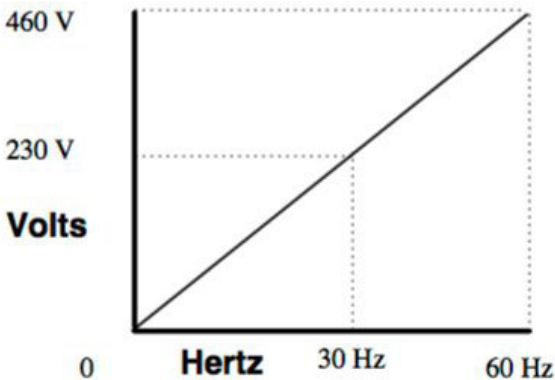


Figure 3. Constant Voltage vs. Frequency

Early on, it was observed that if the inverter voltage and frequency was held constant to the rated voltage (at the rated current) and the rated frequency then you would never over-current (heat) the traction motors. The constant voltage vs. frequency strategy used by the inverter is presented in Figure 3.

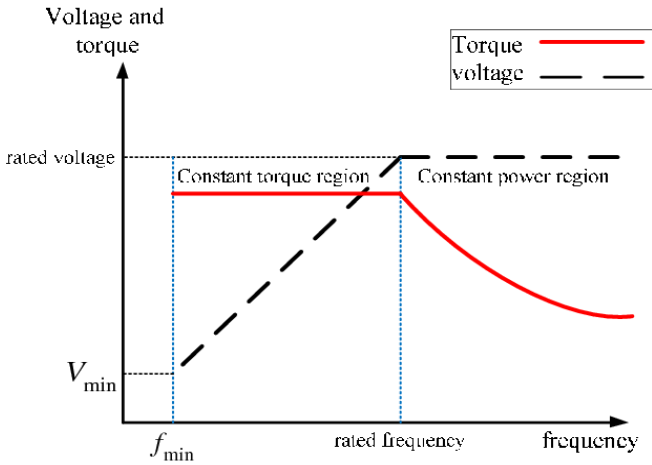


Figure 4. Available Torque as a Function of Frequency

Although it is possible to overspeed the AC motor by running the AC inverter faster than the rated frequency, this only results in marginal speed increases. Doubling the frequency doubles the reactive losses of the AC motor's inductance.

This reduces the available current, which in turn reduces the available torque. As previously mentioned, the traction motors stop accelerating when the drag of the train matches the torque produced by the traction motors. Available torque as a function of frequency is presented in Figure 4.

AC Traction Motors

AC motors come in two different types: synchronous and asynchronous. All locomotive AC traction motors are of the asynchronous type, also referred to as induction motors because the stator voltage induces an electric current in the rotor, which produces torque.

An induction motor, or asynchronous motor, is composed of a rotating part called the rotor and a stationary part called the stator, as shown in Figure 5.

The stator is the outer part of the motor that houses the stator windings and is stationary. The stator windings of a three-phase induction motor consist of three separate insulated windings, made up of electrically conductive wire coils. When an alternating electric current flows through these coils, an alternating magnetic field is generated, inducing an electric current within the rotor which produces torque. Note that this is also how transformers work.

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Figure 5 Induction Motor Stator (left) and Rotor (right)

The rotor rotates within the stator windings without any external electrical connections and is commonly referred to as a squirrel cage design. The rotor consists of laminated longitudinal conductive bars set into grooves and connected at both ends by shorting rings, forming a squirrel cage-like structure. To prevent eddy currents from forming, the longitudinal conductive bars are laminated like a transformer core, as eddy currents produce unnecessary heat generated by resistive losses. The lack of brushes or commutator provides a simple and rugged design.

AC induction motors have no electrical connections to the rotor and no electrical connection between the rotor and stator. Three-phase AC power is supplied to the motor's stator, creating a magnetic field that rotates in time with the oscillations of the current. The stator and rotor circuits are magnetically coupled.

Since there are no external electrical connections to the rotor, all voltage present on the rotor windings must be "induced" across the air gap by the magnetic fields created by the stator current. This principle is used by electrical transformers to pass AC power from one electrical circuit to another. As long as the rotor rotates at less than the magnetic field created by the stator, the stator and rotor circuits remain magnetically coupled.

As the rotor speed approaches the AC frequency of the voltage applied to the stator winding, the rotor and stator become uncoupled. When the rotor and stator become uncoupled, the motor stalls, and the rotor speed drops off. When the rotor speed drops off sufficiently, the rotor and stator become magnetically coupled again, and the motor resumes operation. The difference between synchronous speed of the stator and operating speed of the rotor is called "slip". Therefore, some slip is necessary for an induction motor to work, and VFDs provide a solution as they can vary the frequency of the voltage applied to the stator.

Conclusion

The adoption of diesel-electric transmission systems and the evolution from DC to AC locomotives represent significant advancements in railroad technology. This paper highlights the operational efficiency and cost-effectiveness of these systems, particularly the advantages of AC traction motors.

DC locomotives, with their reliance on DC bus voltage proportional to traction motor speed, have specific configurations to optimize starting torque and top speed. However, the transition to AC locomotives, equipped with AC Variable Frequency Drives (VFDs) and AC traction motors, offers superior performance. The ability of VFDs to convert DC power to three-phase AC power, optimizing each traction motor individually, ensures maximum torque production and reduces wheel slip.

AC traction motors, specifically asynchronous or induction motors, benefit from a rugged and brushless design. The use of inverters to maintain traction motor operation near rated current significantly reduces maintenance costs and enhances performance. Despite the higher initial costs of AC inverters, the long-term benefits, including reduced maintenance and improved efficiency, make them a valuable investment for the railroad industry.

Enhancing Locomotive Reliability Through Auxiliary Battery Integration

Prepared by :

David Caron, Ekyrail Enterprises Inc.

Jason Hettermann, Fugiel Railroad Supply Corp.

Stephen Alessandrini, CN Railway

List of Acronyms

OEM	Original Equipment Manufacture
PTC	Positive Train Control
LDVR	Locomotive Digital Video Recorder
AESS	Automatic Engine Start/Stop
APU	Auxiliary Power Unit
LiFePO4	Lithium Iron Phosphate Battery
BMS	Battery Management System

Introduction

For decades, locomotives equipped with electronic controls have proven to be invaluable to railroads, providing substantial improvements in efficiency and operational effectiveness. These advancements have not only enhanced the overall performance of locomotives but have also contributed to cost savings and environmental benefits.

Among the most important priorities for railroads has been finding ways to save fuel during idle periods and reduce emissions. Addressing these needs, Original Equipment Manufacturers (OEMs) developed the Automatic Engine Start/Stop (AESS) system, a game-changing solution designed to optimize fuel usage and minimize environmental impact.

The AESS system is a fully integrated software solution that carefully monitors several critical operating parameters during periods when the locomotive is idling. These parameters include, but are not limited to, engine water temperature, air pressure, battery voltage, and current. By constantly tracking these key metrics, the AESS system ensures that the locomotive engine remains off when it is not needed, preventing unnecessary fuel consumption and emissions.

The AESS system is governed by the AAR S-5502 standards (www.aar.com), which provide a framework for its operation and performance. Thanks to its efficiency in reducing idle times, the AESS system has proven to deliver rapid returns on investment. By significantly cutting fuel consumption, reducing the frequency of engine maintenance, and lowering overall operating expenses, the system has consistently demonstrated its value to railroads. The long-term savings

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Fuel Savings & Emissions Reduction : Prevents unnecessary idling which reduces fuel consumption along with emissions production.

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in both fuel and maintenance costs help offset the initial investment, making AESS a vital technology for improving the bottom line in the railway industry.

Background

The Rail Safety Improvement Act of 2008 mandated that Positive Train Control (PTC) systems be fully implemented on Class 1 Railroads by December 31, 2015. Alongside this, additional required technologies, such as the Locomotive Digital Video Recorder (LDVR), have become essential components of locomotive systems. These systems, crucial for safety and compliance, continuously draw power when the locomotive is in AESS (Automatic Engine Start/Stop) mode, actively consuming energy from the main locomotive battery, which is itself being monitored by the AESS system.

A key function of AESS is to maintain the main battery at a preset voltage to ensure the locomotive can perform effectively. When the battery voltage drops below a certain threshold, the diesel engine automatically engages to charge the battery, bringing it back up to the required level to power both the locomotive's primary functions and the energy-consuming equipment (such as PTC and LDVR). This process is vital for keeping the locomotive's systems operational while avoiding unnecessary engine startups.

However, as locomotives continue to modernize, additional complexities arise. Modern locomotives now rely on advanced engine computers to manage all critical operating parameters, such as engine performance, fuel usage, and emissions. These computers are powered by the main battery. If the battery is aging or weakened, it may struggle to provide sufficient power during a starting sequence. In such cases, the high draw from the engine starter can cause the main battery's voltage to dip below the normal operating range required for the engine computer to function properly.

When this happens, the engine computer is forced to restart, which can prevent the locomotive from starting normally. This issue often requires manual intervention, such as jumping power from another source, to get the locomotive operational again. These disruptions not only lead to delays but also add to maintenance costs and complicate the seamless functioning of modern, technology-dependent locomotives.

AESS Operation and contributing factors to restarts

Air leaks and low battery faults are often cited as the two primary factors that contribute to the need for AESS (Automated Engine Start/Stop) system restarts. These issues can create imbalances in the system, causing the AESS to trigger an engine restart to restore proper function. Air leaks, for example, can affect the air pressure levels needed to maintain proper engine operation, while low battery voltage may prevent the engine from starting or maintaining necessary power for essential systems.

In addition to these conditions, low temperatures can also play a significant role in triggering system restarts and in certain situations suspend shut downs. Cold weather can adversely affect the performance of both the battery and other components, such as the air system. When temperatures drop, the battery's ability to maintain charge is often diminished, and air systems may struggle to achieve the proper pressure levels needed to function efficiently. These environmental factors can cause the AESS system to engage a restart to stabilize the locomotive's systems.

Together, these three conditions—air leaks, low battery faults, and low temperatures—are the most common contributors to locomotive restarts. Addressing these factors through proactive maintenance and system monitoring will minimize restarts and improve reliability thereby reducing downtime and enhancing operational efficiency.

Auxiliary Power Units



Fig 1 Auxiliary Power Units

APU's play a crucial role in maintaining the critical functions of a locomotive without the need for manual intervention, helping to prevent the main locomotive engine from needing to start. This not only aids in efficiency but also helps reduce unnecessary wear and tear on the primary engine. However, the use of APU's does come with some drawbacks including the overall size. The initial cost of

equipment and ongoing maintenance expenses can be significant. Additionally, while APU's are generally more fuel-efficient than running the main engine, they still consume a small amount of fuel, which can add up over time. (Figure 1)

Air leak Detectors



Fig 2 Air Leak Detectors

Air leak detectors listen for air leaks. See figure 2 for an example of an air leak detector. They have become invaluable tools in identifying and addressing air leaks, allowing for timely repairs that help reduce the need to restart the locomotive engine. By proactively detecting leaks, these tools can improve system efficiency and minimize unnecessary engine restarts. However, despite the potential benefits, the effectiveness of this technology has been hindered by a shortage of manpower at locomotive maintenance facilities. The limited resources available for both conducting the tests and carrying out repairs have minimized the full positive impact that these detectors could deliver.

LiFePO4 Batteries

LiFePO4 (Lithium iron phosphate) batteries could emerge as a viable solution for locomotive starting systems if the technology continues to evolve and demonstrates a significant improvement over traditional flooded locomotive starting batteries. The potential for longer life, faster charging, and better overall performance makes LiFePO4 batteries an attractive option.

However, there are challenges to consider. The high upfront cost of LiFePO4 batteries and the complexities associated with retrofitting existing locomotives

to accommodate this new technology pose significant hurdles. Charging infrastructure and integration with current systems could also present technical difficulties.

Given the slow pace of adaptation in the industry and the price sensitivity of most operations, it's unlikely that LiFePO₄ batteries will replace flooded batteries as the primary starting solution in the near future. For the foreseeable future, flooded batteries will likely remain the industry standard.

Auxiliary Battery working with existing locomotive starting battery



Fig 3 Auxiliary Battery

By leveraging commercially available LiFePO₄ batteries into a unique locomotive architecture and integrating a dedicated BMS for optimized charging/discharging the industry could deploy an external energy storage unit to independently support auxiliary loads without impacting the main locomotive battery. This approach enables the main battery to remain focused on its primary function: providing the required current to start the locomotive engine. In contrast, the external LiFePO₄ battery would handle the essential loads, continuous power requirements of essential systems, including PTC, LDVR, and onboard electronics. See figure 3

This separation of power sources ensures that the main locomotive battery is not subjected to excessive cycling due to the additional loads, thereby preserving

its longevity, reducing degradation, and improving its overall capacity retention. Simultaneously, the external LiFePO₄ battery can supply a consistent voltage for essential systems, relying on its higher energy density and rapid discharge capabilities without necessitating engine operation or frequent charging of the main locomotive battery.

This results in a more efficient energy distribution across the locomotive's electrical systems, lowering the load on the main battery and reducing overall fuel consumption.

The integration of the external LiFePO₄ battery allows for several hours of uninterrupted power for auxiliary systems, preventing the need for the locomotive engine to restart merely to recharge the main battery. This delay in restarting also prevents the AESS (Automated Engine Start/Stop) system from entering penalty mode, which would otherwise hinder the system's ability to optimize fuel savings and emissions reduction. With the main engine not requiring frequent restarts, the AESS system is able to operate as intended, reducing the overall carbon footprint of locomotive operations and improving fuel efficiency.

Furthermore, by minimizing unnecessary engine restarts and optimizing the duty cycle of both the main and auxiliary battery systems, rail operators can see a tangible reduction in wear and tear on the main battery, along with a decrease in maintenance costs. Additionally, the ability to sustain operations without engine restarts directly contributes to a significant reduction in operational downtime, improving overall fleet availability and reducing fuel-related expenses. The auxiliary battery configuration, therefore, represents a highly efficient solution for modern rail systems, enhancing both operational performance and long-term sustainability.



Fig 4 LiFePO₄

Lithium Iron Phosphate (LiFePO₄) batteries (figure 4) are a unique type of lithium-ion battery. Compared to a standard lithium-ion battery, LiFePO₄

technology offers several advantages. These include a longer life cycle, more safety, more discharge capacity, and reduced environmental and human impact. LiFePO₄ batteries deliver high power density.

They can output high currents over a short period, allowing them to serve in applications that require short bursts of high power. Their major advantages include:

- **Thermal Stability:** They are less prone to overheating or catching fire.
- **Long Cycle Life:** They typically last much longer, with cycles often exceeding 2,000 charge/discharge cycles.
- **Environmental Safety:** They use non-toxic materials and are more environmentally friendly.
- **Lower Cost:** The raw materials are more abundant, which can reduce costs over time.

Conclusion: Future development and Evaluation

The integration of auxiliary battery systems using LiFePO₄ (Lithium iron phosphate) batteries presents a highly promising solution for improving the energy efficiency and sustainability of locomotive operations. By allowing auxiliary systems to be powered independently from the main locomotive battery, this approach enables the main battery to focus solely on starting the locomotive engine, while the auxiliary system handles essential loads. This separation not only optimizes energy distribution but also reduces wear on the main battery, prevents unnecessary engine restarts, and helps to lower fuel consumption and emissions.

Although the potential benefits of auxiliary battery systems are evident, a thoughtful and gradual approach is necessary to ensure that the technology performs as expected in real-world conditions. While the core concept of the auxiliary solution is solid, additional testing, refinement, and evaluation will be crucial to ensure the system operates effectively across a range of environments and operational scenarios.

- 1. Performance Under Varying Conditions:** Further evaluation of how the LiFePO₄ battery performs in different operational environments, such as varying temperatures, humidity levels, and load profiles, will ensure its reliability and efficiency across diverse operating conditions.
- 2. System Integration and Compatibility:** Ensuring that the auxiliary battery system integrates seamlessly with existing locomotive infrastructure is a priority. As with any new technology, fine-tuning the system to work harmoniously with current power management systems and safety features will be essential for smooth deployment. Equally, adaptation across locomotive types is a consideration as well.

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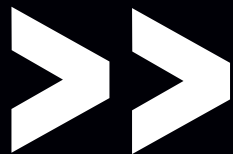
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- 3. Economic Feasibility:** The potential for significant fuel savings and reduced downtime is clear, but cost-effectiveness remains a key consideration. Operators will benefit from a closer look at the overall economic impact of deploying this technology, weighing initial investment costs against long-term operational savings.
- 4. Safety and Regulatory Compliance:** Adapting to new technologies involves ensuring that safety standards and regulatory requirements are met. Ensuring that the auxiliary system complies with all relevant regulations will ensure smooth, widespread adoption.
- 5. Gradual Rollout and Industry Feedback:** Real-world pilot programs and initial deployments will provide valuable feedback, helping to identify and address any operational challenges before full-scale implementation. These programs will allow manufacturers and operators to fine-tune the system and further optimize performance.

Conclusion

With continued testing and collaboration among manufacturers, operators, and industry stakeholders, auxiliary battery systems represent an exciting opportunity for the rail industry to enhance efficiency, reduce emissions, and contribute to meeting sustainability goals. As this technology evolves and becomes more refined, it has the potential to become a central component of the modern locomotive power system, helping railroads improve both their bottom line and their environmental footprint.

Although the track to full implementation may require careful attention to detail and further refinement, the potential benefits of auxiliary battery solution make it a promising step toward a more efficient and sustainable future for the rail industry.

Locomotive Wiring and Governing Specifications

Prepared by :

Gil Shoshani - Marmon IEI

Jim Notarfrancesco - Marmon IEI

AAR	Association of American Railroads
RP	Recommended Practice
DLO	Diesel Locomotive Cable
EPR	Ethylene Propylene Rubber
XLPO	Cross-Linked Polyolefin
ASTM	American Society for Testing and Materials
ICEA	Insulated Cable Engineers Association
LRV	Light Rail Vehicle
NFPA	National Fire Protection Association

Introduction

The paper reviews the AAR specifications for 600V and 2000V wire insulation for Locomotive and Transit Rolling Stock applications. Since the 1970s, Irradiated Cross-Linked Polyolefin (XLPO) wire insulation has been a staple on North American locomotives. During that period, cable smoking during overload conditions was reported by locomotive manufacturers. At the time, traction motor leads used DLO cables with EPR insulation and a protective jacket, as specified by AAR-588. Rated at 90°C, the DLO cable featured dual-layer construction.

In the late 1970s, locomotive manufacturers tested XLPO Irradiated Cross-Linked Polyolefin insulation for traction motor lead applications. The successful test results led to a transition from DLO to XLPO for locomotive wiring, including traction motor leads. The Surprenant Wire & Cable Company, based in Clinton, Massachusetts, was the first to introduce Locomotive XLPO insulation under the Exane™ name.

In 1983, AAR S-501 “Wiring and Cable Specification” was published, outlining tests to simulate locomotive operating conditions, such as abrasion, high heat, cold temperatures, overloads, oil exposure, penetration, crush, and flammability. This specification rated the insulation at 110°C. In 2001, AAR replaced S-501 with RP-585, which specifies a 110°C insulation temperature. However, locomotive manufacturers like EMD and GE increased this to 125°C in their local specifications for higher ampacities and heat resistance. North American Transit vehicles (Subway cars, LRV, etc.) continue to use 110°C wire insulation,

The Irradiation Process

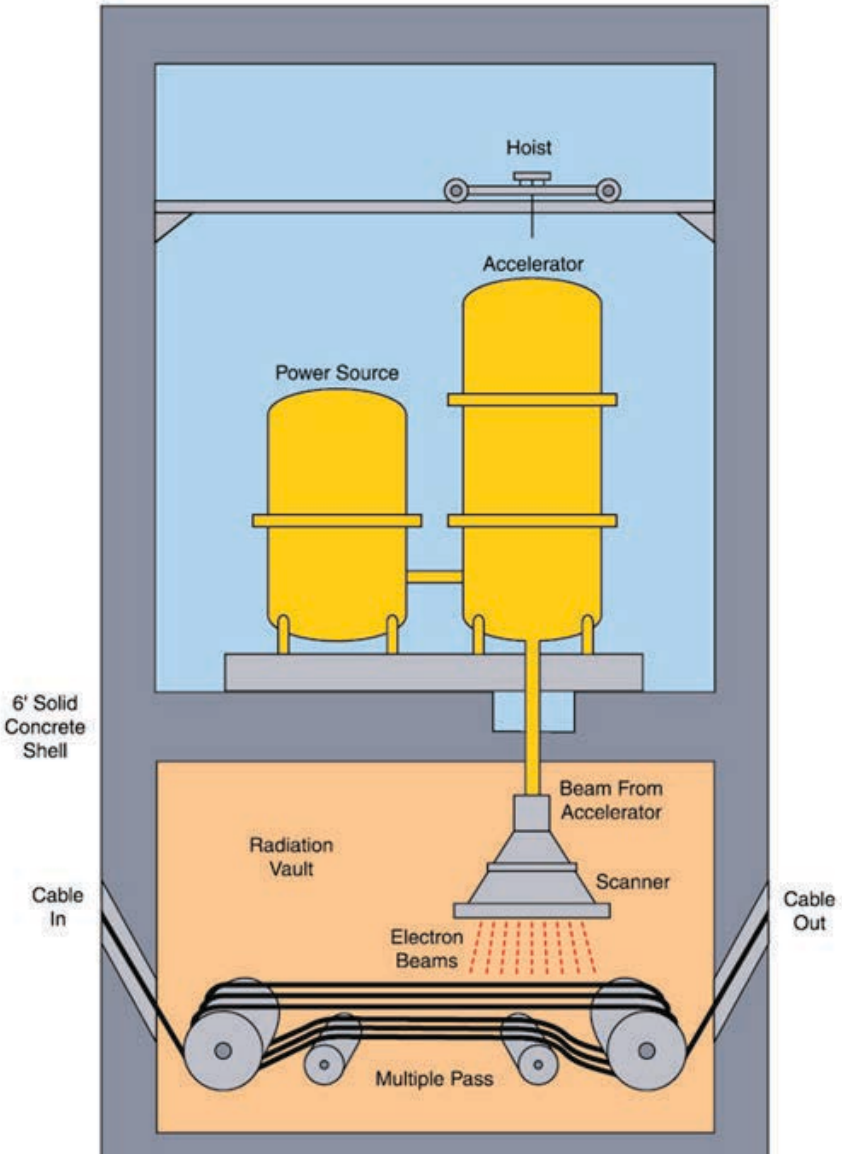


Figure 1. XPLO Irradiation Process



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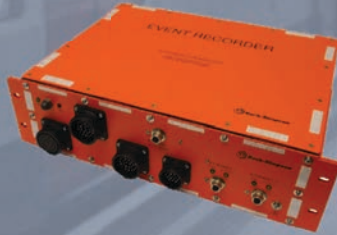
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unlike locomotives which use 125°C. The wire irradiation cross-linking process was pivotal in enhancing the durability and performance of locomotive wiring and is shown in Figure 1.

AAR RP-585 General Wire Requirements



Figure 2. Arrhenius Aging Set Up

RP-585 outlines the minimum requirements for control and power locomotive wire, emphasizing a minimum useful cable life of 20 years at an appropriate duty cycle, determined by the Arrhenius technique shown in Figure 2. The specification prioritizes attributes such as resistance to oils, salt, sand, caustic cleaning solutions, electrical overload, abrasion, cut-through, fungus, compression-crush, and flame retardancy. The wire features Tin Copper class I conductors with free stripping insulation for at least 2 inches and optional separator tape under the insulation. The cable should withstand at least 5 years of storage and not irritate the skin under normal handling and usage. Definitions of locomotive environmental impacts, such as shock, vibration, and acceleration, are included, with an insulation rating of 110°C and an ambient temperature range of -55°C to 80°C. The cable should also operate at a transient temperature of 150°C for 15 minutes.

Wire Physical Properties

The aging test shows the resistance of the insulation to high heat that is caused by high ampacity, duty cycle and Overloads. For new cables, the minimum insulation Tensile strength and Elongation are 1400 psi and 200%, respectively. However, North American locomotive manufacturers have increased these values in their local specifications to 1800 psi for Tensile strength and 250% for Elongation. Accelerated aging test per AAR RP-585 110°C insulation is 7 days at 158°C, retaining 90% Tensile and 50% Elongation of new insulation retention values. Locomotive manufacturers have further increased the insulation rating to 125°C by aging for 7 days at 170°C, retaining 50% Tensile and Elongation of new insulation retention values. Oil resistance tests using ASTM #2 Oil involve three conditions: 18 hours at 121°C, 7 days at 70°C, and 100 hours at 150°C, ensuring retention values, no cracks, ruptures, or splits.

Wire Electrical Tests

The electrical tests ensure very good insulation grade with high insulation resistance and low water absorption. Electrical tests include voltage withstand test after 6 hours of immersion in water, insulation resistance in 25°C air and water, and long-term accelerated aging water immersion test for 26 weeks at 90°C water.

The 6 hours Water Immersion Test is shown in Figure 3.



Figure 3. Water Immersion Test

Cold Temperature Tests

The cold temperature test shows the resistance of the insulation to cracking in cold and Arctic environments. Cold temperature tests involve cold bend test at -55°C (see Figure 4 for cold bend mandrels) and cold shock test at -40°C . The cold shock involves unwinding the wire from a mandrel while in the cold box as shown in Figure 4 (bottom photo).



Figure 4. Cold Bend Mandrels and Cold Shock Test

Electrical Overload

The intent of the overload test is to check the insulation resistance to high heat that is caused by high ampacity for a short period of time. Electrical overload tests cover single conductor overload without dielectric breakdown at 1000V AC, with specific ampacity for different wire gauges. For instance, 3 minute test of 14 AWG at 100A, 12 AWG at 135A, and 2/0 AWG at 1000A. Bundle overload tests involve 7 wires with the same ampacity as a single conductor for a 7-minute test, ensuring no smoke, insulation melting, or charring, with only the center conductor energized with overload ampacity. Figure 5 shows examples of single and bundled conductor overload tests.

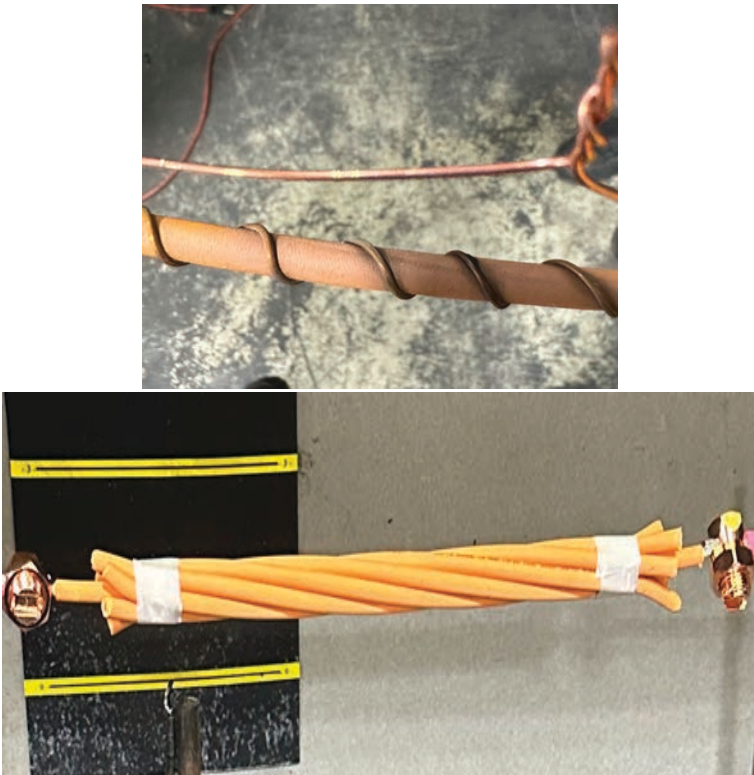


Figure 5. Single Conductor and Bundled Conductor Example

Mechanical Tests

These tests check the wire insulation for Crush, Abrasion and Flexibility that are common conditions in locomotive environment. Wires will rub against each other or to the locomotive frame over time. Good abrasion resistance is critical to the life of the wire. Crush resistance is important for heavy cable bundles that are installed over each other. The flexibility test ensure that the conductor and insulation materials are adequate for locomotive wire installation and cable life.

Mechanical tests include a crush test for 12 AWG, 2000V with a 6000 lbs. passing requirement. The abrasion test has a 1000 cycles requirement with specific weight, such as 12 AWG, 2000V wire with 1500 grams weight. 2 AWG is tested for abrasion with 8 lbs. weight. Additionally, a flexibility test is conducted for wires 2/0 AWG and larger. Figure 6 shows the fixture for the abrasion test and the wire after the abrasion test.

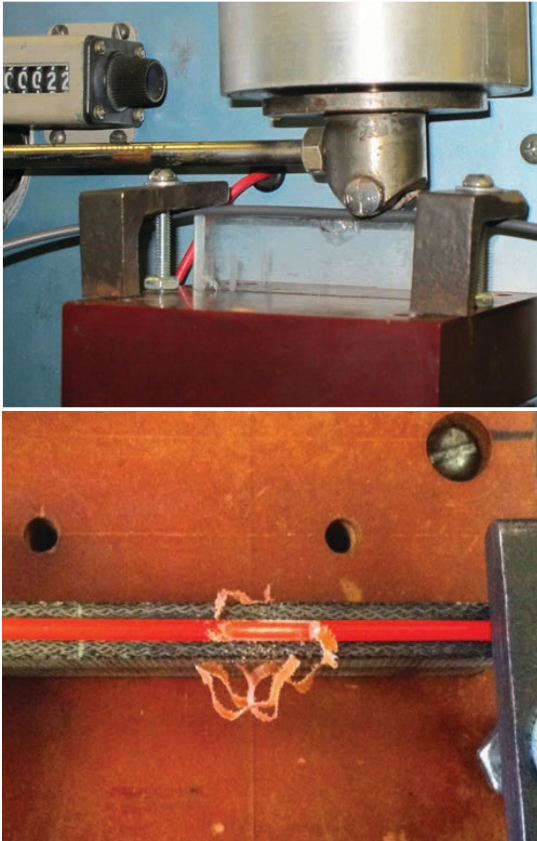


Figure 6. Crush Test and Abrasion Test

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Flame Test

The flame test checks the flame propagation and after flame of a single wire. The on/off flame applications show the wire resistance to propagating flame without a flame source.

The flame test involves small-scale ICEA vertical wire test with five flame applications. Notably, large-scale flame and smoke tests (UL 1685 FT4/IEEE 1202), toxicity tests (BSS 7239 or SMP-800), and small-scale smoke tests (ASTM E662) are not part of AAR RP-585 but can be added in local specifications.



Figure 7. ICEA Vertical Wire Test

Qualification

The cable supplier must meet all test requirements and perform all tests every two years. An audit can be conducted at the wire manufacturer's site for compliance. Any change in chemistry, physical properties, or electrical characteristics requires requalification.

Cable Construction

Tables detailing AAR class I stranding, voltage, insulation thickness per ICEA, diameter, and weight are provided for 600V, 2000V regular duty, and heavy-duty (HD) cables.

AAR RP-585 600V

Table 7.1 Cross-linked polyolefin—600 V stranding and dimensions

AAR Stranding	AWG Size MCM ^{a/}	Maximum Conductor Area (circular mil)	Maximum Uninsulated Conductor Diameter (in.)	Insulation Thickness (mil)	Maximum Insulated Diameter (in.)	Approx. Weight (lb/1000 ft)	Insulation Color ^{b/}
19/30	18	1900	0.052	30	0.110	11	Y
19/0092	18	1608	0.047	30	0.120	11	R
19/29	16	2413	0.062	30	0.128	13	C
19/27	14	3831	0.074	30	0.142	18	C
37/30	14	3700	0.075	30	0.145	21	
19/25	12	6088	0.094	30	0.162	26	
37/0133	12	6545	0.095	30	0.168	29	
27/24	10	10910	0.125	30	0.196	44	
37/24	8	14950	0.142	45	0.249	65	
61/24	6	24640	0.183	45	0.306	102	
91/24	5	36760	0.244	45	0.336	142	
105/24	4	42420	0.264	45	0.356	165	
125/24	3	50500	0.288	45	0.388	195	
150/24	2	60600	0.325	45	0.427	233	
225/24	1	90900	0.395	55	0.515	343	
275/24	1/0	111100	0.445	65	0.585	420	
2750/24	1111 ^{a/}	1110000 ^{c/}	1.370	110	1.639 ^{d/}	3742	

AAR RP-585 Regular Duty

Table 7.3 Cross-linked polyolefin—2000 V—thick wall NEMA 133% insulation level stranding and dimensions

AAR Stranding	AWG Size MCM ^{a/}	Maximum Conductor Area (circular mil) ^{b/}	Maximum Uninsulated Conductor Diameter (in.)	Insulation Thickness (mil) ^{c/}	Minimum O.D. (in.)	Maximum O.D. (in.)	Approx. Weight (lb/1000 ft)	Terminal Bore (in.)	Insulation Color ^{d/}
375/24	2/0	151500	0.518	65	.625	.671	570	0.531	GB
450/24	3/0	181800	0.555	65	.661	.709	711	0.562	GB
550/24	4/0	222200	0.610	65	.715	.765	851	0.625	GB
650/24	262 ^{a/}	262600	0.660	75	.782	838	979	0.666	GB
775/24	313 ^{a/}	313100	0.725	75	.845	.905	1150	0.734	GB
925/24	373 ^{a/}	373700	0.795	75	.914	.976	1354	0.812	GB
1100/24	444 ^{a/}	444400	0.870	75	.988	1.052	1608	0.875	GB
1325/24	535 ^{a/}	535300	0.950	90	1.093	1.167	1994	0.953	GB
1600/24	646 ^{a/}	646400	1.040	90	1.181	1.259	2300	1.047	GB
1925/24	777 ^{a/}	777700	1.130	90	1.269	1.351	2735	1.140	GB
2300/24	929 ^{a/}	929200	1.250	90	1.387	1.437	3255	1.265	GB
2750/24	1111 ^{a/}	1111000	1.370	110	1.541	1.639	3807	1.391	GB

AAR RP-585 2000V Heavy Duty (4/0 AWG and larger)

Table 7.2 Cross-linked polyolefin—2000 V—thick wall NEMA 133% insulation level stranding and dimensions

AAR Stranding	AWG Size MCM ^{a/}	Maximum Conductor Area (circular mil)	Maximum Uninsulated Conductor Diameter (in.)	Insulation Thickness (mil)	Maximum Insulated Diameter (in.)	Approx. Weight (lb/1000 ft)	Insulation Color ^{b/}
19/30	18	1900	0.052	45	0.141	15	
19/29	16	2426	0.062	45	0.158	17	O
37/30	14	3700	0.075	45	0.175	25	G
19/25	12	6088	0.094	45	0.192	32	
37/0133	12	6565	0.095	45	0.198	34	B
27/24	10	10910	0.125	45	0.228	51	
37/24	8	14950	0.147	55	0.267	71	G
61/24	6	24640	0.207	55	0.325	108	
91/24	5	36760	0.244	55	0.364	149	G
105/24	4	42420	0.264	55	0.384	173	
124/24	3	50500	0.288	55	0.408	204	G
150/24	2	60600	0.325	55	0.447	242	
225/24	1	90900	0.390	65	0.535	354	G
275/24	1/0	111100	0.440	65	0.585	420	
325/24	2/0	131900	0.447	65	0.627	494	
450/24	3/0	181800	0.565	105	0.780	711	
550/24	4/0	222200	0.620	105	0.850	851	G
650/24	262 ^{a/}	262600	0.660	105	0.895	979	
775/24	313 ^{a/}	313100	0.725	105	0.960	1150	
925/24	373 ^{a/}	373700	0.795	105	1.030	1354	
1100/24	444 ^{a/}	444400	0.870	105	1.105	1608	G
1325/24	535 ^{a/}	535300	0.970	120	1.235	1994	DG
1480/24	597 ^{a/}	597920	1.000	120	1.280	2140	G
1600/24	646 ^{a/}	646600	1.060	120	1.335	2300	
1925/24	777 ^{a/}	777700	1.130	120	1.405	2735	
2750/24	1111 ^{a/}	1111000 ^{d/}	1.390	120	1.645 ^{d/}	3807	

Conclusion

The paper concludes that 600V and 2000V wire insulation used for locomotives and transit vehicles in North America is Irradiated Cross-Linked polyolefin (XLPO). AAR S-501/RP-585 specify the tests for wire performance in locomotive environments. While wire insulation temperature ratings for locomotives are 125°C, transit vehicles use 110°C. AAR S-501/RP-585 serves as the base performance requirement for wires, with local specifications adding additional tests, such as resistance to antifreeze, Ozone, Notch propagation and temperature cycling test. Additional Flame, Smoke, and Toxicity (FST) tests can also be included in local specifications. AAR S-501/RP-585 cover single conductor cables, while multi-conductor cables made with XLPO or Neoprene jackets are not covered. The specifications also do not address other locomotive wires, such as Thin Wall 125°C 600V, Communication cables, High-temperature PTFE Teflon cables, and Silicone insulated cables for special applications. The expected cable life is 20 years, but field experience shows that the cable life exceeds 30 years or more.

Single Pair Ethernet (SPE)

*Prepared by :
Raul Huerta, HARTING Americas*

List of Acronyms

SPE	Single Pair Ethernet
IEEE	Institute of Electrical and Electronics Engineer
MBit/S	Megabits
GBit/s	Gigabits
IEC	International Electrotechnical Commission
MHz	Megahertz
PoE	Power Over Ethernet
PoDL	Power Over Data Line
LAN	Local area network
PTC	Positive Train Control
Iperf	Tool for network performance measurement and tuning
M / m	Meters
HOTD	Head of Train Device

Introduction

Ethernet connectivity was first introduced to the world over 50 years ago as a new communication protocol innovation memo from the Xerox research lab in Palo Alto, Ca by Bob Metcalf.

In the years since the memo Bob Metcalf along with David Boggs, Chuck Thacker and Butler Lampson designed and the built the first Ethernet LAN at the Palo Alto Research Center (PARC) in 1976 with a 2.94 Mbit/s protocol. By 1980, other scientists in the community worked on the protocol and in that same year released to market a 10Mbits protocol and published this standard as “The Ethernet, A Local Area Network. Data Link Layer and Physical Layer Specifications”

Xerox held the patent for Ethernet design but didn’t have interest in further pursuing Ethernet market development and subsequently Bob Metcalf left Xerox and started his own company 3Com. Bob Metcalf convinced DEC, Intel and Xerox to promote Ethernet as a standard and as part of that process Xerox agreed to relinquish their Ethernet trademark. This collaboration started the path towards the first IEEE Ethernet standards committee IEEE802.3 - Today the committee has over 70 published standards with 50+ new standards under development.

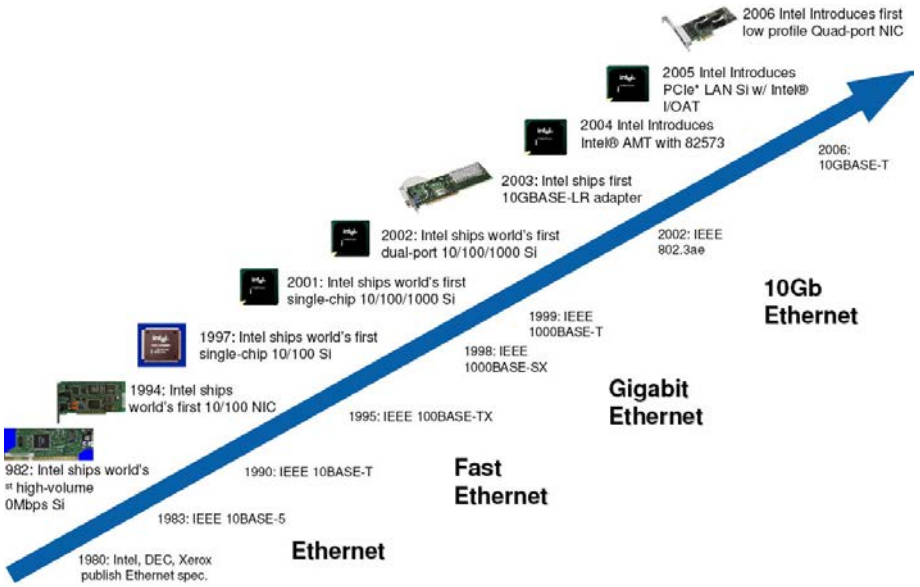


Figure 1. History of Ethernet

Source: <http://www.eetimes.com/electronics-news/4407540/Ethernet-s-40th-birthday-sparks-reunion-at-PARC>

Figure 1 is a snapshot of the fast-paced evolution of Ethernet and its correlation to microchip processing advancement. Today we are at 40GBASE-T / 40,000 GBits protocol over 4-pair cables.

Ethernet In Freight Locomotives

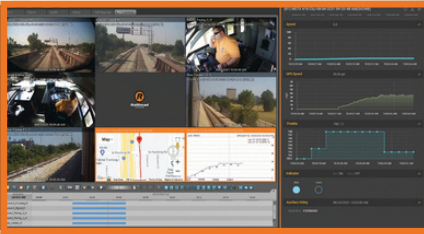
In the past 25 years the freight locomotive platform has evolved; particularly in the last 15 years, with new advanced microprocessor technologies and in cab technologies to support new digital product such as: digital event recorders, PTC, energy management, distributive power, high resolution cameras, signaling systems, over the air modules, and other technology on ancillary devices. All these devices support big data, safety and train handling that utilize Ethernet for transmission of data.



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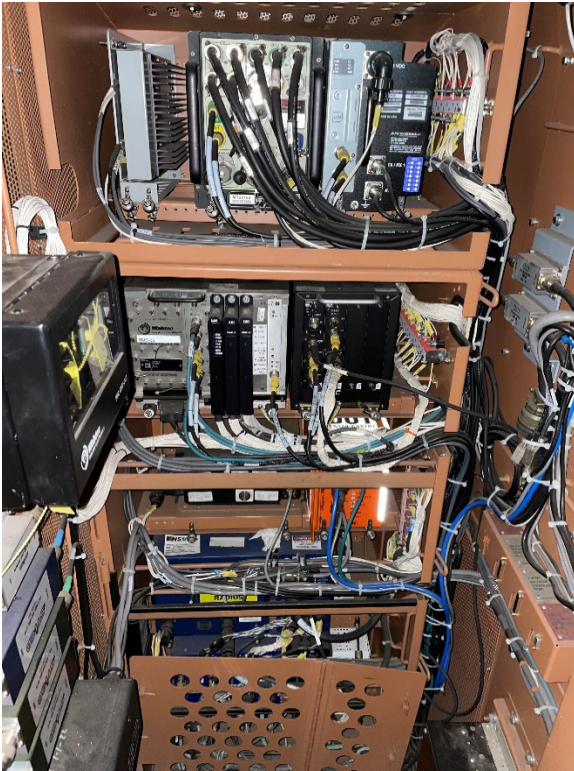


Figure 2. Ethernet Hub in a Modern Locomotive

The digital modernization of the locomotive platform was largely driven by the United States Congress PTC legislation that brought to the locomotive platforms new technologies that were designed to check that trains are moving safely and to stop them when they aren't from a back office that monitors 24/7 train movement. This legislation started a collaborative effort by the railroad supplier ecosystem and the Class 1 railroads to work towards a solution together to meet the PTC compliance date. In parallel during this period the railroads put on their technology roadmaps preventive maintenance, big data, fuel economy initiative, and enhanced real time locomotive data initiatives that were now possible because of technology adoption on the locomotive platform. Figure 2 is the vestibule of a modern locomotive that represents the new technology aforementioned and Ethernet connectivity.

Origins of Single Pair Ethernet (SPE)

The starting point for the development of SPE is the BroadR-Reach® standard developed by the Broadcom Corporation. After the automotive industry identified this new TCP/IP-based transmission method during its search for a successor to the CAN bus, the first SPE standard was published by IEEE 802.3 as the 100BASE-T1 standard. Piloted or semi-autonomous driving requires higher data rates and the Gigabit version followed quite quickly after the first SPE standard for 100 MBit/s. This Ethernet technology 1000BASE-T1 according to IEEE 802.3bp delivers 1 GBit/s transmission speed via just one wire pair. IEEE 802.3ch defines data rates of up to 10 Gbit/s, which are required for high-resolution sensors and video transmissions.

With IEEE 802.3cg, two further SPE standards for 10 Mbit/s were specified. These are 10BASE-T1S and 10BASE-T1L. The 10BASE-T1L standard is particularly relevant for many areas of industry, as it allows transmission distances of up to 1000 m and can therefore replace almost all fieldbuses. The 10BASE-T1S defines a point-to-point transmission over at least 15 m and a so-called multi-drop, which means that at least 8 nodes can be connected to a single-pair bus cable that is at least 25 m long. This so-called “Mixing Segment” does not support remote power supply via PoDL. With the IEEE 802.3da project, this Multi-Drop mode is to be extended to at least 50 m link length, 16 nodes and PoDL remote power supply. In addition, an SPE protocol for 25 Gbit/s has been standardized with IEEE 802.3cy. With this high data rate, it enables the basic technology for autonomous driving as a backbone for zonal computer architectures in the vehicle. For 100 Mbit/s, the 100BASE-T1L standard in accordance with IEEE802.3dg closes the gap for long transmission distances of at least 500 m.

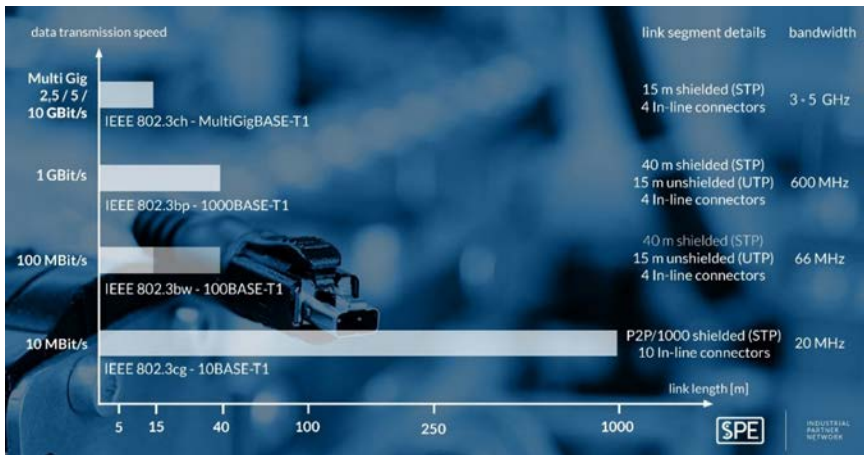


Figure 3. Range vs. Speed for the 100BASE-T1L Standard

Figure 3 is a graphical representation of range and transmission speed for the adopted IEEE 802.3 SPE standards.

As with multi-pair Ethernet cabling, there is also a standard for remote power supply for SPE, analogous to PoE, called PoDL = (IEEE 802.3bu). This combination of data and energy/power utilizes very small connector technology, and a single-pair cable supports the trends towards miniaturization, higher data rates and modularization for more complex systems - all prerequisites for the rapid development of a market for SPE applications. This also applies outside of vehicles in industry, smart cities and building technology as well as many other applications.

This means that SPE technology has already achieved the same performance as today’s predominant “multi-pair Ethernet” (MPE) within a very short period. The only limitation is the currently limited range for 100 Mbit/s and Gigabit SPE (15 m and 40 m respectively), which results from the requirements of the main target group in the automotive industry.

SPE in comparison to 2-pair and 4-pair Ethernet

SPE facts:

- **SPE is a new Physical Layer
→ All IP based application
run over SPE networks**
- **For SPE a complete new
infrastructure and
new devices are needed**
- **SPE provide the opportunity
for cost and space reduction**
- **Environmentally friendly,
because of less material use**

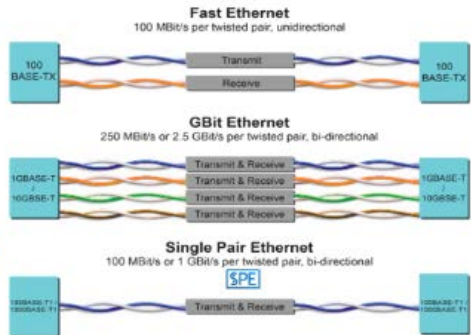


Figure 4. Principle representation of Ethernet transmission method

Figure 4 shows the various Ethernet configurations and Table 1 highlights the performance associated with each.

Data rate	4-pair Ethernet cabling (MPE)		Single Pair Ethernet (SPE)	
	Bandwidth (Cat.)	Transmission Length	Bandwidth	Transmission Length
10 MBit/s	16 MHz (Cat. 3)	100 m	20 MHz	1000 m
100 MBit/s	100 MHz (Cat. 5)	100 m	166 MHz	15 m
1 GBit/s	100 MHz (Cat. 5)	100 m	600 MHz	40 m
2.5 GBit/s	100 MHz (Cat. 5)	100 m	1000 MHz	15 m
5 GBit/s	500 MHz (Cat. 6A)	100 m	2000 MHz	15 m
10 GBit/s	500 MHz (Cat. 6A)	100 m	4000 MHz	15 m

Table 1. MPE vs. SPE Transmission Rate/Length

SPE In Railway Applications

Railway passenger OEMs are being confronted with space and weight problems that have them looking for solutions to address current cabling footprint and future footprint solutions for their rolling stock platforms. Modern railway coach cars builds are being built with display screens, automated doors, individual charging ports, autonomous trains, cameras and AI devices have taken up the already limited space in the coach car. A modern coach uses hundreds of pounds of Ethernet cable on each coach car to support ancillary devices and comfort devices. A platform migration to SPE will free up space for future applications and reduction in weight will improve fuel economy of the train.

Freight railroads have recently taken an interest in SPE as a potential solution to modernize the current MU cable with SPE. Migrating to a MU cable with SPE will be significantly lighter than the current MU cable owing to the reduced size and number of copper conductors while providing Gigabits per second of aggregate Ethernet bandwidth between each pair of locomotives in the consist.

The value in migrating away from the current MU analog protocol to an Ethernet protocol is new capabilities in communication to support new consist control initiatives to create a high-speed communications network between adjacent locomotives. With a new consist control system and Ethernet MU replacement cable a lead locomotive may consume telemetry information from trailing locomotives such as fuel level, health status, wheel slip, and power output. It would also enable the operator to use systems such as the HOTD of a trailing locomotive if the HOTD in the lead suffered a failure. It could also enable the operator to remotely view and operate systems onboard the trailing locomotives from the lead locomotive.

SPE Freight Locomotive Testing

Railroads recently tested SPE connectivity between multiple AC and DC locomotives in December 2024. In this testing, the current MU was replaced with an MU that consisted of three SPE cables and one Ethernet cable shown in Figure 5. The SPE to Ethernet media converters shown in Figure 6 were used to “bridge” the gap between the existing Ethernet network of the locomotive platform and the SPE MU.

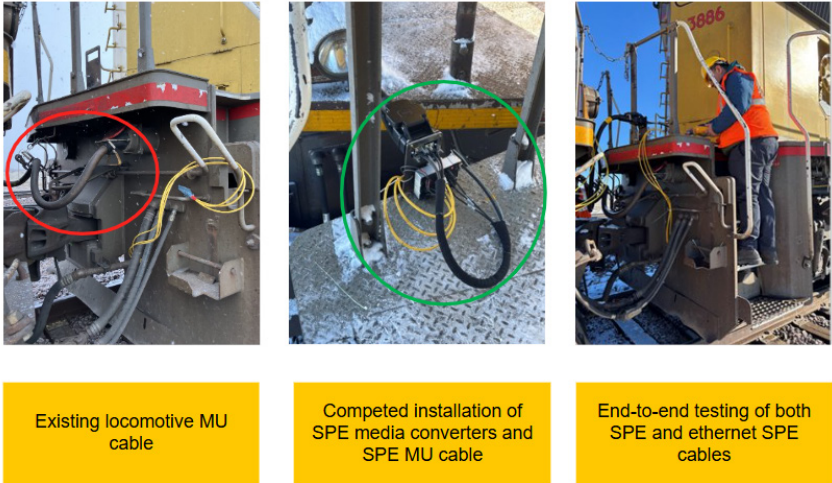


Figure 5.SPE Testing Configuration

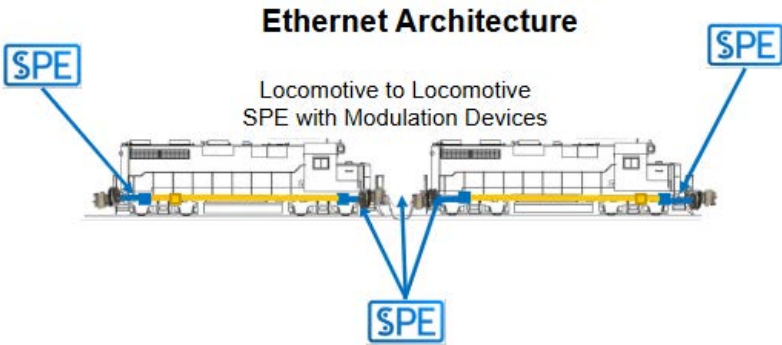


Figure 6. Representation of Ethernet Architecture on freight locomotive w/ SPE

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During the testing a two pair Ethernet cable was isolated for transmission testing, one SPE cable was tested for transmission and in another separate test three SPE cables were tested for transmission simultaneously. The data transmissions were monitored by 9 computers using an Iperf program to capture the data packs and to identify any potential packet loss. The testing scenario was to mimic real railroad consist scenarios to include a dead locomotive in consist.

SPE testing conditions included:

- Throttle Notch positions from Idle to Notch 8
- Dynamic Brake Effort
- Bypass of a dead Locomotive
- Use of a longer SPE Bypass Cable 40 meters in length
- Environmental testing
- All SPE and Ethernet tests passed performance testing.

Conclusion

SPE is the next evolutionary step for Ethernet communication driven by industrial and technology customers wanting to reduce their mechanical and carbon footprint without compromising current data rates for existing and new applications while future proofing their platform networks for future technologies.

The main driver for SPE growth will come from industries where footprint, weight and cost are critical in existing and new platform designs. Key stakeholder markets for SPE are data centers, robotics, automation, automotive, aviation, agriculture, and railway.

Value propositions for SPE in rail:

- Cost- Effective due to the reduction of copper migrating from 2 or 4 pairs of copper down to 1 pair of copper.
- Simplified cabling through size reduction, the cabling infrastructure of Ethernet cables will become less complex and easier to manage during installation and maintenance, reducing labor cost.
- 50% less weight than traditional 2 or 4 pair Ethernet cable.
- Potential for 10 times better range and device coverage with the ability to support 10Mbps to distances up to 1000 meters and 10 times the transmission performance with existing options for 1Gbps and multi-gigabit on the horizon.

Today Ethernet to SPE modulation devices are available on the market and major industrial OEM's and suppliers are testing SPE on their platforms and interfaces for many of their sensors. The Railway market is ready to start migration to SPE with certain applications with SPE to Ethernet media converters and switches as the modulation "bridge" between 2 or 4 pair and 1 pair copper

network architecture on their platforms. With future advancements in the microchip sector this will drive OEM's and suppliers to SPE based products that will get us closer to railway rolling stock platforms using SPE instead of 2 or 4 pair Ethernet in the network architecture.

List of Acronyms

SPE	Single Pair Ethernet
IEEE	Institute of Electrical and Electronics Engineer
MBit/S	Megabits
GBit/s	Gigabits
IEC I	nternational Electrotechnical Commission
MHz	Megahertz
PoE	Power Over Ethernet
PoDL	Power Over Data Line
LAN	Local area network
PTC	Positive Train Control
Iperf	Tool for network performance measurement and tuning
M / m	Meters
HOTD	Head of Train Device



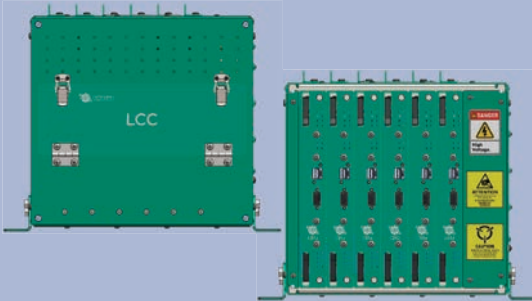
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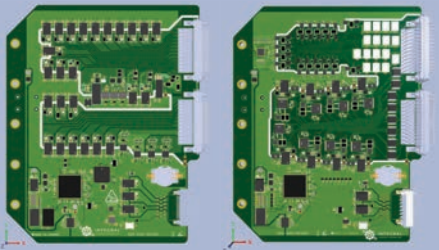
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